THE DESIGN OF STRUCTURE IN SCOTTISH MASONRY BUILDING
c.1100-c.1650

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PhD Thesis The University of Edinburgh 2002

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I hereby declare that this thesis has been composed by me, that the work is my own, and that the work has not been submitted for any other degree or professional qualification except as specified above.

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ABSTRACT

It is known both from documentary sources and from more recent analysis that much if not most medieval and renaissance period building design in Europe was based on a geometric or modular framework. It is also known from similar sources that, whilst in certain cases geometry was also the basis for the sizing of individual structural elements, in others these were determined more logically by conventions or rules of thumb based on simple proportional relationships with other structural dimensions, principally height and/or span, particularly in and from the late medieval period.

This research uses measured surveys of a selection of masonry buildings in Scotland to assess the extent and generality of the use of geometry, or of such proportional conventions in the design of wall structure and vault abutment. The research includes some buildings where an element of structural sufficiency or even economy might be expected, and others where a degree of fortification was required.

The results indicate that, if there were any conventions or rules of thumb based on proportional structural relationships, these varied quite widely across the survey sample: rather than definitive rules, there seem only to have been generalized limits or parameters within which builders worked. The results also suggest a desire amongst many builders to utilize solutions involving constructive geometry, that is based on the manipulation of triangles, squares or polygons. However, such appear to have been used only where they provided a solution which conformed very generally to those parameters found in certain other proportional relationships for structural stability alone, or for an acceptable degree of security or fortification.

For the abutment of barrel vaults the results indicate that a geometric construction may have been used which anticipated, or had a similar effect to, that devised by François Dérand and published in 1643.

CONTENTS

PART 1 THE QUESTIONS AND THE TASK

6 METHODOLOGY

7 ANALYSIS

PART 2 THE RESULTS

8 WALL THICKNESS, SLENDERNESS RATIO AND FORTIFICATION: THE FREE-STANDING WALL

9 CENTRALLY PLANNED STRUCTURES

13 VAULTED UNFORTIFIED DOMESTIC STRUCTURE

14 CHURCH TOWERS

15 TOWER HOUSES

16 CONCLUSIONS

APPENDIX I SOME STANDARDS FOR STRUCTURAL RELATIONSHIPS FROM DOCUMENTARY SOURCES

LIST OF FIGURES

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Glossary

The following has been compiled as a list of expressions used in the text which have been invented for reference to specific concepts for which no commonly used expression already exists, or where a word is used in the text to convey a meaning which is not the same as that normally recognized in our own time.

architect
for the purposes of this thesis, the designer of any building, whether of vernacular or architectural status

calculate
used to refer to medieval non-arithmetical methods of deriving for instance wall thickness from some other structural dimension

core square
the square from which the internal proportions of a structure or part of a structure are formed, the sides of the square being the internal span dimension

Dérand's ratio
the ratio of the depth to which Dérand's vector penetrates wall thickness, to the internal span

Dérand's vector
not a vector in the modern sense representing the magnitude and direction of forces as calculated by arithmetic means, but a line derived by dividing the section of a vault into three chords of equal length, then extending the two side chords downwards from the springing of the vault for a length that is equal to that of the original chord. According to Francois Dérand the wall should be no thinner than the point indicated by the ends of these extensions (v. Appendix I Section 4.4)

Egyptian variant triangle
an isosceles triangle formed of two 3-4-5 triangles set back-to-back on their sides of 3 units

elemental triangles
any triangle whose angles can be accurately constructed with no more tools than pegs and string: equilateral, isosceles right-angled, 3-4-5, paired 3-4-5 triangles set back-to-back on their sides of 4 units (Egyptian), or of 3 units (Egyptian variant)

haunch
the area of masonry measured between the level of the springing of a vault in the interior of a building, and the level of the eaves on the exterior

internal/external width ratio
the ratio of internal to external width

near square
a four-sided figure, whose vertices are of 90 degrees where each opposite pair of sides are not quite equal, but in the ratio of around 1: 1.05, and no more than 1: 1.1

service wall
a wall which is thicker than the other walls of a building in order to contain 'services' such as chimney flues, stairs, garderobes, aumbries etc.

slenderness ratio
the ratio of wall thickness to height

span ratio
the ratio of wall thickness to internal width or span

square derivatives
geometric figures which can be derived from the square by manipulation of diagonals of the square or of half the square:

diagon	1: 1.4142	(rotated diagonal of a square)
auron	1: 1.618	(golden section - rotated diagonal of half square)
√3 rectangle	1: 1.732	(rotated diagonal of a diagon)
√5 rectangle	1: 2.236	(rotated diagonal of a double square)

and any combination or multiple of these

structural design
the design of the structure as understood in medieval terms by the science of geometry and whatever other means were considered appropriate in each situation, rather than as achieved by modern methods of rational arithmetical calculation, based on the known strength of certain materials

PART 1

THE QUESTIONS
AND
THE TASK

1 INTRODUCTION AND BACKGROUND

Whilst there is indisputable evidence that medieval and earlier architects used both modular and geometric forms and manipulations to lay out the ground plans and probably also sections and elevations of their buildings, there is very little indication of how they arrived at those key dimensions of structural elements on which the stability of the building depended, most notably wall thickness. Technical literature analysing the design, form and nature of medieval masonry structure in general terms abounds, but it is mainly aimed in one of three directions, depending partly on source material: first, there have been many attempts to analyse structures using modern methods of calculation, in order to understand the direction and magnitude of stresses and thrusts within the masonry build itself and also those imposed by external forces, principally wind. Almost invariably the buildings which attract most attention are those which were at the cutting edge of experiment, innovation, even daring, originality and sheer size. This is a very natural manifestation of a culture which itself places ever greater reliance and intrinsic value on both technical as well as aesthetic innovation. The great domes and vaults of antiquity and medieval Europe have been the prime subjects.

Secondly, there are the individual writings and drawings by masons and architects from antiquity to the 17th century, together with observations and explanations of these by later commentators, especially in the second half of the 20th century. Since the Second World War historians have unravelled much of the thinking, rationale and processes of structural design in individual cases from these sources. There is much consensus over conclusions drawn and it is possible to build up a reasonably good picture of the subject from their explanations, but again, these studies are very much on an individual basis, and their subjects are sometimes hypothetical, or theoretical rather than actual built examples. Where built examples do form the subject, it is very difficult to form generalizations from these.

Third, there is the research which is based on measurement of surviving buildings, mostly again the great vaulted monuments of antiquity and the medieval period, and which seeks to understand one or other aspect of the original design process, but usually of the *general form* of the building rather than of specific structural elements, and again on an *individual* basis.

Thus, research so far has been characterized by attention to the general form, the outline or footprint of buildings, individual methods, individual buildings and/or architects, and whilst these undoubtedly provide many useful pointers, there has been little attempt to tackle the design of structure itself head-on, over a wide variety of examples in a given area or period, to ascertain precisely what trends there may have been, how any number of methods might have been combined, and what if anything was typical. Such an approach would necessarily involve a long and expensive examination in great detail of a considerable number of buildings. Herein lies the essential rationale of this research project.

The introduction of the theory of structures, of scientifically calculated stresses and strains within individual members as well as entire structures has revolutionized the nature of building, of structural design, and indeed of architecture. Structural design as a modern science is rooted in rational theory, in the known strength of certain industrially-produced or finished materials, and in calculations designed to maximize the efficient use of those materials with minimum outlay. How much of this was common to the knowledge, experience and methods of the pre-industrial architect? Certainly stresses were not calculated in the same way. Were they calculated at all? Was there a perceived need to economize with the aim of achieving a measure of structural sufficiency? What indeed was the medieval attitude to structure? These are the sorts of questions that arise from the evidence published to date, and from an intrinsic fascination with surviving historic masonry structure itself. For this research, while documentary evidence has been deliberately drawn from wherever it could be found, actual buildings have been the principal source material in an attempt to achieve a better understanding of the process of structural design through the medieval and renaissance periods.

In particular, Scotland has been chosen as the location for this purpose. It is ideal in several respects, principally in that it has had a long tradition in masonry building, with a limited variety of the simplest structural forms and building types, the minor changes to which are easily traced over a considerable timespan, and which therefore make an almost ideal body of evidence. Moreover, being on the geographical fringes of Europe it is more likely that any indigenous practices and traditions will have been maintained in relative isolation from outside influences.

The format of this thesis requires an initial note of explanation. The opening chapters set out a conventional review of what has been found to date by other historians concerning the general principles of design, then what has been done on the subject in the Scottish domain. This is followed by an assessment of the general questions arising to which this research is directed, and the means by which these are tackled. Discussion of the findings is then divided for convenience into sections dealing with each building type in turn. Conclusions of these findings then follow at the end of *each* of these chapters rather than all being reserved for the final summing up. This final general conclusion chapter, which is relatively brief, simply draws together some threads from each of the individual chapter conclusions, and presents any general trends or practices which seem to be common to more than one building type or, conversely, the level of disparity between them.

Certain terminology used in this thesis also requires some explanation and qualification. Whilst any hitherto known medieval methods and rules may seem primitive, even naive when compared with these modern concepts of structural design and engineering, it has to be accepted that they were probably nonetheless perceived at the time to be just as 'scientific' and to constitute as much 'calculation' and 'engineering' to the medieval mind as do modern methods to today's engineer. In the famous disputation over the design of Milan Cathedral, the word "*scientia*" was , after all, used to refer to what Ackerman has translated as "higher geometric principles" (1949: 101). In view of this, and the lack of any other appropriate terminology from that period, these terms just mentioned, together with 'structural design' will be used frequently when referring to medieval activity, and should be taken in context to represent the simpler medieval concepts of those subjects, rather than the modern interpretation of rational and arithmetically-calculated values. The term "architect" has similarly been used throughout to denote the designer of a building, where in many cases it might successfully be argued that "mason" or "master mason" may be more appropriate. The term is used as one of convenience simply to encompass all levels of ability and professional status or lack of it. Indeed several other expressions have been similarly borrowed or coined for the purposes of elucidating this relatively unexplored subject and these will all be found in the glossary at the beginning of the thesis on page xii.

Finally, it should be noted that the Harvard reference system has been used, but with one modification. It seemed appropriate to arrange the bibliography in separate subject categories, and these have been numbered with upper case Roman numerals. Each reference in the text commences with this number to enable instant recognition of the bibliography category in which the reference falls.

2 STRUCTURAL DESIGN TO THE EIGHTEENTH CENTURY

2.1. THE GEOMETRIC BASIS

At its most fundamental, architecture has been regarded since classical antiquity, and earlier, as being inextricably founded in the science of geometry. From Plato and Pythagoras are derived also the notions that there is a relationship between musical harmony and simple geometric and mathematical ratios (II Wittkower 1988: 104-107). These, however, together with the various esoteric and even mystical values accorded to such relationships, as reflecting the perfection of the universe, are not the subject of this research. From the ancient world, the recommendation of Vitruvius for geometry in an architect's education for the very practical purposes of measurement and plan drawing are much more relevant (X Book I, i: 4.)

The tools of the architect from several centuries B.C. at least had included basic pegs and string for setting out the ground plan, And it was by pegs and string, or cord, or ropes that building sites were measured and laid out. From the account of Gunzo's dream about the building of Cluny III (II Carty: 1988) to the Church of the Holy Cross on Akhtamar in the Caucasus in the tenth century (IV Rappoport 1995: 162), there are documentary references to this method. Of more sophistication were compasses, a plumb tool (various types) for finding both vertical and horizontal, but perhaps the most significant for this research is the measuring rod. Ezekiel writing around 600 B.C. refers to the use of this implement (Ch.40), and its method of employment changed little over the centuries, various lengths having been used in different parts of the world, and this length is in some cases significant in the building design.

2.1.1 *The Dimensional Module*

A measuring rod can be designed in at least two different ways: on the one hand it can be a total overall length of a certain number of smaller units of measurement which are in general use, say seven feet, or eight or nine feet, however long is deemed to be convenient to physically handle for the particular purpose intended. The actual length chosen is not of any more significance than for convenience of handling. The various calibrations of smaller units on the measuring rod (feet and inches, braccia or whatever) were obviously useful in the design process and for the measurement of existing work, the dimensions used being comprehensible and communicable verbally and in writing to anyone else who had cognitive understanding of those units. This of course is a standard approach to measuring rod design in our own time, be it a foot ruler, or a metre rule, and the concept has a long history also.

On the other hand the overall length of the rod would again be chosen for convenience of physical handling, and it may well be of a certain number of universally or locally used units, but its total length would be regarded in a rather different light. Rather than representing a possibly random number of known standardised units of measurement, it could become in the hands of its user a new unit of measurement, which would be specifically applicable to one or more pieces of work. It would constitute a dimensional module for building purposes, applicable in multiples and fractions throughout a building. Fractions of this modular unit may not conform to existing standard units of measurement. They are likely to be binary fractions of the total module : one half; one or three quarters; one, three, five or seven eighths, etc. An example, has been identified by Kossman: a "great unit" of sometimes 5, sometimes 7 feet, was commonly used by the builders of Cistercian churches (1925, quoted in II Frankl 1945: 48 n.14). This is a more archaic method which has died out in most societies. More on the whole subject of units of measurement, particularly in Scotland, will be found in Appendix II.

2.1.2. *The Structural Module*

In other cases the module might have been taken from the dimension of a key structural member. Vitruvius' concept of *ordinatio* is achieved by "... the selection of modules from the members of the work itself and starting from these individual parts of members, constructing the whole work to correspond." (X Book I, ii: 2). Frankl, amongst others, regards this Vitruvian module as being the measure used as a basis for the measuring rod (1960, quoted in VI Heyman 1995: 142). In any event, the most important point here is that the only linear measurements used within the context of such a modular system that were of significance in the processes of design and construction were the master values for the principal modules. All other measurements were fractions or proportions derived from these principal structural modules.

2.1.3 *The Square and its Early Use*

Although it is difficult to quantify, a certain amount of these rules, design, surveying and building techniques, including the Pythagorean 3:4:5 triangle for constructing a right angle, survived from imperial Rome and earlier right into the medieval period and beyond, for certainly they were available for the layout of the St. Gall monastic complex of c.817-23. Here we can begin to look at one of the most basic building blocks of the entire process of the design of both space and structure: the square.

The square was initially the most basic figure from which others were derived. To construct it on the ground using pegs and string is really very easy. Rectiliniarity can be checked by equalising the diagonals, which then could play further roles, to be discussed later. Bucher believes that squares may have been used at first in the medieval period in a merely additive role. At St. Gall, for instance, he mentions how squares were used to make up the plan, either by adding one to another or by repeated halving, right down to the size of a monk's bed. (II 1972: 37 quoting Horn 1966: 285). Conant has found the regular use of several different rectangular forms derived from the square by rotation of diagonals about their end point, including the diagon or root-2 rectangle, the auron, or golden section rectangle and also the Hemiolion, which is in effect just one and a half squares (Figure 2.1). All of these were used either singly or added together, particularly at Cluny III (II Conant 1968). So it does appear from the evidence so far available that squares and square derivatives of these types were only used in an *additive* process, or one of repeated halving. Examples of this are still, however, limited and measurement of a greater number of the earlier medieval monuments is ideally necessary to lend weight to Bucher's case.

Perhaps the most significant geometric figure in a study of building design in the medieval period is the diagon, the discovery of which is ascribed by Vitruvius to Plato (X Book IX, Introduction: 3 & 4): the rectangle whose length is determined by the diagonal of a square, and the relationship of whose sides will therefore be $1:\sqrt{2}$. The figure has the property that it can be halved or doubled *ad infinitum* and the resultant figures will retain this proportional relationship. The same relationship can of course

Figure 2.1 Figures commonly derived from the square

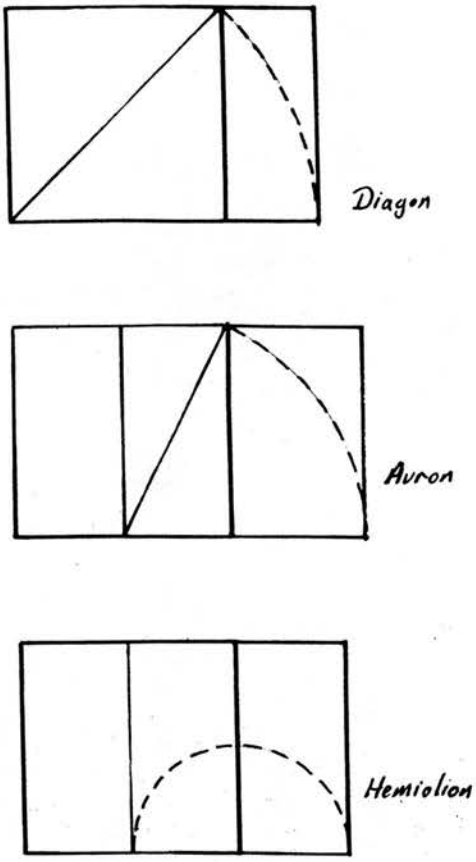
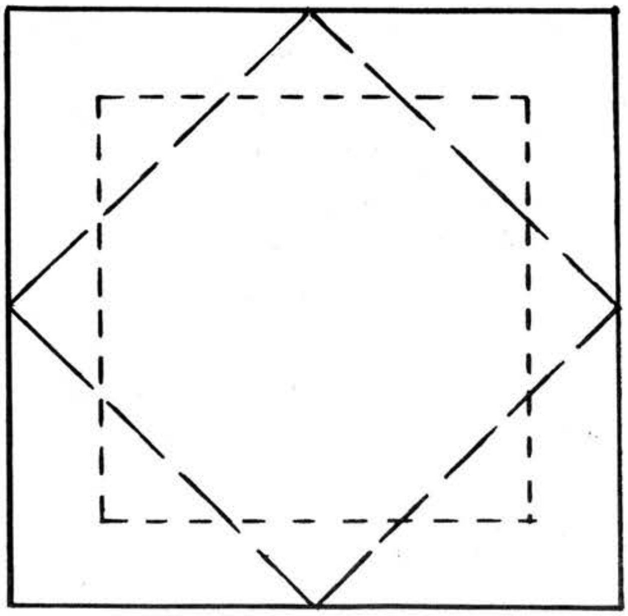


Figure 2.2 The inscribed rotated square



be achieved by the inscription of a smaller square rotated 45° within the larger (Figure 2.2). This relationship has been found in a plethora of western monuments, right through from antiquity to the medieval period, both in plan and sectional format (IX Kidson 1956), and it has been found to be universal also in the monuments of Islam by the research of Bulatov and others (IV Lewcock 1978: 132). Furthermore, it has been demonstrated how root-2 relationships have been used not just in the laying out of whole monastic complexes (II Stalley 1990), but also down to the detail of wall thickness and nave pier design in the cathedral church at Norwich (II Fernie 1976: 77-86). The importance of this latter piece of research cannot be overstated for this project. Fernie demonstrates how the rotated diagonal of a square aisle bay defines the thickness of the nave arcade wall, and the rotated diagonal of one quarter of the bay defines that of the aisle wall. This highly significant revelation is one of only a handful of shreds of evidence recovered from the medieval world that structural design was sometimes indeed derived directly from no other logic than a geometric relationship of elements in the ground-plan. Nicola Coldstream has identified at Ely Cathedral another method of deriving the nave wall thickness using root-2 relationships which is completely different from that employed at Norwich. Both of these will be found, together with other known medieval and renaissance methods of design which will be mentioned later, collated in Appendix I.

All these simple geometric constructions could obviously be achieved using mere pegs and string, and they could be used to achieve a wide variety of simple rectilinear forms. However, they cannot have formed the entire vocabulary of medieval building blocks. Looking ahead to the sixteenth century, Palladio and Serlio both list a series of square derivatives in common usage:

Square	Ratio:	1 : 1
Diagon		1 : √2
Square and one third		3 : 4
Square and one half		2 : 3
Square and two thirds		3 : 5
Double square		1 : 2

Now whilst Palladio recommends these figures as "... the most beautiful and proportionable manners of rooms ..." (X Book 1, XXI: 27), and he is probably taking his cue from humanist thought with its interest in harmonic proportions based on the musical consonances, Serlio tells us that there are "... many Quadrangular proportions

..." and that these (listed above) are only "... the principallist of them, which shall best serve for the use of the workeman." (X Book I, I: Fols. 11 & 12). The implication here is clearly that a much wider variety of square derivatives were in regular use at this time, by implication at *all* levels of the building industry.

2.1.4 *The Triangle*

In addition to the square, medieval builders made increasing use of the triangle, and Viollet-le-Duc identified three types commonly employed: the equilateral, the right angled isosceles and what he called the "Egyptian" isosceles triangle (X 1875: 532), the latter being, in effect, two 3:4:5 triangles, with their sides of four units placed back-to-back. These seem to have been generally accepted as the principal 'elemental' triangles used in the medieval period. Triangulature was used in some regions more than others for such purposes as the cross-section of churches. The Lombardic preference for this method was to result for instance in the final design for Milan Cathedral (II Ackerman 1949). Theoretically the equilateral triangle was regarded as the optimum choice if triangulature was to be used at all, its physical perfection being obvious and perhaps also its ideal representation of the Holy Trinity. However, the Egyptian triangle may well be an example of the medieval mason's propensity to adapt or even invent alternative forms which seemed easier to construct: as far as we know, the measurement of angles in degrees was not practised at that time and the Egyptian triangle was a useful alternative to the equilateral in that it could be simply constructed using pegs and string, or some equivalent for smaller scale planning.

2.1.5 *Gothic Sophistication: The Dawn of Architectural Draughtsmanship?*

At least until the twelfth century and the advent of gothic, the very activity of designing the overall form was thus contained in a series of relatively simple geometric exercises. Attention paid to the actual structure seems to have been basic, even naive. But then as von Simson has pointed out, even architectural decoration in this period, both in the Byzantine east and in the west, was a more principal subject of aesthetic appreciation and value judgement than the design of structure, which attracted relatively little comment, at least that has survived. It was with the exploration of the possibilities of the pointed arch, rib and buttress that an intrinsic interest in structure more obviously arose in the west (II 1962: 4-5).

Given the relative simplicity of design procedures and relative lack of interest in structure, it has been argued that architects may not have drawn up such detailed plans and elevations in the form used later before embarking on setting out and construction. Branner goes so far as to suggest that a ground plan was transmitted directly from the architect's mind to full-scale setting out on the ground (II 1963: 130) which involves something of a stretched imagination for a major cathedral project! Certainly no plans have yet been found from prior to 1240/60, and Branner makes a case that the Reims Palimpsest of around that date is possibly the earliest medieval example (II Branner 1963: 135). Harvey gives this view short shrift, pointing out the scarcity of paper, still less of parchment and their low survival rate in any form from this period, particularly for such mundane uses as working drawings. He mentions the use of such ephemeral means as plaster tracing floors, from which the design, once used, was erased ready for the next; also the importance of professional secrecy in the medieval working environment. He argues that the sophisticated quality of the Reims drawings and indeed of Villard's sketchbook indicates that "there must have been quite a long tradition of such draughtsmanship." (IV 1973: 34-6). Gimpel adds that the earliest plans were probably drawn on plaster or wooden boards (which were discarded later) because the price of parchment was prohibitive at that time. Furthermore, attributes the apparent proliferation of surviving plans of the fourteenth and fifteenth centuries to the falling price of parchment (IV 1983: 117).

The argument is not just confined to western architecture. There is a similar debate about the design and laying out of Byzantine, Ottoman, Islamic and Kievan structures from around the seventh century. Given the probability of middle eastern influence in the western adoption of the pointed arch, it might be unwise to rule out the possibility that other forms and practices might also have found their way westwards. Ousterhout has argued that most Byzantine churches from around the seventh century when the classical method of design using plans, elevations and perspectives as described by Vitruvius (X book I. 2.2) died out, were in many, even perhaps most cases, created without scale drawn plans at all (IV 1999: 62). However, there are documentary references to plans throughout much of this geographical area by the fifteenth century at least, when under the Ottoman empire, and a very few examples actually survive. Most of these relate to bath buildings (Necipoglu-Kafadar 1986), and they are drawn on squared grid-plans, invariably the wall thickness being one square thick, and thus represented as a module for the whole building. The use of such grid-plans is recorded through central Asia, the Islamic world, and even Mughal India (IV Lewcock 1978: 132).

The transposing of such plans on to the building site was of course greatly facilitated by the grid, especially in the cases of large and complex structures: The grid could simply be scaled up and set out on site by pegs and string. According to a contemporary account this was exactly how the huge Süleymaniye mosque in Istanbul was begun in 1550. Filarete is known to have worked in Istanbul and indeed his treatise contains a description of this method, but to what extent the grid was used in the west is hard to ascertain Its use is not recorded here after around 1500 (II Necipoglu-Kafadar 1986: 234).

Whilst the planning of smaller, simpler buildings on site may have been possible without preliminary drawings, such an exercise in the case of large or complex structures is indeed hard to imagine, even though the medieval world no doubt carried many oral traditions and was not nearly so reliant on the written or drawn document as we are today. Nevertheless evidence from both east and west suggests that much more drawing or planning was done than survives: the spread of very similar plan forms across the Ottoman world is taken by Necipoglu-Kafadar as an indication that images of the plan at least travelled, while elevations, which possibly did not, reflected a wider range of locally characteristic tastes (II 1986: 243). Of course a similar propensity for copying or emulating plans, regardless of elevation, existed in the west, right into the seventeenth century. The lack of drawn elevations in the east is not matched by a similar situation in the west, at least not in the realm of gothic cathedrals. Unfortunately this is unquantifiable at present: there is a large body of original unpublished medieval architectural drawings scattered round the libraries of Europe which is awaiting further examination and analysis (II Bucher 1968: 49). There is some evidence to suggest that elevations, or at least details such as windows and arches, were worked out during the construction process: arcs of their outline have been found incised in stone walls and floors from the sixth century Church of the Holy Cross at Resafa, and the eleventh century Çanli Kilise in western Cappadocia, to Rosslyn Chapel near Edinburgh of the fifteenth century. This, together with the custom both east and west for showing the elevation of arches laid flat on the plans (II Necipoglu-Kafadar 1986: 233), might suggest that whole elevations were sometimes worked out on the ground, beside the ground plan when the latter had been set out. Also, as Fawcett points out concerning the inscriptions at Rosslyn, no one has yet attempted an explanation as to how a vertical as opposed to a horizontal tracing 'floor' was used (VII 1994: 171). Much concerning these practices can only be the subject of speculation.

To return to the debate over the date of the development of detailed architectural drawing in the west, the late twelfth and the first half of the thirteenth centuries coincidentally threw up some significant developments, particularly in the field of masonry: the appearance of the new *tas de charge* feature at Chartres, and bar tracery at Reims (both from c.1210). Also a change in emphasis away from interest in the articulation of mass and space to a preoccupation with surface pattern has been noticed in addition to the better known increasing obsession with greater height. Branner thought that it was the requirement for increasing precision in transmission of design instructions to the builders for these advances that may be responsible for the inception of detailed architectural drawing, if that is indeed when and where it started (II 1963: 140).

Perhaps the single most important document surviving from this period is the sketch book of Villard de Honnecourt which, despite its frequent annoying lack of textual and graphic clarity, does tell us much about an architect's method of working: for instance the measurement of angles, not in degrees but as gradients, using calibrations on two sides of a right angled triangle; also aspects of stereotomy: in particular working out the angles at the apex of a pointed arch for the keystone. But Villard does not inform us much about a further development which may have only flowered after his lifetime.

2.1.6 *More Gothic Sophistication: Quadrature*

Perhaps sometime after the 1230s the early process of creating different rectilinear constructions simply by adding them one to another evolved into an altogether more dynamic process: the systems known as quadrature and triangulature - the rotation, inscription and other manipulation of squares, triangles, polygons and other figures. By such means were created not just plans in which every part both great and small were geometrically related, but also the elevations were geometrically derived from the plans in the manner illustrated, albeit much later, by Matthes Roriczer in his instruction book on the correct design of pinnacles (1486), lucidly explained by Shelby (II 1971 & 1977). Bucher reckons that this process was widely used by the mid-thirteenth century (II 1972: 528). Villard actually provided us with an illustration of the inscribed rotated square principle, but his caption refers not to this geometric manoeuvre: "In this way one partitions a stone so that its two halves are square" (quoted in II Bucher 1979: 120). To a post-medieval observer, the rationale of this procedure might appear questionable, as indeed it does to Bucher! However, Villard himself does not appear from the rest of his work to be inept enough to have misrepresented this figure, and so it is difficult to be sure from the appearance of this drawing that he could or did practice quadrature in his design procedures.

It is difficult to be precise about the origins of this more dynamic idea of geometric manipulation . In many ways it is merely a logical progression from the process of creating rectangles by the rotation of a diagonal about a point at the end of that line. In effect, quadrature is merely rotation of the diagonal about its centre point. Shelby on the other hand suggests that some of the complexities of more advanced form of what he calls "constructive geometry" (II 1972: 409) may have originated much later in the publication of '*De Inquisicione Capacitatis Figuarum* ' (author unknown) sometime before 1457. The manner in which Roritzer constructs heptagons and octagons for instance is identical to those prescribed but, of course, this was the only way and may well have been common practice by that time anyway. The expression "constructive geometry" arose since, like the earlier less dynamic "practical geometry", it relies not on Euclidean or any mathematically calculated system of construction, but rather very distinctively upon the derivation of one form from another, simply by graphic manipulation.

Unfortunately the only surviving records of individual methods of this later development that have come to light are of the fifteenth and sixteenth centuries, so an analysis of its development is so far impossible. Furthermore, the few surviving records of it are mainly of German, Austrian and Italian origin and so may not necessarily be applicable elsewhere. Indeed it is noticeable that each architect was responsible for developing his own highly personalised design system based on his own training and experience, together with that of his peers, the end built result of which may well have had much in common with contemporary work but, again, the means and the method of achieving it had been very individualised. This characteristic of medieval and indeed later architecture cannot be over-emphasised, but not only in the context of the individuality of its conception.

2.1.7 *Flexibility in Geometric Structural Design*

If medieval ground plans and sections were formulated from geometric layouts, whether merely additive or more dynamically manipulative, was there any canon which dictated exactly what each geometric line or figure delineated? Did such lines define the inner or outer wall surfaces, or the mid-line of the walls in a given building, and were they consistently so used to define just one of those three options in any one building? Morgan finds unconvincing the analysis of Carlisle Cathedral by Billings (1840) who theorises that the plan is based on a series of circles - straightforward enough. But Morgan is troubled by the inconsistency of the circle in the nave defining the *inside* faces of the walls whilst that in the chancel the *outside* surfaces (II 1961: 13). Milner, in contrast, has no qualms in accepting such solecism in the geometry of Warkworth Castle keep (II 1990: 223). Viollet-le-Duc's Discourses, which set out to argue for the rationality of the Gothic architects, included many plans and sections of great cathedrals, liberally covered in squares and triangles which variously fell on different sides of walls in the same building. (e.g. Notre-Dame, Paris. X Lecture IX Fig. 9, 1959) Again, were these likely to have been "help-constructions," or desirable ends in themselves?

Perhaps an answer may lie in the exhaustive efforts of George Lesser who, seldom referenced by later authors possibly because of the title of his two volume work '"Gothic Cathedrals and Sacred Geometry" (II 1957), analysed the geometric grid of some thirty major religious sites between 1934 and 1957. Eighteen of these are situated round north Germany and the Baltic, and Lesser shows how they are geometrically linked to the great French works of Reims and Amiens, and also Westminster Abbey. The only mentions of the 'sacred' - symbolic, religious, mystical, neoplatonistic or whatever - are in the introduction and penultimate chapters and seem level headed and well researched. Otherwise the work is founded in hard-going practical geometry. Of principle interest for this research, Lesser finds that 'the system' varies: whilst in most of the Baltic cases under his examination the core octagon takes in both the nave and the thickness of the arcade walls, in one case it forms only the internal width of the nave, in another the centre-lines of the arcades (II 1957: 139). His findings generally confirm that there was never any rigid code imposed by such geometric systems which constituted "a guidance rather than a compulsion" (II 1957: 138) and "a living organism, capable of growth and adaptation"

(II 1957: 141). This, however, is not in itself the primary subject of this project. Such questions are more concerned with spatial rather than structural design. Where all this would be of direct relevance is if the geometry delineating spatial design also defined the sizing of individual structural elements and members, the determination of vault abutment, wall thickness, slenderness ratio, etc. For this some answers can be found in a set of project designs for centrally planned "temples", actually churches, by Sebastiano Serlio (X Book 5, Chapter 14, Fols 2-7), which are explained in Appendix I. All of these appear to have a structural as well as spatial design founded in geometrical manipulations, but all of these are slightly different. The geometry has, in effect, been chosen to provide what was perceived, or even calculated to be sufficient structural strength. However, such systems can never have been entirely logical from a structural point of view and, it has to be remembered, these were only projects which never progressed beyond the drawing board.

2.1.8 *Structural Logic, or Lack of it*

The manipulation by architects of geometric forms was not always with any regard at all to structural logic as we know it. I can do no better than quote Sanabria on the subject: "Whenever favourable accidents occur such as...two arbitrary lines intersecting at a useful location, the fortuitous circumstance is exploited to yield dimensions of lesser parts ... the system ... is useful only because it allows decisions to be made where criteria for deciding are neither clear nor exact." (II 1982: 284). At its simplest, this is precisely what Fernie has discovered at Norwich Cathedral, mentioned earlier. A similar method can be found by examining some of Lesser's diagrams where rotation of a core square forming the internal nave dimensions produces the arcade wall thickness. In another instance, Filarete records in his treatise designing a tower of square plan, the wall thickness of which does not appear to have been determined arithmetically in proportion to the *height*, as logic might suggest but, as von Oettingen has interpreted, by quadrature (II Saalman 1959: 99). Into the square outline of the wall plan layout was inscribed another square rotated 45 degrees within the first and with its corners touching the midpoints of the sides of the first square as shown in Figure 2.2. This inner square was then rotated back to align with the sides of the first, and thus the wall thickness was defined, in effect by a relationship with the *length* of the outside face of the wall. The length of the sides of the inner square are of course in a "root-2" relationship with those of the outer square.

To return for a moment to the subject of the modular basis for building design, this of course remained and indeed became integrated with the developments in constructive geometry. The method for a given building project had usually been initially based on the dimension of some specific piece of structure, the square crossing of a church plan for example, or the width of the choir. Such obviously fundamental dimensions were indicative of the overall size of the building as dictated by the patron, and therefore useful starting points for the determination of other dimensions. This 'structural module' idea was basically the same principle, let it not be forgotten, recommended by Vitruvius and probably used long before him. From some time, perhaps in the later thirteenth or the fourteenth century, the concept of the structural module became more complex as constructive geometry was used to work up the design of the whole structure. The best surviving documentary example of this is the instruction book of Lorenz Lechler, of 1516, for his son Moritz.

Lechler starts with a macro module of the width of the choir on which is based all other major structural dimensions, including the choir wall thickness. The latter is divided into three and a micro module is formed by this dimension which is then used to form the side of a square. A smaller square is then inscribed and rotated 45° to fit the first, and this is used to produce dimensions for smaller features such as window mullions and vault ribs. The work was partly explained in papers by Shelby (II 1971), and Shelby and Mark (II 1979). A synopsis will be found in Appendix I. Again, this is a late example, there being nothing comparable surviving from the thirteenth-fifteenth century period.

Again, variety seems to have been the hallmark of this system. Francesco di Giorgio Martini, for instance, did not base his module directly on a predetermined piece of structure for his latin cross church design of c.1490-2 but rather on the diagonal of one of the squares from within the floor plan, as explained in Appendix I (II Betts 1993: 11).

2.2 THE WEAKNESS OF GEOMETRY: THE ADVENT OF RULES OF THUMB

Until the collapse of Beauvais Cathedral in 1284 this system of design by some level of constructive geometry may have been the sole, or at least principal determinant of structural form, either based on a module made from a member of the structure or possibly an alternative method using a module denoted by purely numerical units of measure. It is equally possible that neither a structural nor numerical module were used in isolation but combined in a building project according to which was the most useful or appropriate in a given situation. More of this concept of mixed method will be discussed later.

According to Bucher, the collapse of Beauvais precipitated a quest for definable safety limits for structure, which he identifies as "rules of thumb" (II 1972: 48), and his thesis might well be correct. It is likely, however, that working masons had by then developed many practices which could be so defined. O'Connor recently produced fairly convincing arguments that in an earlier era Roman engineers and masons were preoccupied with simply ensuring that their structures were appropriately designed and strong enough to stand up under their own weight, and the weight of each component part, under imposed loads, both man-made and natural. In a study of bridges in particular, he argues that Roman builders had probably developed rules of thumb for bridge design based on simple arithmetic ratios (V 1993: 164, 166 & 170), and indeed this must surely have been common wherever and whenever structural design was formulated on an empirical basis. Certainly an event as cataclysmic as the collapse of Beauvais must have had far reaching consequences in the architectural world and it is likely that there were increasing efforts to work out a more scientific, or at least a more consistent basis for vault abutment. Perhaps by the fifteenth century Alberti provides some evidence for this: although having nothing to say in this respect for most ordinary buildings, he was recommending a slenderness ratio for walls of towers of about 1:20. As can be seen from other examples (Appendix I), he was not alone in arriving at this convention. There is no sign of geometry here; this is a straightforward ratio that is based on what was deemed to be a safe limit. Likewise by the sixteenth century Palladio recommended the ratio of pier thickness to span of bridges (henceforth 'span ratio') of between 1: 4 and 1: 6. Now it is possible, of course, that bridge builders had always calculated their designs in these terms, and Palladio was merely reflecting what had been common practice for generations. A survey of medieval and early renaissance bridges would soon answer that. Certainly bridge building had progressed much since the days of narrow multiple arches of, for instance, London Bridge. Unfortunately there are no stone bridges in Scotland predating the Beauvais disaster to test this out. The possibility remains, however, that this event did have the effect of persuading builders to change from designing these structures in at least partly geometric terms to regarding them in a more rational light. More examples of this will follow in due course.

2.2.1 *Towards an Understanding of Statical Mechanics*

As far as we know, there was little comprehension of the science that we now refer to as statical mechanics, certainly not enough from which to formulate a calculated theory of structures. What knowledge there was of the management of forces and stresses within structure was very much at an individual level, each architect working on the basis of his own experience and perhaps that of his peers. Harvey has suggested that some may have used scale models to test the thrust of vaults and the resultant requirement for abutment (IV 1972: 116, 163). Where records survive, we know that some architects built additional elements of safety into their personalised system of quadrature, as was the case with Francesco di Giorgio for example (II Betts 1993: 14). Again we must turn to late sources for other examples of this. As already noted, Lechler's instruction book tells us about the systems of quadrature used to achieve mullions and vault ribs, and that these were derived indirectly from the choir width. As the latter dimension was increased, so would the section of the ribs. An assumption must perhaps be made here that his system was devised in the light of experience and contained an element of rule of thumb, with a view to achieving a measure of structural logic. Lechler in fact recommended certain proportions, based on the width of the choir, not just for the wall thickness, but also for wall height to vault springing and to apex, buttress size and even the proportion of glazed window to masonry wall in each bay between buttresses. However, despite the apparent precision of some of his recommendations, he repeatedly advises his son to simply be guided by his own judgement in the light of his own intuition and experience. It must be said that Shelby and Mark found considerable variations on Lechler's advice in the proportions in churches of the area and period contemporary with Lechler's career (II 1979: 118, 120).

Understanding of structural problems was distinctly limited around this time. Francesco's treatise reveals to us that the abutment of vaults in particular was generally regarded as a two dimensional problem (II Betts 1993: 19 n.39). Individual solutions tended to be sought likewise in two dimensional geometry, based on a simple cross section of a church structure, and any principles that were shown to work in practice were stored away as rules of thumb for future application in similar situations. However, it is clear from an isometric drawing of force lines emanating from a barrel vault by Leonardo da Vinci that he at least understood the support of vaulted masonry to be a three dimensional problem, abutment depending not just on the span, but also the height and volume of the vault (II Betts 1993: 19 n.39). It was some considerable time, however, before Leonardo's theories were more universally comprehended and utilised in structural design.

In the meantime, perhaps at the cutting edge of the search for rules of thumb to ensure safe but economical structure in vault abutment especially, was the eminent Spanish architect Rodrigo Gil de Hontañón (c.1500/1510-77). In the period of transition from Gothic to Renaissance forms, this architect may have used a method more akin to modern experimental technology in statics with something approaching a rational basis than anyone else so far. His precise methods are unclear, his thoughts coming to us second-hand and poorly expressed in the treatise of Simón García (X 1681). He wrote about more than one rule of thumb relating to vault abutment, some being incredibly basic, and possibly derived from common contemporary practice in Spain or elsewhere. He writes, "I have often attempted to rationalise the buttress needed for any bay, and have never found a rule adequate for me. I have pursued the inquiry among Spanish and foreign architects, and none appears to have established a rule verified by other than his own judgement" (Rodrigo Gil pp. 174-5 in II Kubler 1946: 146). This prompts Gil's own researches and rules, the detail of which can be found in Appendix I. Of greatest significance, he appeared to recognise the distinction between aesthetic and purely structural issues, which hitherto had been commonly regarded as a single problem: Daniele Barbaro was not alone in attributing "...*both* the beauty *and* the structural strength of a building to the proper proportions." (1556: 24 quoted in II Saalman 1959: 98). Gil was also very advanced in his belief in the technical ideal of structural sufficiency, just sufficient structure to provide adequate strength and stability. Perhaps of greatest significance is what Sanabria believes to be the possibly ground-breaking experimental study of mechanics necessary to achieve it. If indeed Gil did use an experimental approach, and considerable evidence is presented for this, then he may have been amongst the first in the architectural profession so to do. Unfortunately, this was not followed up until centuries later, and then probably quite independently, with no awareness of his work (II Sanabria 1982: 292).

It is all too easy to assume that Gil and Leonardo were the only minds reaching out to what is now known to be a logical and rational approach to structural design because we have their thoughts on paper. From a modern standpoint it is easy to patronisingly regard the majority of the medieval and Renaissance architectural profession as wallowing in a mire of ignorance, wrong-headedness or simply lack of common sense or imagination. As Saalman so succinctly comments, "... the science of statics was no more than a chancy combination of Pythagorean mysteries and the combined experience of as many professional and lay experts as one could bring together" (II 1959: 102), as indeed happened, together with a dose of national pride, for the design of Milan Cathedral around 1400. Whilst Heyman maintains that any intuitive understanding would have taken a form that would not have been useful in the design process, preferring to believe in a more empirical approach over a longer period of time (VI 1995: 141), Mainstone has repeatedly drawn attention to elements of sound structural insight and intuition, in antiquity and later, as the "springs of invention". The notion that *all* medieval architects believed implicitly that the secret of structural stability lay in some appropriate geometric configuration (which may indeed have resulted by chance in a sound solution) does on the face of it seem flawed. Whilst they certainly lacked the benefit of statical theory and calculation, Mainstone is persuasive in his arguments that, in some cases, there was real intuition in both architects' awareness of the magnitude and direction of forces, and in their attempts at solutions (VI Mainstone 1963, 1968, 1973, 1995 & 1997). There is yet to be consensus on this issue, but it does seem that there were probably many differing levels of structural understanding in operation at any one time. Every architect had his own 'secret'.

2.2.2. *The Masons' 'Secret'*

This is perhaps an appropriate point at which to mention this issue which has been hotly debated, but now hopefully laid to rest since being subject to convincing scholarship by Shelby in 1972: the so-called "secret" of the medieval masons. The "secret", having been repeatedly nibbled at by mostly German speaking scholars for over a century, Frankl attempted to clear the air in 1945, claiming that the secret lay simply in the technique of working up the elevation from the plan of a building or its constituent parts, and there is a measure of truth in this. Shelby (II 1972) explains what a highly complex task this was, how the procedures of medieval constructive geometry were not mathematically or logically derivative according to pre-set programmes; there were no established formulae or theorems where, once the basic principle was learnt, the system could be worked through from logic alone. There was no 'quick fix' secret of that sort which was the 'magic' key to unlock the whole system. What is far more likely is that the secret lay in learning over a period of years the colossally cumbersome process of working up, one stage at a time, the geometric configurations which eventually formed the constituent parts of the building design, each of which were different, and involved a separate design procedure. Each one had to be learnt and memorised, as it were, by rote. Further, there were many different master architects and masons, each of whom, although perhaps influenced by others, may well have formulated their own highly personalised systems which were then passed on to their apprentices. To claim that there was some universal secret short cut through this process, is to deny the evidence of what instruction books survive, and indeed also the monumentality of the achievement itself of the medieval architects. As for keeping the secret, Shelby argues that in England and Germany at least there were no institutional means of preserving technical craft secrets until the latter half of the fifteenth century. It was very much left to the discretion of individual architects to keep their own secrets. Even when there were institutional means, the Germans at least seemed very lax about enforcing such secrecy, as the appearance of Roriczer's and other books testify.

2.3 SUBJECTIVE AESTHETICS: FINISHING BY EYE

The medieval and renaissance attitudes to aesthetics may have played a much more significant role in building design than is accounted for by later commentators . Morgan has some worthwhile contribution on the tension between these two facets of architectural design and quotes from a source concerning the design of Siena Cathedral in the early fourteenth century as written in the contemporary *Lettere Sanesi* (as quoted in Hawkins 1813: 183). It was apparently suggested that:

> "the new work ought not to be proceeded with any further, because if completed as it had been begun, it would not have that measure in length, breadth and height which the rules for a church require."

The old structure on the other hand:

> "... was so justly proportioned and its members so well agreed with each other in breadth, length and height, that if in any part an addition were made to it under the pretence of bringing it up to the right measure of a church, the whole would be destroyed."

These judgements indicate quite clearly that although the initial design principle had been established to apply to the whole church building and also that there were certain rules of proportion for church design generally, there would be no hesitation in compromising possibly both programmes in order to achieve a better aesthetic result as judged by eye alone. In another instance, on completion of the massive dome of the Sülimaniye mosque, Istanbul, in the mid sixteenth century, Sinan, having planned meticulously, found the end result unacceptably overbearing. To remedy the situation he had a model made so that he could experiment by eye with alterations to balance the dome's bulk (II Necipoglu- Kafadar 1986: 240). Justification for final adjustment by eye can be traced right back to Vitruvius who readily condones it on condition that "... the buildings lose nothing thereby." (X Book VI, ii: 4). Harvey also mentions the final adjustment by eye, whatever design aids had been used initially (IV 1972: 125) and argues that because this could have been frequently carried out, the lines of any geometrically formed floor plan, let alone elevations, might well be used to define any of the lines of the inner or outer surfaces, or the mid-line of walls, creating just one more potential problem for later analysts.

2.4 PROBLEMS OF ANALYSIS: MULTIPLICITY OF METHODS

All these elements, modular, geometric, empirical, intuitive and rules of thumb have been identified and often described singly as forming the medieval approach to design, but it is conceivable that for each new building, each structural problem, a combination of some or all of them were in operation at the same time, consciously or otherwise. Rules of thumb, for instance, may have been made or modified as a result of finding a satisfying geometric solution which had worked safely elsewhere, and where the possibility of more than one 'system' of, or approach to, design is unravelled in the same structure by a modern analyst, condemnation or criticism has often swiftly followed since this, it seems, is deemed irrational and inconsistent to the modern mind and therefore inconceivable in a structure of major architectural importance. Most of the research published to date has concentrated on one aspect or another, often related to one or more of the greater buildings of the medieval or Renaissance period, never to a whole range of less important structures to ascertain whether there was any consistency of approach or of solution.

Indeed, on reviewing the relevant literature back to the 1840s, there seems to have been an expectation in some quarters that the approach and method of design of buildings in a given period and locality should be the same or similar. Even more certain are some commentators that design approach should be the same throughout all parts and aspects of any one building. To recapitulate, the differing methods may be listed as follows:

i) the use of a module of measurement based on numerical units;
ii) the use of a module of measurement based on an element of structure;

iii) quadrature - the manipulation of squares;
iv) triangulature - the manipulation of triangles;

These methods could be used to create the ground plan of a building, but the lines so constructed could then be used variously to define one or other of the following:

i) the lines of the centre of walls;
ii) the lines of the inside wall surface;
iii) the lines of the outside wall surface;
iv) any combination of these for the different parts of the building.
v) adjustment by eye

Fernie criticises those "... who pick and choose between a myriad of proportions to explain the dimensions of any particular structure [who] may dazzle by their footwork, but they convince in inverse ratio to the complexity in which they indulge." (II 1990: 230). But in making this judgement (and he cites no specific cases) he may unwittingly be ruling out the possibility of an architect having used more than one design method to achieve the results required by the patron, or to overcome the constraints on design imposed by the very real limitations of stone structure bedded in weak mortar reliant on achieving equilibrium of compressive forces at sometimes very high levels. Similarly Morgan finds Penrose's analysis of Lincoln Cathedral (1848), being based on systems of both triangulature and quadrature, flawed, simply because Penrose hypothesises that the two are used together (II 1961: 14). On the other side of the coin Branner, amongst others, actively criticised those seeking a single geometrical demonstration on which any particular church is design was based, arguing vehemently for the principle that many different methods were often used simultaneously, and lambasting those including Frankl who pay it only lip service. He criticises in particular both Ueberwasser and Velte (II 1951) who tried to take the principles of design expounded in Roritzer's Lodge book and apply them to a much wider buildership, with apparently contradictory and unconvincing results (II 1955: 63). Arguments and counter arguments have raged over the last few decades on this subject and consensus has yet to be reached.

Amongst the protagonists was Paul Booz (IV 1956) who contended that no one specific system of design was used generically by all architects, that the systems used were simply the means of building design rather than ends in themselves, and he has raised what is a most significant point. Was geometry an end in itself for some idealistic perfection, perhaps linked in some cases with a metaphysical even mystical agenda, or was it simply a means to the end of designing a structure which was stable, which suited the needs of the client and which appeared aesthetically pleasing to the eye? There are many issues here, too many to deal with in great detail and again, there are many comments from twentieth century historians. At one end of the scale we know from the wealth of documentary evidence that the neoplatonists of the school of Chartres had a great interest in the incorporation of much 'sacred geometry' into the design of that structure, and no doubt where other neoplatonists had a hand in building design, such elements will be found in the geometric form and proportions of those structures. Allusions to a more prosaic aspect of geometric design are made by Johnny Roosval (II 1944), of which more will be said later. To make too many generalisations on this subject is dangerous. In the real world with its huge diversity of human nature, ability and interest, many different things are happening at the same time. Today, just as in the medieval period, there are those who will both create and find esoteric meaning in such construction, both where it is genuine and where only imagined - and there are those who will stubbornly refuse to acknowledge the existence or potential for any such notions anywhere - again whether genuine or imagined - even when so much medieval documentary evidence exists.

The function of geometrical construction and manipulation in the design process is succinctly explained by Roosval in a most useful article on church design in Sweden when he refers to "help-constructions" and "help-triangles" (II 1944: 149-62), implying the role of geometry as being purely a means to an end. In the context of dismissing any metaphysical symbolism immanent in geometric proportional relationships which he claims as later interpretations, Morgan also stated that the procedures of geometric design "... were essentially generated by the need to solve practical problems of building" (II 1961: 17-18).

Perhaps because of the veritable minefield which this whole subject can obviously become, it is worth noting some of those who have tackled it to the point of analysing the geometry of the overall built form and the space enclosed, but have stopped short of trying to explain the structure specifically. Morgan only mentions wall thickness in connection with geometric design once in his entire book, and then only relating to the partition walls dividing the side chapels of King's College Chapel Cambridge, ironically a case of no structural significance at all (II 1961: 77). The very investigators who were intimately involved with large numbers of medieval buildings such as MacGibbon & Ross and Viollet-le-Duc never bothered to look into determinants of wall thickness. For all Viollet's insistence on the rationality of Gothic structure, he actually devotes all his energy to coverage to proportionality of the overall building form and its impact on aesthetics in many cases. Even in his analysis of a classical arcaded structure of his own design (X 1959: 408-9), to illustrate the use and aesthetic qualities of certain proportional relationships, he entirely neglects to mention that the geometric system used also defines the thickness of the piers - he is simply not concerned with this aspect. Likewise with his analysis of the Cathedrals of Amiens and Paris (X 1959: 402-9) he is only concerned with the general proportional relationships of the overall layout. On the sizing of individual elements he is delightfully elusive: in describing a simple quadripartite vaulted square bay with an extra transverse rib, he comments that the abutment required at one corner, from where the long diagonal rib springs, will need to be stronger than that required half way along one side, from where the shorter transverse rib springs. This is of course quite obvious, but Viollet makes no attempt to investigate precisely how the medieval architect might have determined such sizing.

As a final word on the subject, it is perhaps not surprising that many have baulked at the possibility of analysing structure when the complexity of the buildings they have chosen as subjects is taken into account. When it is considered for a moment the number of different surfaces, angles, levels, and significant points there are on the average cathedral, both interior and exterior, from which dimensions or angles may be taken, the task of identifying the architect's original lines which determined a feature as diminutive as the wall thickness is daunting in the extreme. In order to ascertain with more confidence what design methods were used by medieval architects, it is preferable to use simpler, smaller buildings, and ideally a larger number of them within a relatively tightly defined area. The masonry building tradition of Scotland provides very suitable scope for such research.

3 THE STATE OF STRUCTURAL ANALYSIS IN SCOTLAND

3.1 INTRODUCTION

Whilst scholarship on the processes of structural design in general terms have reached thus far, the position in Scotland is very different: scarcely has the subject been touched. Most high profile analysis has been carried out on the greatest vaulted or domed monuments of antiquity, the medieval and renaissance periods. There are, however, few if any buildings in Scotland which fall into these categories, and which survive. The history of architecture in Scotland has been variously written from an evolutionary, or a typological point of view: the development of the tower house, according to the needs of its owners; the different types of ecclesiastical building according to the liturgy, each together with aspects of contemporary style. Much has been made also of the needs of security or defence. Many writers have majored on the history of domestic buildings in a familial, political and social context, describing the lives and events of history set in those buildings. Where questions of style and aesthetics arise, the normal canons and procedures of art history tend to dictate an emphasis on the progressive, the original, the exceptional, the unusual and the very high quality; there is little space devoted to the commonplace, the typical; and of the design of structure across all these categories, there is an almost deafening silence. Scottish architectural history is characterized by a fairly consistent omission of anything beyond the most superficial observations or random guesswork on structure and structural design.

However, in order to find out whether any structural analysis had ever been attempted, it has been necessary to scan the entire body of literature covering the nation's architectural history and a list of the principal works on this subject will be found in the bibliography. It is not totally comprehensive since there is little point in including all the descriptive surveys of individual buildings by writers such as W.D. Simpson published mainly in the Proceedings of the Society of Antiquaries of Scotland. It could indeed be argued that many of these do not fall into the category of architectural history, so much as architectural description. There are also a number of works which do not touch on the nature of structure in Scottish building beyond the most basic, by authors such as Stirling Maxwell, George Scott-Moncrieff, Hubert Fenwick, Ian Hannah, Nigel Tranter, and these have not been included. The four volumes of Robert Billings' 'The Baronial and Ecclesiastical Antiquities of Scotland' 1847-52 are also omitted here as being of descriptive more than analytical nature.

Even the works which are listed in the bibliography have little of substance to say on the subject, although there are a few references which provide some useful information or points of departure for this research. For the sake of completeness, those texts or passages are now mentioned in order to set the scene of the context of the project, beginning with the most general.

3.2 DIMENSIONS AND PROPORTIONS

There is very little worthy of mention on this subject, with a single exception: Fernie's scholarly analysis of St. Margaret's Chapel at Edinburgh Castle (VII 1986: 402). This reveals a system of integrated proportions where the wall thickness has to be two feet in order for the entire scheme to work. Given the non-alignment of one wall this must have been a monumental task, but it is utterly convincing. A full description of the analysis will be found in Appendix I.

In one of a collection of essays centred on St. Magnus' Cathedral, Kirkwall, Eric Cambridge briefly touches on the subject, comparing the nave proportions with those at Durham and with Romanesque principles of design in general (VII 1988: 113). More specifically he quotes Fernie (II 1979: 2) who has found that the 1:√2 rectangle is the most commonly found ratio in the larger Anglo-Norman churches (VII Cambridge, 1988: 122) and notes that this figure features in several significant dimensions at Kirkwall.

Of all other writing on Scottish architecture, there is only one page to be found on proportionality in the structural design process. MacGibbon and Ross included a text by Sir Henry Dryden on churches in Shetland (VII 1896, I: 145-73) in which is a short but informative section (pp.161-62) on proportions. Geometric rather than mathematical derivation is recognised and obviously some survey work has been done in which conclusive coincidences have been found. Such information tantalises and it is unfortunate that neither the full results of these surveys and analyses nor even references are recorded.

Later volumes of the RCAHMS Inventories provide a good account of each building including an attempt at dating, description and, most usefully, dimensions of both overall structure and details. There is, however, practically no attempt at structural analysis, or at relating each building to a wider historical context - similar or contrasting buildings or parts of buildings elsewhere - and little if anything on how the building fits into any historical pattern, whether typical, advanced or exceptional.

Perhaps the sentiment for which Stewart Cruden will most be remembered is his judgement of the tower house form which seems heavily coloured by a twentieth century architect's professional standards, without regard for the fact that these might be more appropriately classed as mainly semi-vernacular structures: "It is not great art: it achieves no sublimity; it forms no laws and conforms to none" (VII 1981: 164). This latter clause is unsubstantiated, and provokes reaction. Cruden gives no indication that he ever did further research into any "laws" or conventions by which tower houses were designed. We shall see later the validity or otherwise of this statement.

3.3 PROCESSES OF DESIGN AND CONSTRUCTION

The only attempts at any analysis of the construction process are to be found in connection with masons' marks. Itself a thorny subject full of pitfalls, of which Joachim Zeune mentions most (VII 1992: 58), before going on to show how useful they can be in charting the construction of a particular building (Melgund, Edzell, Borthwick) and the number and make up of the mason labour force at any one stage. Unfortunately he omits to mention that the number of freemason operatives applying their marks does not account for the number of roughmasons who may be employed at any time on the business of roughing out and laying the rubblework of the main wall structure. Chris Tabraham makes some of Zeune's findings available to a wider readership (VII 1997: 111-13).

Of the process of structural design of the later tower houses, Howard (VII 1995: 75) observes the complexity of a subject such as Craigievar where there is no formal elevation and floor levels in wings are not necessarily the same as in the main block. She assumes that models in the round must have been used, an idea repeated in her conclusion (VII 1995: 214). This seems quite plausible, but is unsubstantiated by any surviving evidence.

Writers up and down the whole of Britain have for centuries now noticed and mentioned the design of a window arch inscribed onto the wall of the lower chamber at Rosslyn Chapel and have compared it with the tracing floors at York and Wells Cathedrals, but as mentioned earlier, Fawcett questions how a vertical as opposed to a horizontal tracing 'floor' was used. (VII 1994: 171).

3.4 STRUCTURAL COMPARISONS ACROSS DIFFERENT BUILDING TYPES

Cruden makes a somewhat flawed comparison of later tower houses on the one hand, with their various jambs as integral elements of the original design, with the various parts of St. Rule's, Leuchars and Dalmeny Churches, or what remains of them, as similarly composite structures (VII 1981: 154). Cruden is trying to make a point which, in principle, is actually very relevant. In the event, he misconstrued it and chose inappropriate examples. Scots masons were often from the early fifteenth century, if not before, very inept at designing a multicellular building as a harmoniously integrated structure. MacGibbon & Ross illustrate this point in connection with the disjointed approach to some cruciform plan churches where nave, choir and transepts are all joined separately to the crossing tower with dividing arches rather than meeting at a crossing unified by groin vaults (VII 1887-92 III: 2). This was often because each of these parts was actually built at a different time. Fawcett mentions the same problem using as more appropriate evidence Yester and Corstorphine Churches (VII 1994: 167). Similar separateness without a tower can be seen at Ladykirk church where the roofs of the transepts are built entirely separate from that of the nave/choir. All this is possibly significant in that it suggests a tradition of each part of a building being treated as a separate structural problem requiring a possibly separate solution.

In this context, it is worth mentioning that MacGibbon & Ross themselves run into problems when asserting that the reason for such churches' window heads terminating below the spring of the vaults was to "... avoid even a small groin ..." (VII 1887-92 III: 3), a point laboured at some length. Had they thought to examine other building types with the same 'structural problem', they might have reached a different conclusion, for in many vaulted domestic structures, such groins are in fact very common and are often quite competently handled, depending on the general quality of the building. Such contradictions suggest that examination of individual building types in isolation can be dangerous and misleading.

One aspect of this whole subject which seems to go unrecognised is that the structural design of any one building type viewed in isolation may be affected by different factors from those influencing others. For instance, to a master mason, a tower house could, in its most basic form, be a similar structural problem to a church tower; but the question is, are they actually treated the same. It is these very omissions in existing literature which are a point of departure for my own research.

3.5 SECURITY / DEFENCE

To what extent were tower houses of any age defensive? Probably more ink has been spilt on this old chestnut than any other aspect of the subject and too many over-generalised conclusions have been reached. It is not the purpose of this research to enter into the debate to any great extent except to comment where fortification has a direct bearing on structural design, in particular of course, wall thickness.

Cruden (VII 1981) was perhaps the main progenitor of the 'military' or at least 'defensive' tower house concept, not altogether unreasonably, but with some possibly unwarranted exaggeration, particularly on the defensive purpose of spiral stairs. At the other end of the spectrum is Charles McKean. In an exhibition (1990), numerous lectures and publications (VII 1990, 1995 and 1996) McKean has consistently tried to create the impression not only that tower houses and palaces up to the seventeenth century have been generally misrepresented as grim defensive fortresses, (although there is actually a notable absence of serious academic writing to that effect), but furthermore, of the originality of his claim that this was not the case. With contrasting scholarliness Geoffrey Stell (VII 1981) covers the whole subject of defence in a paper specifically directed at this subject matter and suggests that wall thickness may have been related as much to height, or ground conditions as it was to defence. Fawcett similarly takes an eminently level-headed view in the defence controversy, pointing out the changing priorities of builders over time, and the rise of symbolism (VII 1994: 237). Glendinning et al. note the fashion for "recent historians competing in their rejection of the military interpretation of these buildings" (VII 1996: 23) but the pendulum is in danger of swinging too far. Some degree of reassessment is becoming due. There has been much reaction against the views of Simpson, Cruden and others with really very little substance or facts in support. Much is simply generalized opinion or conjecture often in support of an argument emphasising the sophistication of Renaissance society. There was actually much insecurity in Scotland generally, especially during the middle decades of the sixteenth century, as the numerous "wappinschawings" and exhortations to fortify towns and cities recorded in the minutes of council meetings testify (e.g. Aberdeen in particular).

In passing, some mention is appropriate of the probably romantic myths about spiral stairs and their role in defence: an upwards clockwise direction apparently giving a retreating defender some extra advantage with his sword hand - assuming he is right-handed of course. Then there is the origin of the 'turnpike' nomenclature. It is impossible to know exactly where and when all this started and I do not intend expending time and space on it. Howard refers to earlier towers as having "a defensive turnpike stair" (VII 1995: 72). Was it really so? There is no other comment in this body of literature on the subject. The most helpful thoughts on the matter have been expressed by Fitchen (IV 1961) who has suggested that the thick wall in medieval building effectively formed its own scaffolding platform as it was built, and the spiral stairs in its thickness formed the access ladders.

3.6 STRUCTURE AND STRUCTURAL DESIGN

This is the principal business of this research and it is of primary importance to sift what previous writers have to say on the subject. It has to be said from the outset, however, that treatment hitherto is sparse, the occasional hypotheses, assumptions, deductions and conclusions seem to be based less on meaningful research than on guesswork aimed with varying degrees of intuition. Architectural history remains stubbornly to this day principally about aesthetics and utility. Yet every building, whether a work of art or not, has to be constructed in such a way that it will stand up when complete, and will continue to do so for as long as possible, however abused by mankind or the elements. However, structural strength continues to attract little more than scant interest, particularly when applied to building which does not appear to be teetering dangerously close to safety limits, like the great Gothic cathedrals of France and domed structures of antiquity and the Renaissance. The subject in these cases is perceived to be more the domain of structural engineers for analysis. In Scottish architectural history few have seen any aspects of structural design worthy of comment. There is little or nothing built here which is perceived to be at the cutting edge, or at the limits of stability to excite the engineers' interest.

At the other end of the scale wall thickness is also interesting when it is exceptionally massive, and writers over the last century have delighted in titillating the appetites of their readers with the gargantuan proportions of fourteenth and fifteenth century tower house masonry. MacKenzie quotes an interesting thirteenth century French poem in which 15 feet is cited as satisfactory thickness for "a great tower of stone" (VII 1927: 93). However, most studiously avoid the subject altogether when it becomes less exciting in the post-Reformation period, or when discussing other building types. For the most part attempts at structural comment are naive, unsubstantiated and frequently illogical. Sadly for standards of Scottish architectural scholarship, some of the worst in this respect has been written most recently.

Various papers which touch on the subject have been produced by McKean with some elements of truth but explained with much muddled or oversimplified logic and faulty conclusions. Perhaps the substance of his approach can be seen in a overly simplistic article 'Dating Buildings by Wall-Thickness' (VII 1996: 9), which does little more than indicate that tower house wall thicknesses generally decreased over time, which was already well-known, and therefore theoretically their date can be estimated by their wall thickness. He argues that the wall thickness of a single building programme would logically be constant and therefore if there are some thinner walls, these will be later. Hence, the building history of a structure can be determined by its various wall thicknesses, which may have some generalised relevance but it takes absolutely no account of other determining factors of wall thickness, nor does it apply to building types such as churches where the approach to the matter hardly changes in centuries. McKean unfortunately concentrates on tower houses in isolation and looks no further. Similar logic is applied in a later and equally problematic publication, this time referring to Melgund and Carnasserie castles: "In each case the wall thickness of 'the tower' is greater than the villa extension and since no one would build an unnecessarily thick wall, for reasons of cost if nothing else, it seems likely that the two parts of these houses were built at different times." (VII 1996, VI: 2). According to Zeune (VII 1992: 61-2), Fawcett (VII 1994: 269), both of which were available for McKean's reference, this is incorrect: both structures were almost certainly built in single programmes.

In his assessment of Huntly Castle, McKean explains the walls' greater thickness at vaulted lower level: "It seems probable that thicker walls were required to contain the weight of the stone-vaulted ground floors, becoming thinner (and more economical) as they rose." (VII 1995: 2). Suddenly there is a different reason than the fact that in this case the ground floor was actually an earlier build which, again, is already well documented. On the other hand, perhaps as this paper was published in the previous year, he had changed his mind about the basis for determining wall thickness.

McKean's efforts on the subject for which he is theoretically well-known, are under-researched, illogical, inconsistent and unscholarly in both substance and presentation.

In a rare departure for Scottish architectural history, Deborah Howard attempts to address the question of overall vault/floor joist span in tower houses and I have to quote her in full:

> "Since the maximum span of a stone barrel vault was around 20 feet, this became the traditional limit to the width of a residential block. During the Renaissance, experiments were made to break out of this formula by adding a vaulted corridor alongside the row of vaulted service rooms .... The inspiration for this solution may have been the royal palaces. At Linlithgow, Falkland and probably Holyrood, inner skins with vaulted corridors surmounted by galleries had been added in the first half of the sixteenth century. ... the addition of the lower corridor allowed the broadening of the reception rooms above, though the length of available timbers span the ceilings of the upstairs rooms was still a constraint." (VII 1995: 68).

There is an obviously well-intentioned attempt here to engage in an explanation of late medieval structural design and there are some grains of truth in it - building spans are rarely more than 20 feet but most property referred to is private/domestic and interestingly the same span 'rule' might be said to apply today of that property group, since, in social terms, wider spans are simply not required. True, in engineering terms, it would be economically unsound to span a greater width with simple commonly available standard sizes of timber joists, and larger timbers would undoubtedly have been more difficult and therefore more expensive to win and transport. As it happens, this dimension was commonly exceeded in timber roof spans, as and where necessary, mainly in the great halls of Scotland's feudal and ecclesiastical aristocracy and indeed royalty. Examples include Kildrummy 41 feet, Darnaway 35 feet, Bothwell 32 feet, and Stirling 46 feet. There are many more. As to 20 feet being the limit for stone vaults, the number of contemporary stone bridges in Scotland of between 30 and 40 foot span from at least the mid-fifteenth century shows this to be a serious misconception.

Of variations of wall thickness within a single building there is virtually no significant mention, other than in the individual building surveys of MacGibbon & Ross, Simpson, Slade, Salter and the RCAHMS inventories. Even here, there is no real attempt at analysis or explanation. There are two rather puzzling references to tower house walls being battered: the first by Simpson who refers to "... our older Scottish tower houses ..." where "... the walls are ingathered as they ascend, the intake being accentuated in the upper two thirds of the structure ... the inside face of the wall ... is vertical, while the outside is thus intaken ..." (VII 1961: 238). This may well be the source (unacknowledged) for Colin Coutts' identical assertion in 'North East Castles' (VII 1990: 84). It is a truly astonishing statement: having personally examined a considerable number of tower houses in various parts of the country, I have yet to find such a battered wall. Here is a classic case of perhaps mythical history being created and perpetuated by the pen, where a little more use of the measuring tape would be preferable. Significantly perhaps, no examples are given by either writer. It is conceivable that Simpson was thinking of some Irish towers where this characteristic is found, (I Craig: 1982, 23, 81, 97). Clara in County Kilkenny is a good example of this, but then Simpson was writing specifically about *Scottish* tower houses.

Cruden mentions the wall thickness of fourteenth century tower houses - of which there were relatively few, and argues that the "great thickness [was] scarcely diminished in the upper levels because of the need to provide abutment for the thrust of the high vault" (VII 1981: 106). However, he does not draw a comparison between these and the towers which did not have a top floor or high vault to reveal if, or to what extent the presence of a high vault affected the wall thickness.

The abutment of vaults is also referred to briefly by Cruden, when discussing the flying buttresses at Rosslyn Chapel where "... they are used illogically because the thrust of the vault is evenly distributed along the length of the side walls from which it rises." (VII 1986: 169). Cruden is mistaken here: the thrust cannot be evenly distributed along the side walls since it is interrupted by clerestorey windows. But neither Cruden nor anyone else asks why it is that so many Scottish churches of the fifteenth century, with continuous barrel vaults 'thrusting evenly' onto the side walls, are abutted likewise at intervals by simple standard buttresses. If Rosslyn is a structural aberration or solecism, then so are the chapels of Seton, Borthwick, Dunglass, Yester and many others. There are indeed many questions to be answered here, and yet there are no other attempts to justify or explain the presence of buttresses that are more than superficial. It seems to be assumed that, being part of the repertoire of Gothic and late medieval design, they are simply to be expected.

That accounts for the some of the more controversial efforts on the subject. On the other side of the coin perhaps the only useful comment and springboard to further research comes in characteristically pragmatic and realistic style from the pen of Geoffrey Stell: "... whilst perhaps influenced initially by the capabilities of the medieval siege engineer, the nature and thickness of the castle walls and their associated plinths can more often be related to the height and mass of walling above ground or to the ground conditions below, than to the fear of breaching or undermining." (VII 1985: 201). Here is a more level-headed awareness of some of the real problems facing the medieval builder which constitutes one of the primary points of departure for this research.

On a general level there is, naturally enough, general consensus that wall thickness of domestic tower houses diminished between the fourteenth and seventeenth centuries but rarely is any attempt made to assess the criteria by which it was determined in general or in any individual case. There is no attempt so far to account for the gradual adoption of thinner walls for tower houses other than the vaguest references to expense, and to the lessening requirement for fortification. These are both of course very valid points, but there is still no in-depth study or quantification of how the transformation took place.

In the whole corpus of research in Scottish architecture and building, there is only one area which is even remotely concerned with the processes of structural design and construction, and perhaps naturally so since it is in our own time very much the preserve of the engineer: bridges. The work of Harry R.G. Inglis published in several classic papers (especially V 1910 & 1913) examines all too briefly several aspects of bridge design. Possibly taking a slightly over-generalized view, he equates narrowness of arch span with greater antiquity, which is of course broadly correct, but he omits to mention many potentially conditional and related factors, such as pier thickness to span ratios. He also arrives at a quite plausible basis for calculating the average time taken to build a single arch span but, again, over-generalizes, failing to mention the likely differences between the cases of, say, a small and simple twin arched bridge founded directly on rock, and on the other hand, Berwick's fourteen spans which wallow in good thick mud (V 1913: 309-15). In his earlier paper Inglis comes so close to the nub of the matter, pier thickness, but in isolation as a dating criteria and not in its relationship to span (V 1912: 164).

3.7 CONCLUSION

The paucity of knowledge of this subject here in Scotland is evident: there are many here who are eminent in the writing of architectural history, but those who are interested in the analysis of medieval structural design, and are of the calibre of Eric Fernie are operating in a more global field, concentrating on the larger or more daring monuments. Regrettably Fernie himself has left Scotland leaving a vacuum for serious research into questions concerning measurement, geometry and structure, and there is still much work to be done.

4 LOOKING FOR GENERALITIES AMONG INDIVIDUAL SOLUTIONS

Frankl wondered as long ago as 1945 "... what was *really* done in Gothic times ..." (II 1945: 51 italics mine). Since then, as we have seen, much has been uncovered. The geometric principles on which many church designs were based have been unravelled, but only on an individual basis, and some are so complex as to still be open to question. What does seem certain is that there were many different, even personalised systems of geometric design, highlighted for instance by the very different approaches that have been mentioned earlier at Ely and Norwich Cathedrals. This gives rise to the question, how generalized were any of these methods?

Mainstone has claimed that "... the rules have considerably more generality than the *scientia geometriae*." (VI 1968: 306), particularly in relation to determining the sizes of buttresses from the profiles of the vaults they support. He may well have been correct on a general level, but he was referring to only two examples which did happen to relate, and neither of these were built structures: they were theories: that of Francois Dérand of 1643, (often incorrectly attributed to Blondel who used it in his *Cours d'Architecture* of 1675-83), and that of Rodrigo Gil. In passing, it has to be said also that both Dérand's and most of Gil's theories were based on geometric manipulation. But there may be a subtle difference between the geometry of these methods and that of, say, Norwich Cathedral. The latter is based on the plan, taking no account of the shape or height of the vault. The chosen geometric configuration appears to dictate the wall thickness, which thus seems merely to be a by-product, as it were, of the plan. On the other hand, with Dérand and most of Gil's methods, the shape and size of the vault in section dictates the geometric solution. So perhaps we can take it that these constituted 'rules' rather than *scientia geometriae* in its basic form. An examination of these and other what might be called 'rules' appearing in Appendix I does seem to give some support to Mainstone's claim. A summary of these is appropriate at this point, and presents a most interesting picture.

First of all, it quickly becomes obvious that there was some consensus in medieval times that three feet was a good working minimum thickness for the external load-bearing walls of most domestic and small institutional structures; this allowed sufficient volume to provide stability and to accommodate the fireplaces, aumbries, putlog holes etc. which would be built or cut into the wall. Something nearer four or five feet was thought appropriate for towers, and it is in respect of this building type that the notion of slenderness ratio is recognized as the basis for structural design. A ratio of 1 : 20 seems to have been generally considered appropriate for high (and generally unfortified) buildings, that is structures that are higher than five storeys or 45 feet. Some considered this suitable for the entire height, others were happy to diminish the wall thickness at higher levels. Jean Rondelet thought in the nineteenth century that this 1 : 20 tower ratio was suitable for lower buildings where the side walls were in effect braced or stiffened by the roof timbers. This brought the wall thickness down to as little as 21" in some cases. Rondelet obviously had his reasons: he had surveyed 280 buildings in France and Italy, from antiquity through to the seventeenth century, and the results of his theories do seem to be remarkably close to the actual dimensions of the ancient and medieval structures he surveyed. He had carried out a very considerable number of experiments on models also.

For the abutment of vaults different priorities apply. The vault span generally replaces the wall height as the principal determinant of wall thickness. There seems to have been some general consensus, which is expressed for us by Rodrigo Gil, that the ratio of buttress to span alone should be around 1 : 4. (Many theorists tend to express wall thickness and buttress projection together, simply as "buttress".) This ratio is generally expressed irrespective of the building's height, but then it should be remembered that, according to some sources, including Lechler's instructions and the *Lettere Sanesi* (quoted on page 22 above), there were conventions which linked span with height in church building. Doubtless the architects whom Rodrigo consulted would not have entirely ignored the building height when choosing their buttress to span ratio of around 1 : 4, but still there abound theories by Rodrigo himself and others which seem to ignore it. Only later in García's *Compendio* does Rodrigo produce theories for defining both buttress depth and safe height for a vault of a given span. In the final analysis, there does seem to be some consensus amongst the sources consulted of a buttress to span ratio of between around 1:3 and 1:5 even, perhaps strangely, by the architects who, it appears to later analysts, designed wall thickness by constructive or proportional geometry in *plan* alone, such as Serlio.

The inclusion of wall-thickness as an integral part of a scheme of proportionately related volumes and spaces has been demonstrated by Fernie in his analysis of St. Margaret's Chapel. As he states, the walls here could only be two feet thick otherwise all the other dimensions would not relate (VII 1986: 402-403). It has to be said that the integration of wall-thickness into such a proportional scheme is probably rare. Nonetheless the span ratio is still around 1 : 4.8. In Fernie's analysis of Norwich Cathedral the ratio is the same 1 : 4.8; in Coldstream's of Ely it is almost the same at 1: 4.67. In fact it is noticeable how in most of the built works there is a general tendency for span ratio to fall into a bracket of between 1:4 and 1:5. It is only the theoretical and project work which falls outside those limits. So it does seem that Mainstone's claim about "generality" in the rules is broadly correct and, furthermore, that even built works of dates prior to the Beauvais watershed fall into this category, suggesting that some rules were perhaps being subconsciously made and adhered to in that earlier period. This, however is a dangerously small sample on which to base a thesis. The problem which arises is how generalized is all this? How many other examples will fit this pattern?

Broken down into simplified questions, this research asks in any one building tradition which may be defined by geographical boundaries, and set in the medieval and renaissance periods from around 1100 to around 1650:

a) what method(s) were used for calculating wall thickness and vault abutment at any particular time in the medieval and renaissance periods?
b) do there appear to be rules of thumb governing such calculations?
c) if so, what were they?
d) to what extent were these rules standardized
    - over time ?
    - across a range of different building types?

Whilst these sum up the general thrust of the research, there are other questions which also require to be addressed, in essence prompted again by Mainstone. Although in his mind were the great buildings of antiquity, the medieval and Renaissance worlds, (e.g. Hagia Sophia, Brunelleschi's Dome), the questions addressed in his 1997 paper constitute a formative influence on the idea of this project: how, to what extent, and for how long was centring used in the construction of arches and vaults; whether "... parts of the structure were sized primarily to withstand the forces exerted at some critical intermediate stage during construction rather than those to be expected on completion" (VI 1997: 328). He is not the only writer to whom this point occurs. Ruddock also raised "the question of whether each arch [of a bridge] could stand independently without the balancing thrusts of its two neighbour arches ..." (V 1979: 6). Research into geometric design and rules of thumb would obviously be incomplete without this element. So, with all this in mind, let us now turn to setting some realisable aims and objectives.

5 AIMS AND OBJECTIVES

5.1 INTRODUCTION

The principal aim of this research is to find answers to all the afore-mentioned questions using the relatively simple stone buildings constructed in Scotland over the medieval and Renaissance period; to ascertain whether design was based on constructive geometry or some other rules of thumb and then to what extent was there consistency in their use across several different areas of application: across different building types; across different geographical areas of the country; and over the period c.1100 - c.1640 in order to ascertain what changes, if any, took place.

The enquiry into the consistency or otherwise that rules were applied across a range of different building types is fundamental to this project, and here, rightly or wrongly an assumption is made: that pre-industrial master masons will have perceived each commission in terms of a set of structural problems; whatever the building type, it would be broken down into individual structural problems. By reducing all structures to these lowest common elements, analysing each in turn and comparing treatment of the same problem in different building types it should become clearer to what extent structural rationalism was pursued and how it may have been achieved, or at least, how it may have been perceived.

Unlike much architectural history which deals in progressions, developments and exceptional advances in style or form, this research is based more on that which is or was *typical*, what was common and even possibly consistent. We are looking for trends. The quest is to chart the endurance or otherwise of building traditions in a changing world rather than for the great leaps of progress that it is fashionable in our own age to seek out and from which to create 'history'. For while the boundaries of structural adventurism might have been pushed out by the great cathedral builders of the medieval period, the vast *corpus* of building across Europe was carried on by masons who, whilst probably aware of such works, were never required to achieve the same. Their work and indeed the limits of their skills can theoretically be inspected with impunity in relative isolation from such works, particularly in a country geographically on the fringes of Europe reliant very much on a building workforce of indigenous origin, who were only required to design and build structure on a relatively less sophisticated and small scale. This itself gives rise to one further question.

It is sometimes debated how much of Scotland's medieval and Renaissance stone building stock can be described as architecture and how much vernacular building. There will always be a large grey area between the two. Recent writers are beginning to recognise and stress the aesthetic merits of what was regarded in some cases as quite simple and functional building, particularly of the Renaissance period, and many of these claims are well founded. There is undoubtedly a quite legitimate complaint, often expressed, that standards applicable in other parts of the British Isles, particularly England, have in the past been indiscriminately applied north of the border, notably by Sir John Summerson (1953 & later).

Clearly, in line with the different climate, available building materials, economic, political, social and even religious environment, some different criteria for aesthetic sensibilities are applicable. Whilst this particular research is not primarily or specifically concerned with traditional or recently revised views on what constitutes designed architecture or functional vernacular building, notions of what elements of structure are solely for actual stability and what are for visual, psychological or 'aesthetic' quality will undoubtedly be a by-product of the project. In this respect, perhaps by a process of elimination, it will contribute to an understanding of a Scottish concept of aesthetics in the late medieval and Renaissance period, and this has become a further conscious aim of the research.

Thus, for the purposes of this thesis, whilst the word 'architecture' will inevitably find occasional use, 'building' will more frequently appear, and whilst care has been taken to ensure some level of propriety in each case, it is accepted that opinions may differ and in any event there is, as stated, a large grey area between the two. For the most part, the research is primarily concerned with building structure, and aesthetics are a secondary issue.

These then are the general aims towards which the research is directed. In order to obtain a result, several achievable more narrowly defined targets have been identified. They involve two of the simplest and most universal structural problems that builders anywhere have ever had to tackle in the achievement of overall structural stability and strength, and the greater proportion of available resources for this project have been directed towards the analysis of just these two problems.

5.2 ASSESSMENT OF STRUCTURAL DESIGN CRITERIA: WALL THICKNESS

Now it may be that during a given period in a given region, there was an accepted norm or canon for wall thickness; it was standard for every building quite independent of any other factor. This is hypothetical , of course, and it may turn out to be incorrect, but it should not be dismissed out of hand. As a general rule on a more realistic level it is more likely that wall thickness will relate to some other dimension in the structure. It may be that this other dimension will always be the sole determinant of wall thickness in order to achieve structural stability. Alternatively it may be the sole determinant up to a certain point, then another dimension also has a bearing. At this point there has to be a certain amount of guesswork but it seems logical to suggest that wall thickness requirement would be seen as a ratio relationship to either wall height (commonly known as slenderness ratio), or roof span (what I will call 'span ratio'). Of course a combination of these may have been used. Another possible factor is the extent to which account may be taken of the length of wall between abutments.

Yet another possibility, and by no means a remote one, is that instead of these simple arithmetically based ratios, wall thickness may well have been determined solely by some geometric means, based on the ground plan, which will of course still result in an arithmetic ratio but more likely to incorporate irrational numbers. Filarete's tower, mentioned in the introduction, where the wall thickness may have been determined by the length of one side wall perfectly illustrates this.

The overall results of unravelling this conundrum could serve several significant purposes:

i) generally qualify the traditional and unspecific assertion that later walls were simply thinner than earlier ones;

ii) assess what level of extra wall thickness was attributable to defensive/security requirements;

iii) chart and quantify the progressive demise of 'voided wall' type building in favour of design based on the enclosure of room and circulation/service space.

5.3 ASSESSMENT OF STRUCTURAL DESIGN CRITERIA: VAULT AND ROOF ABUTMENT

Now it is of course realised that there is some overlap here with the previously mentioned criteria for determination of wall thickness. In one sense this present enquiry is really subordinate to span ratio, above, but there is actually more to it than that, as will become evident. The main purposes behind this second area of enquiry are:

i) to ascertain masons' awareness of safe limits;
ii) to explain the various configurations of vault haunches found;
iii) to assess the role of buttresses, principally in ecclesiastical building;
iv) to qualify the traditional and unspecific claim that tower houses were vaulted to increase their structural strength.

5.4 THE SCOTTISH CONTEXT

To return to a more general view, a research project of this nature could be seen in one of two different lights. On the one hand it could be regarded as an investigation into medieval and Renaissance buildings that are Scottish to assess the practice, such as it was, of structural design in this one specific nation state during that period, and how it related to the prevailing conditions peculiar to that country.

Alternatively it is tempting to opt for a more universal study of the subject, merely using Scotland as a case study. To some extent both will apply. In one sense Scotland is an ideal case study - being relatively self-contained in her building tradition, relatively isolated from the rest of European influence, also having a relatively homogeneous building tradition in the use of stone and in the continuity of more than one particular building type (the tower house and also the single cell church) over several hundred years. Conversely, Scotland's very isolation makes her building tradition quite possibly unrepresentative of anything but her own. Certainly some of her structural types, such as the tower house, are virtually unique. Set against that, however, it has been emphasized that each building is being broken down into its individual constituent structural problems, which will of course be more universally applicable. In any event, if a study of this nature was to be used in such a universal or comparative manner, some broader knowledge of the building traditions of other countries such as France and Germany would be necessary in which to set the Scottish study in context. That is no mean task, for, as far as I am aware, research of this nature has hitherto not been carried out in any other country.

The scope of this survey is large and unwieldy enough in covering stone buildings in Scotland. In order to contain it to some extent, structures bedded in clay rather than lime mortar are excluded, as are timber-framed buildings. These are obviously huge omissions from the whole corpus of the Scottish built environment, excluding practically all urban building at a stroke as well as most rural vernacular structures and border bastle houses. However, these are of course the very categories of buildings which generally just do not survive, and where there are examples there is no way of telling how representative they are of the greater, long since lost population. Needless to say, there may have been a number of structures over the whole country, or indeed limited to one region, which are omitted from the survey due to their loss as a result of poor design or workmanship, and it is acknowledged that such omission will give a false reading to any statistical database results.

Whilst drawing out parameters of the research it is appropriate also to mention that the vast majority of the stone building in Scotland of the period under review is sited in the heavily feudalised and economically wealthier lowland districts. Conveniently this lends greater homogeneity to the sample of structures used which are predominantly of sandstone, in contrast to many highland examples which are of schistose or other metamorphic rock types. To the latter, it is admitted that differing building practices and tradition may have been applied in some cases, but these have not been included in sufficient numbers to warrant separate attention.

The period chosen for this research, from the twelfth to the mid-seventeenth centuries, is long, but from several aspects necessarily, and indeed desirably so. The earlier pre-Wars of Independence period is one of international influences in Scotland - primarily Anglo-Norman. The buildings in Scotland after this period and after the hiatus of the wars are in many cases of a very different type and style, and theoretically design methods may have changed also. It will be an objective of the research to find out whether or not this was the case. The Scottish tradition was never entirely free of influences from abroad, and these undoubtedly increased through the sixteenth century with many visible manifestations. This period through into the seventeenth century is associated with renaissance thinking, and whether these visible developments were matched by less obvious changes in methods of structural design is also an object of this research. The fundamental shift in building style from around 1660 makes for a convenient terminus for the study.

To summarise, the principal aim of this research project is, by means of measured surveys, to identify the methods, practices and rules of thumb used in structural design by masons in Scotland up to around the mid-seventeenth century, to assess to what extent these may have been standardised, and to what extent they appear to have changed or developed over that period. Secondly to assess on the one hand contemporary perceptions of structural sufficiency or rationalism, and on the other, notions of security, symbolic or real.

6 METHODOLOGY

6.1 INTRODUCTION: "ENTERING THE MIND OF THE DESIGNER"

Familiarity with the abundance of ruined structures here in Scotland laying bare their secrets to the inquisitive, and a few measurements of various structural dimensions suggested the possibility of an inquiry into these questions, simply using the surviving buildings themselves as documents. This country has a long tradition of masonry building, with some building types enjoying several centuries of popularity, changes in many cases being evolutionary in response to changing priorities in such considerations as economy and security. Furthermore, the buildings are in many cases structurally very simple with relatively few significant features which, for the purposes of analysis, carries a tremendous advantage over the enormous complexities of Gothic cathedrals where almost any line drawn across a plan, section or elevation may touch, and therefore be construed to define the position of many a structural feature.

Building surveys, however, are time-consuming and expensive and, where great cathedrals and churches are concerned, practically very difficult. When Frankl asked that question "what was really done in Gothic times?" (II 1945: 51), he was content to "leave to others the necessary investigation of the buildings themselves." Since then various methods have been developed to assist the structural analysis of historic buildings, and it is appropriate to digress for a moment to look at what methodologies have been used by other researchers in this and related fields.

There has been the photo-elastic technology of Robert Mark (1982). Jacques Heyman used a more conventional approach, examining the principal lines of thrust within structure, mainly vaults, arches and domes (many papers since 1966). Both have since been criticised, if not roundly condemned in some aspects (by, for instance VI Yeomans 1996: 215-16, and VI Mainstone 1997: 321, 324-5) since, amongst other things, they take little account of the very diverse nature of masonry build, of the difference in behaviour between ashlar facing and rubble fill. Possibly anticipating some of this criticism Heyman qualifies some of his earlier calculated analysis by stressing that "the problem of the design of masonry is essentially one of geometry. The calculation of stress is of secondary interest; it is the shape of the structure that governs its stability." (VI 1995: 141). In any event these modern analytical methods, together with the more recent Finite Element Analysis (VI Morris, Black & Tobriner 1995) enabling historians to achieve computer analyses of structure, are all concerned principally with the performance and behaviour of the finished work. There is only one methodology which has attempted to address the geometrical or other basis for the original design: the MILES/DBM system developed at the University of Essen from 1980 by Professor Wiemer. A report (VI 1994) discusses its performance in connection with the analysis of just two moderately sized churches in Germany involving over one thousand individual measurements, taken over a considerable period of time. In the event, a colossal investment in time and finance produced a result which did indeed trace the critical module governing the design of an entire church.

The MILES/DBM system seems to be admirably suited to this job in theory, and the results do seem to answer Frankl's question. The issues of proportionality and design by constructive geometry can all be evaluated for the first time without the need to know beforehand from documentary sources the architect's own individual method of geometric manipulation. But it did not appear to be able to take account of the widely differing building forms required for a survey that would be broad enough to answer these questions, and to accommodate all the individual circumstances pertaining to so many structures in Scotland.

The survey of a wide and representative sample of structures is indeed necessary to ascertain precisely what level of generality was present; what were the trends. There is a great danger in trying to make an obvious solution such as Norwich 'fit' any number of other buildings. Architectural historians everywhere engaged in researching this subject would do well to heed the warning of Robert Willis as long ago as 1842, who recommended that investigators should "...bring together a body of examples from which general rules might be deduced. It is only by comparing many examples that this can be done, for general rules deduced from single instances are commonly worthless." (X 1842: 3). However, this does not rule out the use of such methods as a tool, alongside other clues, to ascertain what might have been more generalized practise.

On methodology, Mainstone mentions the importance of comparisons with surviving structures of similar date (VI 1997: 335). In order to assess "generality" this is surely paramount. He talks also of "entering the mind of the designer " which "calls for more than drawings and more than the expertise of today's structural engineer. Certainly modern calculation can throw no direct light upon it." He warns "the analytically minded engineer not to attribute to his forerunners twentieth century objectives, ideas, insights and procedures." He stresses that the answers will be found mainly in geometry, for "it was then chiefly geometry that determined whether a structure would be stable and otherwise adequate." Whilst not ruling it out altogether, he maintains that neither arithmetical calculation nor the latest Finite Element Analysis method are the keys to understanding historical structures (VI 1997: 338).

An interesting example which bears this out can be found in the work of O'Connor on bridges (V 1993). He adopted precisely this method of simple measurement in his appraisal of the rules governing ancient Roman bridge design. He found it to be simple and effective. However, having thus found these rules of proportion, he then set out, perhaps surprisingly, with modern mathematical methods to analyse the same structures. In a chapter of highly sophisticated scientific process based on methods formulated by Heyman, he concluded that the Roman structures had survived generally because the stresses within them were in equilibrium, a somewhat obvious point in view of their survival, which only gives added weight to Mainstone's contention (VI 1997: 338) that modern methods of calculated analysis have very little to add to the simple method of measurement which he recommends. Furthermore, O'Connor's analytical findings are very limited in scope since they relate almost entirely to stresses within the arch ring itself, almost completely ignoring the 'geometry' of the support and abutment of the piers. A more circumspect approach, from within "the mind of the designer" (VI Mainstone 1997: 338) is required. We are fortunate indeed in having a record of what perhaps might have been the first such attempt to understand in retrospect the mind of the medieval designer. Francois Dérand in his *L'Architecture des voûtes ou l'art des traits et coupe des voûtes* of 1643 managed to divine a purely geometric method for the sizing of abutment for any given arch or vault, based perhaps on the configuration of the supporting timber formwork. His theory (explained in Appendix I) is indeed simple in the extreme, perhaps too simple: it was later criticised as taking no account of the weight of the vault or its height above ground level. However, it is not certain how Dérand arrived at his theory, nor how widely he tested it, if at all.

6.2 THE DANGERS OF "ROMANCING THE STONE"

There are inevitably great dangers associated with research of this nature. There is an old adage 'anything can be proved with numbers'. Great accuracy, realistic and circumspect analysis are required. Many are the warnings against approaching the analysis of a building with a preconceived notion of some hidden geometric ideal awaiting discovery (e.g. II Branner, 1955: 63). Special heed is paid to Eric Fernie's timely counsel: "The investigator ... should always conduct the exercise by means of calculations using measurements derived from the building itself, and not by the inaccurate if more romantic method of drawing lines on plans." (II 1990: 230). He refers of course to plans drawn previously by others and in some cases published. There is a danger here that any irregularities may have been 'corrected' and a certain amount of idealisation may have taken place.

Such warnings are all very well, but there are of course problems in building surveys, especially for instance involving the measurement of very high cathedrals. In any event they may not even have been executed exactly according to the architect's design, and even if that had been intended, experience has shown that medieval masonry was never executed with total accuracy. The design may of course have changed during the course of construction (e.g. Milan Cathedral), or the work may have been finished 'by eye' and such changes may not be documented. Even if it had, most buildings have since suffered various alterations to original dimensions by sundry means - settlement, weathering, distortions from structural stresses, repairs and alterations.

The romance of uncovering long lost 'secrets' of medieval design can lead to bewildering, or at worst , questionable scholarship. Whilst not necessarily doubting the validity, for instance, of Morgan's thesis on canonical design (II 1961), the unexplained diagrams smothered in geometrical constructions delineated in red at the end of his book can leave the reader more puzzled than enlightened. Ackerman takes Maria Velte to task for her analysis of the section of Cologne Cathedral. She uses Dehio's drawing to demonstrate that a system of quadrature had been used in the design when Dehio had produced just as convincing an argument for triangulature (II 1953: 157). Milner's discovery that amongst the loosely regular plan of Warkwork Castle keep are some 'golden section' rectangles is just about plausible, but suspicions may be aroused when he promotes what was probably a fairly normal, rational and even prosaic use of constructive geometry to the status of "an intellectual exercise on a high scale" (II 1990: 223). There is always a possibility that it was just that, but other than a plan diagram we are given no other corroborative evidence. The attribution of the design to "a mind which was highly educated in the system of mathematical proportion, certainly beyond the experience of a local mason" (II 1990: 224) may of course be true in that the architect may possibly have been a mathematician, but the plan actually required no more intellect or mathematical ability than that of many a master mason armed with pegs and string. Do the appearance of the golden sections really raise the status of a building to some intellectual level, or did that particular form happen to suit the planning requirements of the patron, the exigencies of the site, and even perhaps the lengths of string available to the builder as he laid out the foundations? The golden section has always been just one of those rectangles so easily obtainable by even the innumerate and its perceived romance seems to have seduced some into quite irrational fabrication.

6.3 MEASUREMENT: THEN AND NOW

The measured surveys are without question the most important single element of the research. If pre-industrial masons worked to straightforward rules of thumb based on proportional geometric relationships, the most fundamental requirement of their craft would have been the ability to apply measurements of consistent units to every aspect of a particular task. To a large extent, for my purposes, the size of each individual unit of measure is of little consequence. Certainly, though, it would be something of a bonus if the units were known in each case, and in some cases where building accounts exist for structures which have survived, it would probably be feasible to recover them. However, where simple proportional relationships are concerned, these can be obtained by measurement in any units and herein lies the crux of the methodology. If pre-industrial masons designed structure by constructive geometry, and formulated rules of thumb either by the same method or by proportional relationships, these will have been obtained by the simple expedient of consistent measurement in any given task, and by that same simple expedient, those same rules of thumb should be recoverable. Although in some cases units of measurement do prove to be of significance, the larger part of the research is based on the analysis of proportional relationships alone. Its fundamental importance cannot be overstated.

The specific structural problems which will be addressed have already been mentioned: that of the decisive criteria in the determination of wall thickness, and also in the abutment of vaults. There are quite possibly other structural relationships where rules of thumb might be found, but these are probably the two upon which basic structural stability and strength rely most, and it was realised from the outset that there would be insufficient resources in a project of this scale to attempt to seek, let alone find much more.

The process of measurement itself, although basically simple in concept, requires fundamental accuracy, rigorous attention to detail and consistency of approach, at least as far as is possible within limits imposed by circumstances, which will be mentioned later. In each structure, whatever the type, every structural dimension had to be taken since, although some may seem irrelevant, it could not be assumed from the outset to what extent the particular subjects under scrutiny might be affected by other structural elements integrated nearby or attached in whatever way.

6.4 SUBJECTS FOR MEASUREMENT

Specifically all, or as many as possible of the following, required measurement in each building, and in each part of a building:

1. Overall external length, width and height, the latter both at eaves and apex;
2. Overall internal length, width and height, at each level;
3. Wall thickness of each side of the structure, at each level;
4. Where vaults exist:
    - height at springing, at apex;
    - span, approximate curvature;
    - dimensions of abutment, whether buttresses or thick wall;
    - openings (windows, etc.) in the abutment;
5. Where internal partition walls exist;
    - location in relation to main structural walls;
    - purpose (merely partition, or 'service'-bearing e.g. fireplaces);
    - thickness;
6. In all of the above, general quality of construction.

6.5 FRAMEWORK FOR CHOICE OF SITES FOR MEASUREMENT

As mentioned in Chapter 1, the use of every site in the country, though possibly desirable for a highly accurate overall picture, is clearly impracticable, and a sample that is reasonably representative must be sought. To repeat Mainstone's thoughts on the problems of reconstructing the ideas and methods of past designers, "there was an almost *unlimited number of ways* in which the basic discipline could be followed " (VI 1997: 337 emphasis mine). In order to identify as many of those ways as possible, a sample should ideally consist of sufficient buildings to be representative of each of the following:

(a) Generic building type, and within each such type, each sub-type.

Obviously typology can be subjected to subdivision until each category consists of just one or two examples. This is clearly self-defeating and the following were settled upon as constituting a workable compromise:

Free-standing and Curtain walls

Centrally Planned Structures
    fortified round towers
    ecclesiastical polygonal structures

Churches, unvaulted, single cell i.e. without nave arcades and aisles.
    without buttresses
    with buttresses

Domestic Ranges (generally of two or three storeys).
    unvaulted
    with multiple ground floor vaults

Churches, barrel vaulted, single cell.
    without buttresses
    with buttresses

Domestic Ranges (generally of two or three storeys).
    with longitudinal ground floor vault

Church Towers (western rather than crossing).
    with buttresses
    without buttresses
    with spire
    without spire
    with ground floor barrel vault
    with ground floor ribbed groined vault
    any combination of the above

Tower Houses (i.e. generally of more than three storeys).
    unvaulted
    with longitudinal ground floor vault
    with longitudinal ground floor and top or upper storey vault
    with multiple transverse ground floor vaults

Conspicuous by their absence are the larger ecclesiastical structures with full nave arcade and side aisles which were roofed variously in timber or ribbed vaults.

Surveys of many such structures were attempted but the problems of accurate measurement, particularly the less accessible dimensions in parts of the upper structure resulted in inaccurate or incomplete data. Even in the cases where surveys were successfully carried out, the problems of effectively analysing these highly complicated structures placed them beyond the scope of this project in the time available. The number and complexities of the variables and possible structural relationships are very high in comparison to the simpler buildings used: the number of possible points in a typical nave arcade on which some geometric construction might be based are just too numerous.

(b) Chronological period.

Four periods have been loosely identified, not to typecast each example for all time, but merely as an initially useful working basis.

c.1100 to c.1300: Anglo-Scottish
The period of international , especially Anglo-Norman influence up to around the beginning of the Wars of Independence.

c.1300 to c.1370: Wartime
Relatively little building; demise of English influence.

c.1370 to c.1480: Early Scottish
Late medieval building of indigenously Scottish character and feudal in imagery, layout, etc.

c.1480 to c.1560: Transitional
Influence of changing social order and patterns of ownership; introduction of firearms, increasing incorporation of ideas from abroad as well as revival of early forms.

c.1560 to c.1640s: Renaissance
Completion of above transitions, 'baronialising' and then 'de-baronialising'.

It becomes obvious that it will be a formidable task to achieve acceptably representative results in all these periods, for each of the building types. At an even more fundamental level, the job of assessing what is the entire population in each period/group just in order to calculate what is a representative sample is even more overwhelming. Steps were actually taken to achieve this. A population count of the hundreds of Scottish tower houses was carried out at great expense in terms of time, but it soon became evident that to carry out site surveys of a similar proportion of these structures to that of, say, church towers was an utterly impractical proposition. Even the problems of assessing the total population of some building groups was found to be impractical: small Norman churches, for instance, have often been altered, added to, partly demolished and rebuilt, several times over since their original construction.

In such circumstances it is impossible to place them as a whole in any particular period. In the end, it was simply decided to survey as many of each building type, of each period as was practical and affordable with the resources available. Whilst in statistical terms it is accepted that this is terribly unscientific, in the circumstances it was the only practical course of action.

6.6 FACTORS IN THE CHOICE OF SITES

Building measurement can, of course, be carried out either by working on site or from previously published plans, or even from dimensions quoted in published texts. There are advantages and disadvantages associated with all of these which are worthy of brief consideration here. Plans, drawings and measurements mentioned in texts are available in various national surveys (all available in the NMRS) and the publications of MacGibbon and Ross (VII 1887-92), the RCAHMS Inventories and Salter's (VII 1993-5) pocket books, though the latter could only be regarded as rough guides. Even in MacGibbon and Ross's scale drawings, as well as those of the National Art Survey and the Polish World War II survey, there is a danger of inaccuracy, and an approach not consistent with the purposes of this thesis in at least three respects. First, it is often impossible to know what account has been taken, when measuring wall height, of a sloping site, or of changes in the ground level; secondly, it is very difficult or impossible to detect on such plans small but highly significant differences in thickness of side from end walls, or of first storey from upper storeys; thirdly, observation and measurement of micro-structural features such as stairs, windows, etc. are not possible with meaningful accuracy at these small scales. Also of course, plans drawn up to a satisfactory scale do not exist for all the required sites.

On the other hand, the advantages of measuring from readily available plans include the benefit of being able to measure parts which may not have been accessible on site, a most important consideration for the purposes of research such as this. In addition, there is a saving of transport costs, and of time, and the avoidance of personal risk, particularly in the survey of ruinous structures.

However, these hardly outweigh the benefits to be gained from actual site visits, some of the advantages of which include:

- where measurements can be taken, there is the guarantee, within one's ability to measure, of accuracy and of consistency of approach;
- measurement is possible of individual elements such as vaults, arches, buttresses, stairs, fireplaces, doors and windows;
- a much better overall assessment is possible of the quality of the building, of the materials used, of the craftsmanship and finish, and therefore of the professionalism of its builders;
- observation of constructional details of individual masonry elements is possible, enabling assessment of constructional procedures and levels of consistency and standardisation where applicable.

Other considerations in the survey of actual buildings are many and various. Let us look at the advantages and disadvantages in particular of surveying on the one hand complete and occupied buildings, and on the other incomplete ruins.

6.6.1 *Complete Structures*

In general, complete buildings with all floors intact enable accurate measurement of all structural dimensions and observation at all levels, but unlike ruins, do not reveal cutaway construction of vaults, walls and other masonry features. Account must also be taken of plaster that both conceals and thickens masonry structure, and in some cases may conceal alterations to the fabric.

If property is not in the hands of the National Trust for Scotland or Historic Scotland, then obtaining permission for access was one of the greatest and most time-consuming problems, particularly if ownership was not known. Unnecessary expense and wasted journeys could result. Access to some parts of inhabited buildings may be restricted by considerations of privacy and/or security.

6.6.2 *Ruins*

Access to ruins is generally easier. Their problems, however, come in different ways:

(a) Structures in state care

These tend to have restricted opening times; access to some parts of the building is deemed to be dangerous and therefore restricted, although special permission may be obtained - which means the expense of a separate return visit. In most cases the original structure has been subject to and sometimes confused with later stabilisation. Study of individual masonry features must therefore be undertaken with care.

(b) Abandoned Ruins

Ruined structures standing partly or totally unguarded in rural situations are the greatest sources of interest and are the most rewarding sites. If no attempt at stabilisation or restoration has been attempted and if only minor collapse has taken place, these sites can provide more information than any other source. Yet they are also sometimes the most problematic and dangerous, access and measurement often being obstructed by both man-made and natural obstacles and, particularly, density of vegetation. Access to higher levels is often dangerous or impossible, most commonly due to the collapse or loss of stairs.

Difficulties in obtaining measurements could be frequently encountered in wall lengths when part of the structure is totally lost. Often the latter could be overcome by reference to adjoining structure. In some cases whole structures that have been entirely lost can still be accurately measured by their 'ghost' imprinted on the wall of a building they once adjoined, for instance the west range once attached to the palace block at Huntly Castle (Figure 6.1).

Figure 6.1 Huntly Castle: 'ghost' of the demolished west range

6.7 MEASURING EQUIPMENT

Given the extent of the survey, mostly by a single surveyor operating alone, simple but effective practical equipment was used.

6.7.1 *Horizontal Dimensions*

The principal device was a thirty metre fibreglass measuring tape with steel clasping device on the loose end. Where the corner of the building, to which the tape clasp was to attach, was excessively weathered, or the corner stones are missing altogether, a six inch steel wire nail was used to pin the tape end to the ground adjacent to the corner. For shorter spans, a five metre pocket self retracting steel tape with hooked loose end was used. Wet weather could cause problems, mud and water quickly rendering measuring tapes unusable unless constantly dried and cleaned.

For out-of-reach higher level shorter horizontal measurements, a 2.4 metre measuring bar was made from a thin rod of hardwood, the centre being attachable to the Senshin telescopic vertical measuring rod (described below). This was found to be difficult to use in even light winds and impractical to handle above a height of about 5 metres. Nevertheless, this device was very useful for measuring wall thickness of tower houses at first and second floor levels where these were otherwise inaccessible.

6.7.2 *Vertical Dimensions*

For vertical measurements such as the building height, the 30 metre tape was dropped from the wall-head (where access was possible) with weight attached to counteract wind effects. Even with that the tape was difficult to use in light winds. For buildings up to about 10 metres, a Senshin 8.27 metre plastic and fibreglass telescopic measuring pole was used as an alternative. This tool is excellent for measuring vault and ceiling heights and most vertical structural dimensions in small churches and towers of up to three storeys. It is not recommended by the manufacturers for use in wet conditions and experience showed it to be unsuitable for use in high winds when extended beyond about 6 metres. On calm days, however, it can be fully extended and held by the base up to at least 2 metres above ground, giving a total reach in excess of 10 metres.

Over 10 metres, a Silva Clino Master clinometer or height meter was used. In effect this is a miniature hand-held theodolite, commonly used by foresters for measuring the height of trees. This was found to be a highly versatile and convenient instrument, costing £116, and accurate in optimum conditions to about 0.25 metres on a typical tower of, say, 13 metres. The only problems encountered were its dependence on being used from a position accurately measured out from the base of the building, which is dependent itself on what obstructions are present. It is reliant on a steady hand.

Electronic radar type measuring instruments commonly used by estate agents, and widely available at modest cost, were found to be useless, being unable to measure distances over about 5 metres and obviously inoperable for height where floors/ceilings have been lost which was the case in the majority of sites.

6.7.3 *Observation & Recording*

On some occasions plans photocopied from MacGibbon and Ross or elsewhere were used but otherwise all recording was done with pencil and notebook, and with a 35mm camera using both wide angle and telephoto lenses and a flash gun.

Photographs were found to be an invaluable *aide memoire* for referring back to the building to check on quality of stonework, constructional details, etc. Wet weather obviously made photography difficult outside.

6.8 IN THE FIELD

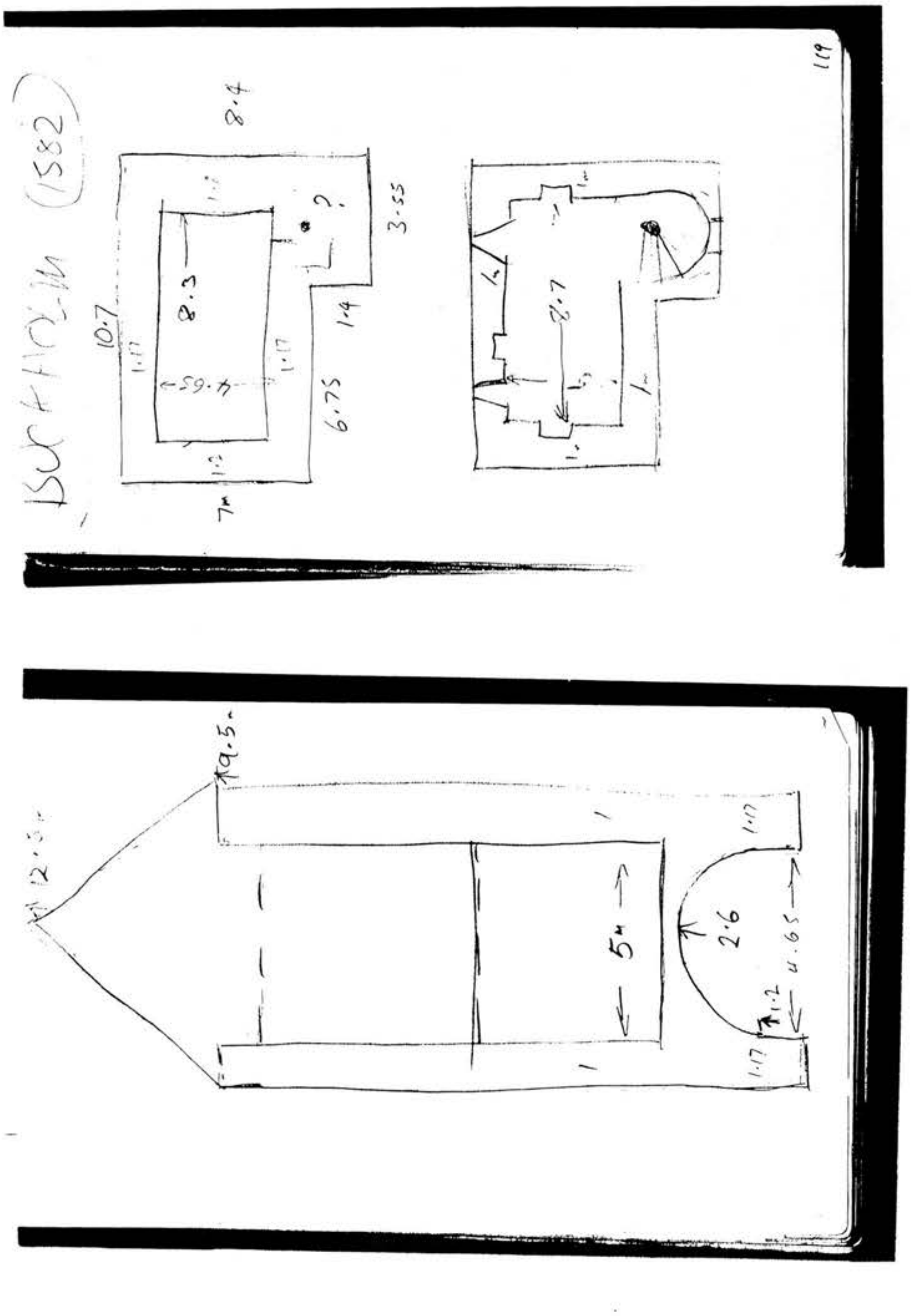
6.8.1 *Planning, approach and systems*

The choice and range of survey sites was to some extent dictated by practical constraints of time and finance. Inevitably, once one or two definitely accessible sites had been identified in a certain area, maps would then be consulted for anything else in the near vicinity which might be worthy of investigation.

It was felt that the physical survey should be carried out in as objective and consistent manner as possible. Therefore, little preparation was undertaken by way of investigation into building history prior to each site visit. Such researches were sought later. As mentioned, copies of published site plans were often taken to avoid having to draw plans of each floor on site, although this was found to be a useful exercise for achieving a close and detailed understanding of a structure.

Surveys were conducted in as far as possible a logical and systematic sequence to avoid omissions. Generally, the overall structural dimensions were tackled first outside, then inside, from the ground storey upwards. If not already to hand, sketch plans of each floor were drawn, then a section (Figure 6.2). Details of stairs, fireplaces, doors and windows then followed if required. The danger of working strictly to a systematic schedule such as this, is that the unusual can sometimes be missed and time was always taken to stand back and to let the stones themselves tell their story. Some of the deepest insights have been conceived at such times, and some of the less obviously visible clues noticed.

Figure 6.2 Sketch plans & section of Buckholm Tower



6.8.2 *Accuracy*

The gathering of measurements and other information from actual buildings was the principal activity in this research. It was the buildings themselves which were the primary sources, the 'documents' from which this thesis was derived. Accurate measurement was fundamental to the success of the project, but many of the buildings surveyed presented considerable problems in this respect. Whilst most sites had no doubt been laid out with tolerable accuracy, span being constant along the entire structure and corners being true right angles, wall thickness could vary in some cases by up to around 10 centimetres. In other cases wall thickness was constant, but span varied. In such cases many readings had to be taken at different points, and then retaken, and then a view taken as to what was the *intended* dimension, which might depend on any number of factors and individual circumstances. Wall height was also often difficult to judge: the internal and external dimensions often differed and the ground level of either could have changed (usually risen). The building may be on a slope and again a view had to be taken. Usually the maximum height was used in order to assess the highest slenderness ratio to which the architect was willing to work. One of the greatest dimensional variations found was that of vault internal apex height. This could vary considerably along its length, and individual voussoirs could be laid very unevenly. The extent of such inaccuracy in itself is regarded as a significant indicator of building practice in the period under review. The final dimension used in data analysis was necessarily the subject of much objectivity and circumspection.

Experience showed that, in spite of every effort to achieve accuracy, and to assess with objectivity what the intended dimensions had been, it was nevertheless possible to measure the same structure on more than one occasion with different results. This is a reflection partly of the accuracy with which the building had been originally laid out and built, partly the extent to which it had suffered weathering and other damage since. Measurement of such buildings is not always an exact science and small variations inevitably arise, differing in range between buildings. Where such variations exceeded about 2%, that is for instance a variation of 10 centimetres in the thickness of a wall supporting a roof span of five metres, then the data for that structure would not ordinarily be included for analytical purposes. In the final analysis, it should be born in mind that, whereas total accuracy might not always have been achieved or indeed might never be achievable in every individual case, this research is not so concerned with individual results in isolation. It only depends on each building's dimensions insofar as they play a part in establishing more generalized trends and patterns.

6.8.3 *Conditions and hazards*

Considerable trouble was taken to achieve a representative sample of buildings and to measure all their dimensions of structural significance with appropriate accuracy. Such work was not without its risks and hazards, particularly when on ruinous sites. Falling masonry, slippery wet stonework, and flea infestation were the main concerns against which appropriate protective clothing was obviously essential. Access to such sites was also occasionally complicated by cattle, barbed wire or dense vegetation, and due consideration was made to the landowner's interests before, and when negotiating any of these. In wet weather, measuring equipment, some of which was borrowed, could become difficult to use or worse, actually spoiled, and this was also a consideration when on site.

7 ANALYSIS

Data collection, whatever the dangers, was a relatively simple and at times exhilarating business compared with analysis. This listing of measurements in usable form was time-consuming and whilst assistance from computer technology was considered, the advantages simply did not match the considerable investment in time that would be involved in setting up an appropriate system. In any event, no data processing system could begin to take into account all the plethora of individual circumstances, alterations etc. that are peculiar to each site, and in the end there is no substitute in a project of this nature for manual analysis of each building individually.

7.1 METHODOLOGY OF ANALYSIS: COLLATION OF DATA

Firstly schedules were drawn up for each category of building in each period, listing all the dimensions relevant to the analysis of each structural type, and with some basic totals, averages, modes and comparison of overall size, footprint and wall thickness of the survey sample all collated. Once the average and mode for each group was found, then the variation or divergence from those figures by the buildings in the group could be assessed.

At this stage it was appropriate in some cases to attempt some analysis of the units of measure employed. This exercise was principally to ascertain whether wall thickness was determined, or affected to any extent, more by the actual unit of measure employed at a given building site than by a proportional relationship to height or span. Was there a practice amongst architects of simply sizing the walls of all buildings falling into a certain structural category by a fixed standard for that category? It has to be confessed that, without the benefit of surviving building contracts for the buildings measured, there was no completely reliable way of discovering the precise unit of measure used. (A separate study of units of measurement was conducted and the findings are summarized in Appendix II. Following this is a schedule [Appendix III] of all the surviving building contracts from this period for the whole of Britain which have been published.) There are a few tests which can be applied to the surviving structure and which may provide the required information. However, these are at best rather 'hit-and-miss', and can never be guaranteed to produce a fail-safe result. Amongst the problems involved in such an analysis were the following:

(a) The possible variations of the standard foot are almost infinite, as has been shown in Appendix II.

(b) When looking to measure to an accuracy of the nearest three inches (probably the smallest binary fraction of a foot commonly used in building dimensions), there are two immediate problems: medieval masons, like any others, would probably have worked to tolerances approaching this amount; subsequent weathering and / or settlement may also have altered dimensions by anything up to this amount over the whole building.

(c) Whilst a specific wall thickness dimension of a certain number of whole feet with or without a binary fraction might have been planned initially by the architect, perhaps in a proportional relationship with height or span, it must be born in mind that, just as Lechler and others recommended adding extra thickness for poor quality stone or build, and reducing it for high quality work, so such adjustments may have been applied to the buildings used in this project.

These are just a few of the probably innumerable discrepancies, variations, accidents and miscalculations that may have affected the finer degrees of building dimension and structural design.

In attempts to ascertain the unit of measurement used, several assumptions also had to be made: first, that dimensions specified in the original building contract will almost invariably have related to *internal* dimensions, unless a tower, or unless otherwise specified; second, that these dimensions will have been in terms of *whole* numbers of feet; and third, that the wall thickness, if mentioned at all, will have been specified in terms of the *same* foot units, either whole or with binary fractions. All these assumptions were based on what has been found in surviving contracts.

If, taking all these assumptions and potential problems into account, a certain foot measure consistently presented itself in both internal dimensions and wall thickness, and the wall thickness dimension seemed to be a conveniently rounded number, then it was assumed that an exact and prescribed structural dimension for the latter may have been found. Furthermore, it may be surmised that this wall thickness was not necessarily based on a proportional relationship with some other macro dimension such as span or height, but on a judgement by the architect that a generalised wall thickness dimension would suit for this building, and possibly other buildings falling into that general size category.

7.2 COMPARISON

Following the metrological approach, calculation of the slenderness ratios and span ratios of each building was then necessary and, again, assessment of the average and mean of these, as well as variation from them. Comparison was then made with other building types, and also with the documentary and other standards for calculation of wall thickness in Appendix I.

Then came some departure from the safety of calculated analysis and on to the invariably more shaky ground of drawing lines on plans. To avoid as far as possible 'finding' the geometrical figures and dimensions that were required to prove some theorem or other, plans were drawn up on A3 graph paper with one, five and ten millimetre squares, to a scale of 1:50. Graph paper of that scale has an uncompromising ability to reveal precisely the extent of any discrepancy and, in any event, results could usually be corroborated by calculation. In the case of much larger buildings a scale of 1:100 was used. The advantage of drawing the plans to scale as opposed to analysis purely by arithmetical calculation far outweighs any disadvantages: possibilities, solutions, comparisons can all be seen at a glance and, in research which is in some measure groping in the dark, any visual aid is of invaluable use. Again, graph paper at this scale reveals graphically and measurably the precise extent of any differences, and was used extensively in analysis.

There are at least two methods of approach in graphical analysis. The most obvious, whilst we are considering the use of methods construed by previous theorists such as Rondelet, is to apply their various graphical methodologies to our own survey sample. This was done with Rondelet's theories not only on wall-thickness but also on vault abutment, as were the theories on that subject of Dérand, Gaulthier and Rodrigo Gil.

Measured drawing was also used experimentally: not so much for vault abutment sections, but on plans where, once the measured ground-plan of a building had been drawn up, the myriad of possibilities which might be opened up by geometric rotation or other manipulation could be tried simply with ruler and compasses.

Comparison of similar structural problems in different building categories was made in order to assess whether they received similar treatment, or if certain rules and conditions seemed to apply to each building type in isolation, for whatever reason.

Reference was also made to cases likely to prove exceptions to any rule, such as church towers which were known to be fortified, and cases where structural failure was known to have taken place, in order to see whether such exceptions prove any rules which seemed to be appearing.

Finally, it is worth restating that all these analytical exercises were carried out without any pre-determined expectation other than those that documentary or other history has bequeathed us, and it has to be accepted that these are very limited in their guidance: the principal evidence we have is that provided by Rodrigo Gil, as contained in Simón García's *Compendio de Arquitectura*:, and this is worth restating in full:

> "I have often attempted to rationalize the buttress needed for any bay, and have never found a rule adequate for me. I have also pursued the inquiry among Spanish and foreign architects, and none appears to have established a rule verified by other than his own judgement. Upon asking how we shall know whether such and such a buttress is enough, we are told that it is needed, but not for what reason. Some take the fourth [of the span], and others arrive [at an estimate] by certain orthogonals, and dare to have confidence..."
>
> (quoted in II Kubler, 1944:146).

The reference here to "certain orthogonals" is tantalizing, but what those methods might have been can only be guessed at.

Similarly Lorenz Lechler, while setting out some fairly specific rules for proportional relationships in structural design, advised his son on more than one occasion that he must not rely totally on these rules but should learn to make decisions on his own knowledge and experience (II Shelby and Mark, 1979:115).

Alberti was an academic, but probably not of structural engineering. His interest in architecture was generally in questions related to aesthetics, although he did occasionally write about structures, the wall thickness of towers, for instance, as well as many other matters of very mundane and practical nature. Of any other 'rules' it must be accepted that he may have known nothing, either through ignorance, or because his sources in the building professions and crafts were simply unwilling to share their knowledge. In the light of this, it is perhaps significant that he does mention structural strength in a more oblique way: on the damage caused to walls by the thrust of insufficiently buttressed arches, he implies that there are no rules by which abutment can actually be determined: "defects which *cannot* be provided against, but which may be repaired after they have happened." (X Book X. Ch.XVII, 238, emphasis mine). It might be expected that in sections entitled "amending defects in walls" (X Book X. Ch.XVI) there might be some indication of stability requirements, particularly on how to thicken a wall that is "thinner than it ought to be" (X Book X. Ch.XVI, 238). No such mention is to be found here or in Book IX Chapter VIII on "Laws in the Business of Building and Ornament."

From these sources especially, it seems that the only general rule that can be reasonably expected, is that there were no specific rules at all! Nothing more can be expected. Either there were no specific rules which applied across the board to certain aspects of structural design, or if there were some, the architectural profession of the day were keeping them very confidential. The mention in the *Lettere Sanesi* concerning Siena Cathedral of the existence of certain rules governing the design at least of churches should perhaps be remembered. However, even for these, an aesthetic rather than purely structural end was probably foremost in the minds of those responsible. In the final analysis it must be born in mind that the situation in Scotland may have been different. Furthermore, the objective of this research is not only to find out if there were *any* specific and definable rules, but to ascertain the generality with which they were applied, and indeed also the existence or otherwise of any broader safe limits within which the medieval and renaissance architect mason regarded it safe to work.

PART 2

THE RESULTS

8 WALL THICKNESS, SLENDERNESS RATIO AND FORTIFICATION: THE FREE-STANDING WALL

8.1 INTRODUCTION

The most fundamental piece of structural design must be a simple free-standing wall, and the same problems will always face the builder of this basic form in masonry: how deep and wide to dig the foundations; how thick to build the wall in relation to its height, taking into account the materials used, and their quality. How much extra should be added to that to achieve the desired level of security? These are the two principal objectives of this chapter: slenderness ratio and fortification. Before that, there is one matter that requires at least a brief mention, foundations.

Unfortunately a detailed study of this subject is actually beyond the scope of this research. Very few property owners are willing to allow their topsoil to be disturbed, let alone anything deeper. However, from informal discussions with heritage organisation architects and maintenance teams, the paucity if not total absence of foundations from a large but unspecified number of medieval and renaissance buildings in Scotland is an accepted fact. The examples of Melgund and Redcastle, where in each case the ground under one corner has fallen away, illustrate some interesting layering of various grades of stones which, for all its neatness, still represents miserably insignificant foundations for the size of structure (figures 8.1 & 8.2). Simple boulder foundations were commonly used, evidence of which can often be seen above ground, as at Knock Castle (figure 8.3). The walls above ground are of course a much more straightforward matter, and it is important before attempting any analysis of the various building types to establish just how the medieval mason in Scotland set about the task of designing a simple wall. Theoretically that sounds a straightforward enough task and it would be, for there are plenty of surviving specimens around to examine. Our problem is that in the medieval period there is a reasonably high expectation that many if not most walls were erected for more than just the marking of boundaries. An element of security, even of fortification was probably

Figure 8.1 Melgund, Angus. Mid 16th century: foundations

Figure 8.2 Redcastle, Angus. Late 15th century: foundations

Figure 8.3 Knock Castle, Aberdeenshire. Late 16th century. Boulder foundations

inherent in the design, and it is the teasing out of the difference in the medieval mind between mere structural stability and added fortification that must now be addressed.

Finding a precise meaning or definition for this aspect of security in building is not as straightforward as some would claim. Several interpretations come to mind: fortification might on the one hand be construed as visible impressions, and specific indications of defence and security perceptible to an outsider. On the other hand, from the owner's point of view, fortification would constitute a more calculable quality: an inside knowledge of accessibility, strong and weak points, and indeed the thickness and quality of masonry walls. Because of the original military characteristic of feudalism and basis of power, fortification, or at least the impression of it, was generally deemed through the medieval period right into the seventeenth century, to be synonymous with status and power. Just as a nobleman would be depicted on his tomb in full military regalia, the imagery of his home and centre of feudal administration was of appropriately martial aspect. Due to the requirements for a licence to crenellate, it was also seen as evidence of a degree of royal favour, or at least trust, for many were granted only with the condition of right of access by the monarch. In some circumstances, individual fortification was valued as a key element in the in the security and defence of the nation and/or of a particular region or locality. Castles of the western seaboard of the thirteenth centuries were necessary for security in that region in the face of Norse incursions. The 1535 Barmkin Act likewise attempted to enhance security in the Borders.

These various general meanings of fortification were of course open to an infinity of different interpretations by builders, both the potential owners and their architects. To begin with, every site had its own unique and individual characteristics, levels of protection offered by rocky scarp, marshy ground, the sea or a loch and other impediments to approach. Sites differed in availability of suitable building materials affecting the cost of construction and, therefore, the amount of wealth available for both the overall size of the works and accommodations, and also the effectiveness of the defences - including perhaps the height and thickness of surrounding walls.

Potential owners varied in their own individual requirements and circumstances. Wealth and income from whatever source was a principal determinant of size and lavishness, as well as effectiveness, as just mentioned. Perhaps more relevant than any other factor though, was the degree of personal security or insecurity felt by the owner in respect of the likelihood of hostilities from whatever source. To some extent this would have been dependant on location, some having historically been more susceptible to hostile action than others, others being less expectant of such action. Again, the western seaboard and the borders are worth mentioning in this respect. On a more personal level each owner will have had some idea of his standing with his feudal superiors, neighbouring landowners, his own relations, and his vassals, tenants and other associates. He will have been aware to some extent of potential threats from any of these quarters. Quite apart from any of these whose danger could to some extent be assessed, there would have been the ever present worry of thieves, vagabonds and malefactors, and the problem of guarding in safe-keeping all that is regarded as worthy of keeping safe - wife, children, livestock, legal documents, precious items and other chattels, etc.

Within the general context of these conditions, however, is a factor of probably as much influence as any other. Irrespective of any actual threat of hostility is the owner's personal *perception* of threat: feelings or characteristics of security or insecurity differ widely in everyone and the desire or need to surround oneself with security measures, whether real or sham, varies from one individual to another, a factor of which some historians would do well to be more aware.

Statistical interpretation in our own time of medieval fortification is subject to what survives as tangible evidence for us today and our perceptions can be subject to much distortion. On a general level, that which was most substantially built is what has survived in possibly disproportionately high numbers. Statistics of the amount of building for high ranking or wealthy members of society in Scotland at any one time has never been assessed and a study of such numbers alone would be eminently worthwhile. It would doubtless draw attention to the fact that a very large number of this sector of society dwelt in relatively insubstantial dwellings right up to the sixteenth century. Many had only ever built in timber, albeit with stone foundations. Many had built in stone but with such thin or poorly built walls that they were later rebuilt more substantially, or once abandoned they quickly became ruinous and have since been all but lost. Sir Robert and Lady Arbuthnott, for instance, being "of a particularly pious turn", (VII Gordon Slade, 1978-80:433) and who travelled much, constructed for themselves a relatively humble hall house in the 1470s with walls only 1-1.3 metres thick. Their minds were on higher things perhaps, and they felt secure, with no requirement for high or thick walls with crenellations. Notwithstanding all that, the losses, even of more substantial fortified structures, are also considerable: damage or destruction by hostile or malicious action or abandonment often resulted in rapid decay and/or collapse, hastened by the visits of enterprising recyclers of building stone. While there may be such distortion of numbers, the most fundamental principles applicable to what survives remain, and these are largely measurable in terms of the thickness, and to some extent height, of masonry structure.

It is against this background that a meaningful inquiry into the medieval approach to, on the one hand, the achievement of structural stability, and on the other, fortification must be sought. Because of all these caveats, this ideally requires highly accurate measurement of all surviving structures, on every side, together with assessment of the surrounding site, and of the history and circumstances of the building's conception. Such an approach is simply beyond the scope and resources of this research which is concerned more with generalities over a wider field. Moreover, much of the required information is impossible to recover for various reasons. A more cursory investigation will suffice for our purposes.

8.2 ASSESSMENT OF FORTIFICATION

The most convenient and most convincing yardstick by which to measure fortification would be some documentary evidence from the era under scrutiny. Unfortunately for our purposes, little such evidence exists. The innumerable licences to crenellate might have been expected to give some quantification of structural fortification but they do not. In fact they specify almost everything but: turrets, gun holes, yetts, machicolations, "battaling", "corbal sailze", portcullis, etc., even ditches, fosse and ramparts, in fact everything that was immediately *visible*, which wall thickness of course is not. Curiously even the mention in the construction of Tarbert Castle of Robert the Mason "*quia in absencia domini regis augmentauit muros in latitudine vltra conuencionem*" (X Exchequer Rolls of Scotland, 1264-1359, Vol. I:53) does not quantify how much extra thickness than "convention" he actually built, or indeed what the convention actually was.

Of some interest in this respect is the tower of Hoddom near Ecclefechan, built in 1565 by Sir John Maxwell. In a letter from Thomas Randolph to Sir William Cecil at that time concerning its construction Randolph refers to Hoddom as a "fort" as opposed to the "fair tower" also being built by Sir John at Annan. The wall thickness of Hoddom averaged a massive 8' 10" up to the third floor (VII Maxwell-Irving: 2000, 153-159). Most contemporary towers in the south-west had walls of between three and five feet in thickness, around four feet being most common. This differential gives us some idea of notions of defensibilty in terms of wall thickness at that time.

The Barmkin Act of 1535 (quoted in Appendix I) is the only documentary evidence we have of what constituted some sort of standard for a wall which theoretically was designed to offer a level of security. It specified the construction in border areas of Barmkins of 60 foot square, with a wall height of 18 foot 6 inches (c.5.6 metres) and one ell (37 inches) thick. The obvious question which has to be asked here, is whether this was a reflection of contemporary practice, or was it setting a new standard? Also was mere structural stability foremost in the minds of the lawmakers, or the ability to withstand battering of some sort? Were they thinking first of a slenderness ratio of 1: 6, or of a certain height, or of a certain wall thickness? Which was the priority? In any event the Barmkin Act specifically related to conditions in the borders in the sixteenth century, where farms and landowners were subject to the sudden lightly armed raid, rather than the prolonged siege; where such landowners also may have found it difficult to afford anything more substantial.

In the circumstances, we must revert to the surviving structures themselves and, because no single example in any one period is known to have set a particular standard, we are working to a methodology based on relativity, comparing one wall against another across the board, looking for trends, patterns or commonality. That might seem simple enough, but it is not. From the outset it is understood that fortification of structure, apart from arrow or gun loops and wall-head paraphernalia, consists most fundamentally of two elements: height, sufficient of it to hinder or prevent access by ladder or siege tower; and thickness of masonry, sufficient to be proof against both under-mining and battering by ram, or by artillery of whatever sort. Now of course these same two qualities of structure also constitute the slenderness ratio, the relationship fundamental to structural stability. To try and analyse defence independently from structural stability will be meaningless. To analyse the two together, however, is fraught with complication. Geoffrey Stell highlighted the problem when he pointed out that the thickness of curtain walls in the late medieval period varied widely between about one and four metres, and he cites the reasons for this variety as being as much to do with height, structural stability and the need for intra-mural chambers as it was to do with potential for defence (VII 1981:37). The incidence of mural chambers is actually relatively rare, or at least rare where such chambers materially affect the wall thickness. The possibility of height and stability being an issue, though, is more worthy of enquiry. To achieve an understanding of the problem we really need initially to concentrate on these most basic structures: the free-standing walls of curtain-walled castles, of barmkins and of abbey and cathedral precincts. A list of the principal surviving works appears in Figure 8.4. The structures are listed under each period category, in ascending order of wall thickness, and include height where the original height is known, and slenderness ratio.

Figure 8.4 CURTAIN AND BARMKIN WALLS

ANGLO-SCOTTISH to 1296

Site			Thickness (M)	Height (M) (maximum)	Slenderness Ratio 1:
AROS		Argyll	1.1		
ACHADUN		Argyll	1.5		
DUART	(land)	Argyll	1.6	9	5.6
DUNDONALD		Ayr	1.6		
AROS		Argyll	1.7		
AIRDS		Argyll	1.7		
SWEEN		Argyll	1.7	10	5.9
MIGVIE		Aberdeen	1.8		
ROY		Inverness	1.8	7.6	4.2
INVERNOCHTY		Aberdeen	1.8		
MINGARY	(sea)	Argyll	1.8	8.5	4.6
LOCHINDORB		Moray	2	6.1	3
INNIS CHONNEL		Argyll	2	8	4
SWEEN		Argyll	2	10	5
SKIPNESS		Argyll	2		
COWIE		Kincardine	2		
ACHADUN		Argyll	2		
ELGIN		Moray	2		
CAERLAVEROCK W		Dumfries	2	7.6	3.8
DUNVEGAN		Inverness	2		
LOCHLEVEN		Kinross	2.1		
BALVENIE		Banff	2.1		
KINCARDINE		Kincardine	2.2		
KINCLAVEN		Perth	2.2	7.6	3.5
DIRLETON		E. Lothian	2.3	11	4.8
COULL		Aberdeen	2.3		
TIBBERS		Dumfries	2.3		
ACHADUN (forework)		Argyll	2.4		
LOCH DOON		Ayr	2.4	8.5	3.5
TIORAM		Inverness	2.4	9.1	3.8
DUART	(sea)	Argyll	2.4	7.9	3.3
BOTHWELL		Lanark	2.4		
KILDRUMMY		Aberdeen	2.6		
INVERLOCHY		Invernes	2.7	9.1	3.4
KIRKCUDBRIGHT		Kirk'bright	2.7		
MINGARY	(land)	Argyll	2.7	14	5.2
ROTHESAY		Bute	2.7	9.1	3.6
DUNIVAIG		Argyll	3 +		
DUNSTAFFNAGE		Argyll	2.8	9.1	3.3
KINEDDAR		Aberdeen	3		
AUCHAN		Dumfries	4		
AVERAGE			2.2	8.9	1 : 4.1
			WARTIME: 1296 - 1370		
SKELBO		Sutherland	1.2		
BALMBREICH	SE	Fife	1.6	9	5.6
MOULIN		Perth	1.7		
BALMBREICH	others	Fife	1.8	9	4.9
SPYNIE		Moray	2		
TARBERT		Argyll	2.4		
TANTALLON	E	E. Lothian	2.7	12	4.5
	S, west section		3.3	15.2	4.5
	S, east section		3.8	15.2	3.9
AVERAGE			2.3	12.1	1 : 4.7

EARLY SCOTTISH: 1370 - 1480

DUNOLLIE	W & S, cliff	Argyll	0.7		
CATHCART		Renfrew	0.7		
BREACHACHA	S & W	Argyll	1		
ARDSTINCHAR	N,W & S	Ayr	1		
CESSFORD		Roxburgh	1.1		
LOCHORE		Fife	1.1 - 1.2		
KISIMUL	N & W	O. Hebrides	1.2	9	7.5
SMAILHOLM		Roxburgh	1.2 - 1.5		
BLACKNESS	S & E	W. Lothian	1.3	4.5	3.5
ALMOND / HAINING		W. Lothian	1.3		
CRAIGMILLAR	N	Midlothian	1.4	8	5.7
MUGDOCK		Stirling	1.4	6	4.3
BREACHACHA	N & E	Argyll	1.5		
ARDSTINCHAR		Ayr	1.5		
DUNTRUNE		Argyll	1.5	8.5	5.6
THREAVE at ground level; battered & parapet lost			1.5	6	4
BOTHWELL	E	Lanark	1.6		
BOTHWELL	S	Lanark	1.6		
GIRNIGOE	S	Caithness	1.6		
ST. ANDREWS		Fife	1.7		
SMAILHOLM		Roxburgh	1.7		
KILCHURN		Argyll	1.8		
HAILES	N, Western sec	E. Lothian	1.8		
LACHLAN		Argyll	1.8 - 2	13	6.5 - 7.2
BLACKNESS	N & W	W. Lothian	1.9		
CRAIGMILLAR	E	Midlothian	2	8	4
YESTER		E. Lothian	2	12	6
KISIMUL	E	O. Hebrides	2.1	13	6.2
HAILES	E	E. Lothian	2.1		
DIRLETON		E. Lothian	2.1 - 2.4		
BOTHWELL	N	Lanark	2.3	13	5.6
TERRINGZEAN		Ayr	2.3		
DUNOLLIE	N & E	Argyll	2.3		
DOUNE		Perth	2.4	12	4.9
HAILES	S	E. Lothian	2.7		
DALHOUSIE		Midlothian	2.9	10.5	3.6
AVERAGE			1.7	9.5	1 : 5.3

TRANSITIONAL 1480 - 1560 (BARMKIN & LIGHT ARMS)

SEAFIELD	Fife	0.8		
ST. ANDREWS cathedral precinct	Fife	0.9	6	6.7
LOUR	Peebles	0.9 - 1.1		
TANTALLON outer works	E. Lothian	1.0		
CORSBIE	Berwick	1.1		
SEAFIELD	Fife	1.2		
FLODDEN WALL	Edinburgh	1.2	7.3	6.1
NIDDRY	W. Lothian	1.2 - 1.3		
TUSHIELAW	Selkirk	1.3		
LOCHWOOD	Dumfries	1.3		
INVERALLOCHY	Aberdeen	1.3 - 1.6		
SADDELL	Argyll	1.4		
NEWARK	Selkirk	1.4		
CORRA	Lanark	1.4		
NEWARK	Fife	1.4 - 1.5		
DUNSCAITH	Skye	1.6		
ST. ANDREWS CAS. N, seaward	Fife	1.6		
CRAIGNETHAN N & S	Lanark	1.7	?	?
REDCASTLE	Angus	1.7		
BALGONIE W	Fife	1.8		
AVERAGE		1.3	6.7	6.4

TRANSITIONAL 1480 - 1560 (ARTILLERY)

EDINBURGH CAS. Half Moon	Midlothian	1.75
STIRLING French Spur	Stirling	2
ST ANDREWS E thickened from 1.7	Fife	2.3
ST ANDREWS SW ditto	Fife GF	2.9
CRAIGNETHAN E	Lanark	3
STIRLING forework	Stirling	3.6
CRAIGNETHAN W	Lanark	4.9
BLACKNESS thickened from 1.3	W. Lothian	5.5
DUNBAR	E. Lothian	6.5 max.

POST-REFORMATION 1560 - (BARMKIN & LIGHT ARMS)

CRAIGIEVAR		Aberdeen	0.7		
BALVAIRD		Perth	0.7		
AULDHAME		E. Lothian	0.8	4	5
REDHOUSE		E. Lothian	0.8	4	5
LAG		Dumfries	0.8		
CASTLE CRAIG sea		Ross & Crom	0.8		
MACDUFFS		Fife	0.9		
BALGONE	S	Fife	1	6	6
AUCHINDOUN		Banff	1.1		
SALTCOATS		E. Lothian	1.1		
WHYTEBANK		Selkirk	1.1		
BUCKHOLM		Roxburgh	1.1	5	4.5
BURLEIGH		Kinross	1.2	6.8	5.8
HOLYDEANE		Roxburgh	1.2	4.9	4.1
CASTLE CRAIG	land	Ross & Crom	1.3		
AVERAGE			1.0	5.1	5.1

To set the scene and give an idea of some trends a further list (Figure 8.5) has been drawn up for each period showing numbers of structures of every different wall thickness. The gradual trend towards thinner walls with the notable and obvious exception of artillery fortifications hardly needs further explanation, but in the light of Stell's comment, it does beggar the question, were the walls becoming thinner *because* they were becoming less high?

Figure 8.5 CURTAIN & BARMKIN WALL THICKNESS

Thickness [m]	Anglo-Scot -1296	Wartime 1296-1370	Early Scottish 1370-1480	Transitional Light arms 1480-1560	Transitional Artillery 1480-1560	Post Ref Lt. arms 1560-
0.7			11			11
0.8				1		1111
0.9				11		1
1			11			1 AVG
1.1	1		11	1		1111
1.2		1	111	111		11
1.3			11	11111 AVG		1
1.4			11	1111		
1.5	1		11111	1		
1.6	11	1	111	111		
1.7	111	1	11 AVG	11		
1.8	1111	1	111	1	1	
1.9			1			
2	111111111	1	111		1	
2.1	11		111			
2.2	11 AVG					
2.3	111	AVG	111		1	
2.4	11111	1	1			
2.5						
2.6	1					
2.7	1111	1	1			
2.8	1					
2.9			1		1	
3	1				1	
3.1						
3.2						
3.3		1				
3.4						
3.5						
3.6					1	
3.7						
3.8		1				
3.9						
4	1					
4.1						
4.2						
4.3						
4.4						
4.5						
4.6						
4.7						
4.8						
4.9					1	
5						
5.1						
5.2						
5.3						
5.4						
5.5					1	
5.6						
5.7						
5.8						
5.9						
6						
6.1						
6.2						
6.3						
6.4						
6.5					1	

AVG: Average

As is all too obvious from the previous list (Figure 8.4) the mortality rate for curtain and barmkin walls, or at least their upper parts, has been high, and that of the later, thinner walls disproportionately higher still. Nevertheless, the situation must be examined with what evidence is available, and Figure 8.6 shows a similar arrangement by period of ascending slenderness ratio figures.

FIGURE 8.6 COMPARISON of SLENDERNESS RATIOS
(not including any figures relating to hypothetical use of 1535 Barmkin Act height)

Ratio 1 :	Anglo-Scottish - 1296	Wartime 1296 - 1370	Early Scottish 1370 - 1480	Transitional 1480 - 1560	Post Reformation 1560 -
2.7					
2.8					
2.9					
3	**1**				
3.1					
3.2					
3.3	**1**				
3.4	**11**				
3.5	**11**		**1**		
3.6	**1**		**1**		
3.7					
3.8	**11**				
3.9		**1**			
4	**AVG**		**11**		
4.1					**1**
4.2	**1**				
4.3			**1**		
4.4	**1**				
4.5		**11**	**1**		**1**
4.6	**1**				
4.7		**AVG**			
4.8	**1**				
4.9		**1**	**1**		
5	**1**				**11**
5.1					**AVG**
5.2	**1**				
5.3			**AVG**		
5.4					
5.5					
5.6	**1**	**1**	**11**		
5.7			**1**		
5.8					**1**
5.9					**1**
6			**1**		
6.1				**1**	
6.2			**1**		
6.3					
6.4				**AVG**	
6.5			**1**		
6.6					
6.7				**1**	
6.8					
6.9					
7					
7.1					
7.2			**1**		
7.3					
7.4					
7.5			**1**		

AVG **Actual average in each period.**
i.e. not including any average relating to hypothetical use of Barmkin Act height

Artillery fortifications have not been included. They are, of course exceptional in the later periods and are only shown for interest and comparison. Whilst a certain logic might suggest that these should be integral with other less military structures, just as the equivalent 'artillery' fortifications of the thirteenth century are included, the latter are more representative of a building culture which was inherently military rather than merely domestic. The later artillery works, on the other hand, represent a conscious and marked digression away from a decreasingly military building culture. They digress from the prevalent trend towards thinner walls and cannot compare with slenderness ratio in the same way as their earlier counterparts; hence their separation in statistical illustration.

Regrettably the statistics available for the later periods are so sparse as to be of dubious value, but nevertheless a general trend is evident, from a comparison of ratios of the Anglo-Scottish with the Early Scottish periods alone, towards more slender walls. So, as walls were built thinner in absolute terms, the rate at which their thickness diminished was more than the rate at which their height was reduced. This of course is a highly generalized view. Also it should be stated that we are not comparing like with like: the towering mass of Tantallon designed to keep the Douglases safe from the rest of the world is being set alongside the wafer-thin gesture of a wall encompassing Red House in East Lothian, which had to be thickened round the elegant entrance arch for the sake of stability and possibly also appearance on entering the enclosure.

Some other trends become immediately obvious from the statistics. Most noticeable is the gradual decrease in wall thickness from 1.5 - 3 metres prevalent generally up to the end of the wars of independence, through a spread of 1 - c.2.5 metres in the 'Early Scottish' period, and 0.8 - 1.8 in the 'transitional' phase, to a mere 0.7 - 1.3 metres after the middle of the sixteenth century. For comparison, Figure 8.7 lists wall thickness of a few key fortified towers of each period, which in most cases show a similar picture.

The aim at this stage, however, remains to assess what part, if any, slenderness ratio played in the design of free-standing walls. To this end it would be helpful, if not essential to find some absolutes, or yardsticks, against which to measure the bulk of examples. For little more than interest's sake at this juncture, Jean Rondelet's recommendation for slenderness ratio of free-standing walls was between 1 : 8 and 1 : 12, depending on the level of stability required. This obviously bears no relationship at all to medieval and renaissance Scotland. Then there is the 1535 Barmkin Act specification which was tantamount to a slenderness ratio of 1: 6, but this was very specifically directed at a certain time and place, for a particular purpose. Of greater use would be a wall that was designed from the outset to have negligible military value, that was built only with sufficient thickness to provide stability. Such is hard to find in an era when castles were obviously intended to afford at least some security and protection. However, not all walls of all castles are designed as much for security as others, and ideally, if a castle could be found where both fortified and unfortified walls exist together, built at the same time, then theoretically we might have the basis of a purely structural slenderness ratio, with a comparative standard for fortification alongside. Examples of this are actually not hard to find but, paradoxically, they are in many cases useless for the purpose of finding a basic universal slenderness ratio. Perhaps a good illustration of this is Mingary in Argyll. At this juncture, let us take the opportunity to begin an examination of developments in each of the loosely defined periods. We can continue to explore these methodological issues at the same time, using wall structures of the first 'period' to illustrate the problems and possible solutions.

Figure 8.7 OTHER FORTIFIED TOWERS & TOWER HOUSES

SITE		WALL THICKNESS (M)
	ANGLO SCOTTISH to 1296	
THREAVE		2.4 GF 2.1 1F
LOCHLEVEN		2.3 avg
DRUM		3.5 GF 2.75 above
	WARTIME 1296 - 1370	
HERMITAGE	(early 14th C. original structure) (c.1400 three smaller jambs)	1.65 1.65
TANTALLON	(gatehouse)	2
DUNDONALD	(E)	2.2
DUNDONALD	(W)	2.5
	EARLY SCOTTISH 1370 - 1480	
HERMITAGE	(late 14th C. main block)	2.3
HERMITAGE	(bakehouse jamb)	1.65
CROOKSTON	(vaulted GF)	3.2 & 3.7
CESSFORD		3.8
BORTHWICK		4.3 GF 3.7 1F
	TRANSITIONAL 1480 - 1560 (LIGHT ARMS)	
LITTLEDEAN		1.8
STIRLING	(Princes Tower GF)	1.7 & 2.4 1.4 1F
STIRLING	(Elphinstone Tower)	2.1 GF 1.8 1F
	TRANSITIONAL 1480 - 1560 (ARTILLERY)	
NIDDRY		3
TANTALLON	(gatehouse thickening of c. 2.4) (east tower thickening	totalling 4.5 4.5
CRAIGNETHAN	(lodging W wall)	5
	POST REFORMATION 1560 - (LIGHT ARMS)	
NOLTLAND		2

GF: Ground Floor
1F: First Floor

8.3 THE ANGLO-SCOTTISH PERIOD

Mingary is situated with its back to the sea, the wall facing that direction being 1.83m thick and 8.5m. high, giving a slenderness ratio of 1 : 4.6. The more vulnerable landward wall is 2.7m. thick but 14m. high giving a slenderness ratio of 1 : 5.2. The seaward wall is set directly on a craggy cliff edge and is relatively inaccessible, so it might perhaps be deemed to be an unfortified wall whose slenderness ratio reflects a design for stability only. But it is slightly exceeded by that of the higher landward wall. Here is encountered some of the complexity in extracting slenderness ratio for the purposes of stability alone. Firstly, how should the height of a wall be defined? For structural purposes we are concerned with the measurement of *free-standing* masonry. For many curtain walled castles the interior ground level is higher than that outside, sometimes because the castle is built on a rocky eminence. So for assessing structural stability, the internal dimension is required, but for the purposes of fortification the external height is most significant. At some sites this external height is augmented by that of a rocky scarp or cliff on which the castle is set. Mingary falls into this category and, because of this, its seaward wall of 8.5 metres might well be deemed of equivalent defensive height to the landward wall of 14 metres.

The quest for some absolute in this subject which is otherwise beset by relativity and individual circumstances takes us to the next most obvious possibility, the *maximum* slenderness ratio in each period. This shows altogether more promise: in both the thirteenth and fourteenth centuries this is 1: 5.6. Well at least that is the figure emanating from the data in hand. It must be borne in mind that we have but a small sample available and, more significantly, medieval masons almost certainly would not have worked in ratios of a precision only achievable by pocket calculator. It is unlikely also that they would all have worked consistently to some particular ratio that would be regarded as a sacrosanct safety standard in the same way that engineers might today. In practice whatever maximum ratio is found is more likely to constitute an approximate guide to the general limits within which the medieval mason worked, and these were more likely to have been expressed in whole numbers. On that basis let us draw an assumption that most masons between the twelfth and fourteenth centuries in Scotland operated on an understanding that a free-standing structure required *at least* one unit of thickness for between every five or six units of height, in order to achieve stability. A coincidence perhaps, but this is not dissimilar from the 1: 6 ratio resulting from the dimensions specified in the 1535 Barmkin Act.

With that in mind, let us now peruse the other data at our disposal. For some purposes we must revert to imperial measurement for reasons that will become obvious. Minimum wall thickness is impossible to assess conclusively, since so many especially in this early period have been lost. However it is likely that about 2'3", (c.0.7m.) was the minimum practicable. This is certainly found in the fifteenth century and was probably in use prior to that for at least some unfortified structure, although it should be borne in mind that many if not most lesser 'walls' of that era were more likely to have been of timber. As for wall height, this dimension varied between a minimum of 20 feet and, exceptionally, 45 feet, with the majority between 25 and 30 feet. Remarkable is the frequent appearance in the statistics of about nine metres, 30 feet in the nice round terms that the builder would have understood. Interestingly, examples of less than that figure are found to benefit from some other source of added security: surrounding totally or partly by water in the cases of Kinclaven, Caerlaverock, Lochindorb and Loch Doon; siting on a rocky scarp or cliff for Duart and Mingarry. At this height of 30 feet a slenderness ratio of 1: 5.6 results in a wall thickness of 1.6 metres, which is indeed about the minimum found, in this class of building anyway. However, it is fairly obvious that this dimension was not deemed sufficient for security purposes, many examples around that figure being untypical in some way. By far the majority of true fortified curtain walls were between 1.8 and 2.4 metres, that is 6 to 8 feet thick, with some around 9 feet and more. The frequent occurrence of round numbers of feet is itself worthy of comment, but it also indicates a problem in the data gathered.

Curtain walls are often very difficult to measure. In order to ascertain the thickness, a broken down section, a gap, a gate or other aperture is required, preferably at or near ground level; alternatively access to the wall head. In many cases measurement in safety is simply not possible. Most measurements in this class of building have therefore had to be drawn from a variety of published sources, and the number of wall thicknesses of two metres precisely, whilst none at 1.9 metres, is very prominent. It is strongly suspected that measurements of many of these examples have been heavily rounded and may well be nearer the latter figure, that is of course around six feet.

Evidence from surviving building contracts may be helpful in confirming this. It will be recalled that wall thickness was rarely mentioned at all: from 1313 to 1442, out of twenty six constructions for which contracts can be found, wall thickness was specified for fifteen. Of those, five were expressed in ells: two of 4 ells thickness, three of 2 ells. Now whilst it must not be forgotten that in England the ell sometimes referred to a unit 45 modern inches long (1 1/4 yards), the principle of the convenience of this unit in wall thickness definition cannot be ignored. The Scottish ell was 37 inches, two of which might well have been conveniently rounded by modern surveyors and historians encountering the problems of measuring the structures themselves to 2 metres. The ten other contracts specify for wall thickness of substantial buildings of this period round numbers of feet, with only two exceptions which incorporate half feet. It would be safe to conclude from this that the curtain walls of Scotland were at least intended to have been of a round number of feet or ells rather than of metres. The convenient roundness of 30 feet for a popular wall height has already been noted. This all points also to the likelihood of simple rounded slenderness ratios being part of the masons' training and practice, not necessarily as rigid canons to be applied unimaginatively, but as the basis for practical decision-making in projects characterized by variety, peculiar circumstances and clients with individual requirements.

The extent of this is hinted in a graph (Figure 8.8) which relates the wall thickness to height in examples where the latter is known. No pattern readily presents itself in the very random scattering of our examples over the page except perhaps a very loosely defined trend of wall thickness responding in some cases to height. Otherwise the subject is simply characterised by variety.

Fig. 8.8 Curtain Wall Castles - Wall Height (unadjusted):Wall Thickness
Anglo- Scottish period

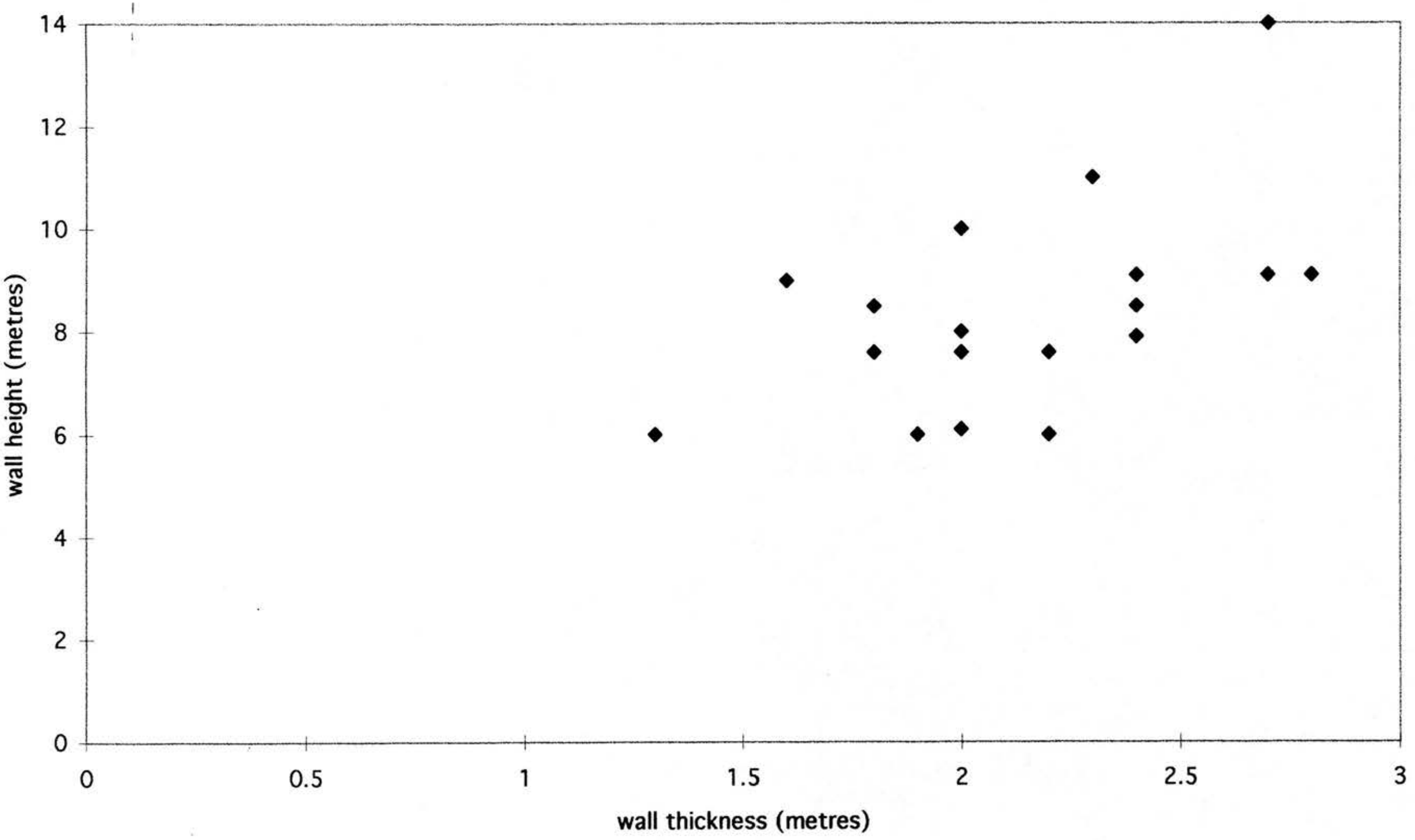


Fig. 8.9 Curtain Wall Castles - Wall Thickness:Adjusted Wall Height
Anglo- Scottish period

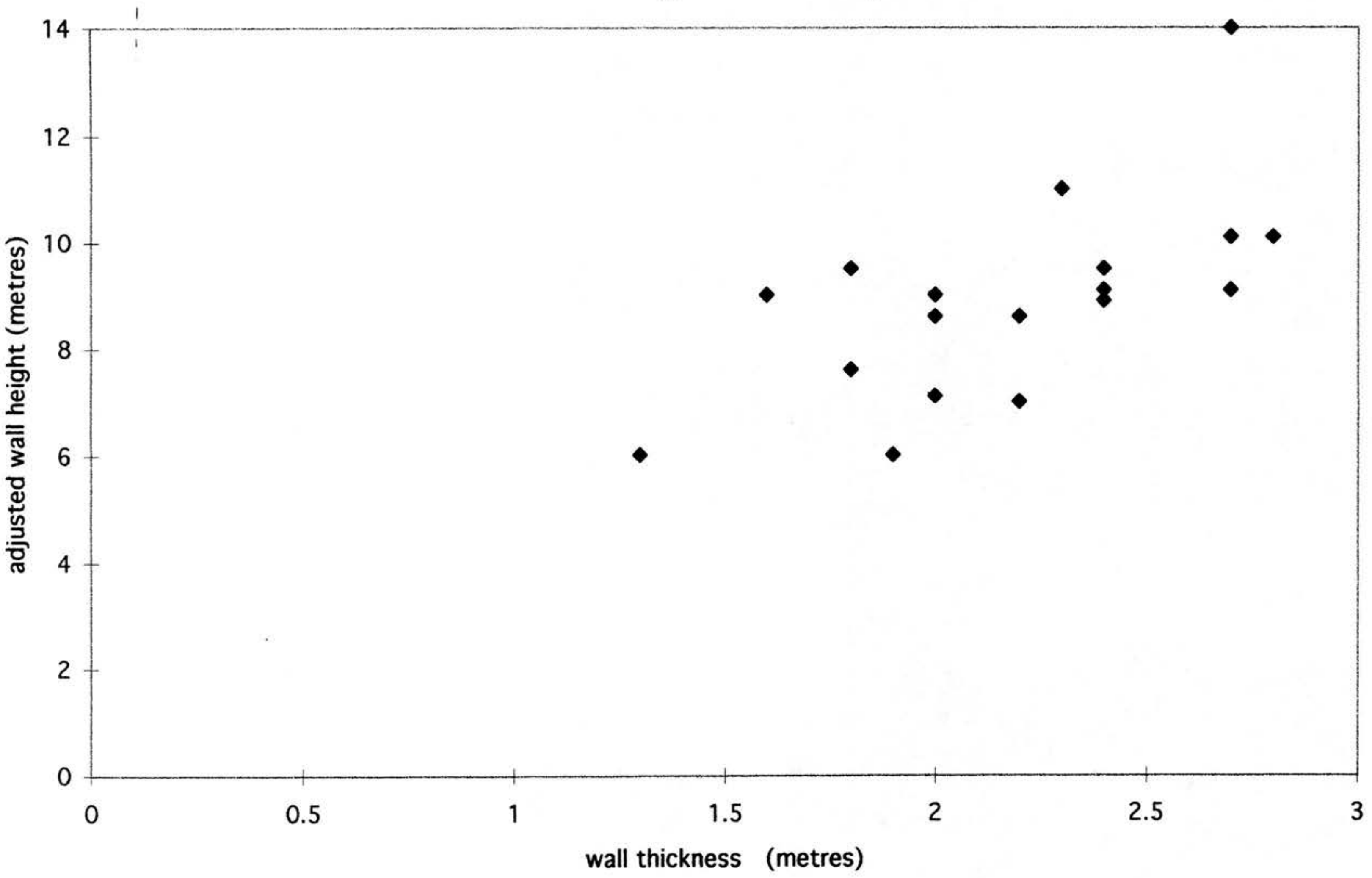


Figure 8.9 shows the same graph with some adjustments. The castles mentioned earlier which were surrounded by water or atop a crag have been 'awarded' an extra metre in height. Castle Sween has had one metre deducted to allow for the fact that it belongs to a slightly earlier era of more slender building tradition which will be discussed later in connection with church building. The subject begins to assume an altogether tidier form. There is a more pronounced pattern of wall thickness responding to height. It is not a great difference, but one which is nevertheless instructive: it indicates that some economy may have been made in terms of height in such cases, but interestingly not in thickness. It appears that such wall building may have been seen in terms of some appropriate thickness, possibly in certain round numbers of feet, but that there was no convention that such thickness should necessarily be in a set proportion to the height.

To summarize, the following generalisations for curtain walls of this early period can be identified:

- an absolute minimum wall thickness cannot be defined safely: about 3'6" was found at Aros but too many have been lost to expand on this;
- a minimum wall thickness of about 5 feet for fortification;
- a generally preferred fortified wall height of around 30 feet, with variations on this either way to allow for different levels of perceived vulnerability or threat, or possibly for enhanced prestige and status;
- a range of slenderness ratio customarily from 1: 3.2 to 1: 5.2 and up to a maximum 1: 5.6, but with little evidence of a mode or preference.

Within these loosely-defined limits curtain walls were built, but the primary specification to which they were designed was probably height, as the most visible quality of impression and fortification. There then seems to have been a customary preference for wall thickness in whole feet, commonly 6, 8 or 9 feet for fortification. There is still a possibility that the final choice of which whole number of feet was determined, or at least affected, by a perceived requirement to fall within the loosely defined range of commonly used slenderness ratios.

In order to achieve a more comprehensive understanding beyond these simple observations, detailed site measurements would be required, together with a more scientifically worked out basis for calculating compensatory adjustments to heights.

Parallel information from a wider spread of examples in England and Wales would also contribute much to achieving an understanding of the complex relationships between structural stability, fortification, dominant unit of measure and slenderness ratios. The background history if it is known of the original builders and their intentions would be very useful too. All that would add up to another thesis!

In the mean time some introductory comments bear restating, that castle design will probably have been as heavily influenced by the perceptions and aspirations of the owner, as the design methods of the architect / mason, as has probably been the case universally. Each one will bear the marks of such individuality. It remains to see to what extent all these characteristics were perpetuated in the ensuing periods.

8.4 THE WARTIME PERIOD c.1300- c.1370

During the wars of independence relatively little was built and, of that, little survives intact. However, those examples which we do have show remarkably similar patterns. The minimum wall thickness for serious fortification is still 1.6 metres, the maximum slenderness of 1: 5.6 is the same. Even the exceptional bulk of Tantallon conforms very much to previous trends for slenderness. To simplify matters and because there are so few examples in this group, further discussion of its details will be incorporated where appropriate with that of the next period.

8.5 THE EARLY SCOTTISH PERIOD c.1370- c.1480

The wars, together with various other factors such as expense, rendered the curtain-walled castle obsolete to some extent, but not totally. Much repair, rebuilding and finishing where previously incomplete was carried out at many of the major sites. One feature which became commonplace now was the building up of accommodation and service ranges round the walls in stone where previously there had been timber structures, if any at all. Dirleton, Caerlaverock, Bothwell and Hailes all come to mind in this respect. Of new curtain-walled castles, the most substantial were St Andrews, Spynie (completely rebuilt since) and Doune, while on the west coast Kisimul, Breachacha and Dunollie form a group of smaller structures, each with a single rectangular tower sited on the curtain, Dunollie also having a round bastion.

Above all, this was the era of the tower house, and in our study of curtain walls in relation to slenderness ratio and fortification, a change occurs that has a fundamental bearing on aspects of structural design. Curtain-walled castles in Scotland were in many cases based on the old motte and bailey concept, where the lord's tower on the motte had been independently defensible on its own, so that it could hold out even if the defences of bailey were breached and it fell. But the donjon tower was of very limited accommodation and invariably sited on the curtain, on which the security of the whole extended feudal household was very much dependant. The introduction of the tower house was, at a very general level, tantamount to the expansion of the donjon and its physical separation from the curtain, which then became reduced in importance. What eventually becomes a barmkin wall, whilst still a first line of defence, was now by no means as significant in that role as the earlier curtain wall. Its structural design may, therefore, be likely to reflect that change.

Looking at the surviving castles listed in Figure 8.4 it is immediately noticeable how, generally, the thinner examples are indeed the barmkin walls or other outer fortifications of thick-walled tower houses: these are not in the same class as the curtain walled castles; they were not relied on as the sole defence. That said, there are exceptions such as Dalhousie, which L-plan tower was armed with a 2.9 metre thick curtain wall, itself later equipped with a substantial round tower overlooking its gatehouse. The principle remains, however, that free-standing curtain walls were increasingly being built as one of two types: either as a fully fortified enclosure, with or without corner bastion towers, or alternatively as a relatively expendable courtyard enclosure serving only as a first line of security which otherwise relied much more heavily on the strength of the tower house from which it was almost invariably detached. The walls of the barmkins, to give them a conveniently but possibly over-generalized classification at this stage, were commonly of between 1.1 and 1.5 metres thick. Old style curtain walls account for most examples of greater thickness.

Assessment of height is difficult: few barmkins survive and, of these, none to their original height. Those examples where the height is known are nearly all more substantial curtain walls, though an absolute distinction between curtain and barmkin walls is hard to define in some cases. There may be a possibilty for extending the basis for analysis, and that is to draw a comparison with the 1535 Barmkin Act specification of 18 feet 6 inches (5.6 metres) height and one ell thickness. However, the resultant 1: 6 slenderness ratio is difficult to apply here. Whilst undoubtedly this falls just above the average for this period, the average or indeed any such benchmark is of no relevance since there is no apparent mode in this period at all: the ratios for the group vary more than any other. There is no pattern other than complete diversity. Also most surviving walls are considerably higher than that of the Barmkin Act, so we are left wondering what was the basis for the Act height.

As for maximum height, the occasional example of 12 to 13 metres is an interesting phenomenon and beggars many questions: were there just as many structures of such height earlier which have simply been lost? Was this extra height for an enhanced level of defensibility? The security or otherwise of the Scottish nobility in the fifteenth century is a subject that really would benefit from further research at a multi-disciplinary level. As mentioned earlier, it has been fashionable over the last decade to play down concepts of defensibility in Scottish medieval and renaissance architecture. Also, security is a highly individual and personal matter and ideally each case needs separate assessment on its individual merits. A study of wall thickness and height could contribute much towards such a multi-disciplinary approach. In the meantime, suggestions of image and status have been played up, and there is perhaps some mileage in this that is worth exploring.

The development in France of a conscious castellated aesthetic as can be seen, for instance, in illustrations in the Duc de Berry's books of hours, involved the accentuation of several characteristics and features, not least of which were the profusion of military detail at wall head and skyline, structural height and the quality of verticality: the illusion of height. Much of the former decorative paraphernalia were imported wholesale to Scotland. It would seem logical that the latter also might be seen as part of the package. With so few Scottish examples to call on, amongst them the hardly decorative Kisimul, it is with profound caution that any French connection is suggested for what is, after all, not a particularly marked or common change in curtain walls at least. What cannot be ignored, however, is that height, and the impression of it is very visible, and it was the *visible* appurtenances of defence that were the subject of licences to crenellate. The obvious emphasis on the visible, together with the desire to impress, the gradual simultaneous proliferation of the very vertical and high tower house, all add up to a conscious acceptance of this characteristic which is undoubtedly popular in France at the same time. There could be a French connection.

An entirely different aspect to this subject, and a useful indicator of attitudes to bare structure in direct comparison to fortification is to be found in fortified courtyard ranges. As mentioned, these are not to be regarded so much an entirely new phenomenon in the fifteenth century, but more the construction, or in some cases reconstruction of accommodation or service ranges round the inside of a curtain or barmkin wall in stone which in earlier times would have been of timber. The significant dimension for our purposes, of course, is the wall thickness of the outer fortified wall where this is different from the inner, courtyard wall. Figure 8.10 lists a number of these which were built throughout from new rather than merely new ranges tacked on to existing older walls, as at Caerlaverock, for instance. The figures present a most instructive comparison with those of the earlier period. The minimum external wall thickness has decreased a little and now is in excess of only 1.4 metres, much the same as for contemporary curtain walls, and with similarly even diversity up to more than 3 metres. The relative structural sufficiency of the courtyard side walls gives an idea of the perceptions of differing needs of security and bare structure. The diversity within the unfortified dimensions is at least partly due to the use in some structures of vaulting, mostly at ground floor level, occasionally above also. More will be said about these in a later section.

All that aside, what can be concluded about wall thickness determinants in this period? Returning to figures 8.4 and 8.5 it seems that :

- walls were tending to be built less thick than earlier;
- there are no longer any preferred conventions of dimension as were apparent in the previous period, although the popularity of about 1.5 metres (5 feet?) is just about evident;
- of slenderness ratio there is an even greater variety with absolutely no indication that this relationship was of any significance in the builders' minds at all.

In the light of the latter, the suggestion of a preferred range of slenderness ratios found in the previous period begins to appear flawed, although that possibility still cannot be entirely ruled out.

What does seem apparent is that in terms of wall thickness alone, whilst some builders were following earlier conventions of very thick walls, 1.5 metres and more, others were building thinner than that dimension. These latter cases almost invariably fall into one or other of the following categories: extra protection from water, rocky scarp, (e.g Ardstinchar, Dunollie, Lochore, Kisimul), or they were only less important barmkin walls providing the first line of defence to a much stronger tower house on or behind the wall (e.g. Smailholm, Blackness S & E walls, Craigmillar, Cessford, Mugdock, Breachacha). In others the fact that 1.5 metres or more was ordinarily still considered essential for security is perhaps illustrated by the wall thickness of other fortified courtyard ranges (figure 8.10) and tower houses (figure 8.7) of this period, nearly all of which are more than this figure, and indeed often over 2 metres.
Where post-war practice appears to differ from pre-war is that in the earlier period, where the siting of a castle benefited from the extra protection of water, rocky scarp etc., some height may have been dispensed with, later it was wall thickness that was reduced also. The question arises, does this indicate a growing consciousness of the concept of slenderness ratio?

Figure 8.10 FORTIFIED COURTYARD RANGES

Site		Wall Thickness:	Courtyard side	Outside	Difce.
			WARTIME 1296 - 1370		
BALMBREICH	(S, chapel block)		1.3	1.8	0.5
TANTALLON	(W, hall range)	GF	1.25	2.5	1.25
		1F	1.17	2.3	1.13
			EARLY SCOTTISH 1370 - 1480		
BALGONIE	(N, hall range)	GF	1.5	1.55	0.05
		1F	1.25	1.4	0.15
NEWARK Fife			1.2	1.65	0.45
CRICHTON	(N, kitchen block)		1	1.65	0.65
CRICHTON	(SW, hall range)		1.7	2.05	0.35
RAVENSCRAIG	(N, central range)		1.7	3.35	1.65
			but designed to be	4.27	2.57
			TRANSITIONAL 1480 - 1560		
MACDUFFS	(gatehouse range)		1.1	1.8	0.7
NEWARK, Fife			1.1	2.1	1
BALVENIE	(bakehouse block)		1.75	2.3	0.55
			POST REFORMATION 1560 -		
TOLQUHON	(gatehouse range)		0.47	0.55	0.08
but NB	*(gallery range)*	*GF*	*0.8*	*0.8*	
		1F	*1*	*1*	
PITSLIGO			0.8	1	0.2
EDZELL (gatehouse range)		GF	0.85	1.05	0.2
		1F	1	1.05	0.05
but NB	*(kitchen range)*		*1.1*	*1.1*	
TOLQUHON	(hall range)		0.8	1.15	0.35
CRICHTON	(NE, Earl Bothwell's range)	1F	0.8	1.6	0.8
HUNTLY (west range)			0.9	1.7	0.8

8.6 THE TRANSITIONAL PERIOD c.1480- c.1560

It was during this period that the 1535 Barmkin Act was passed, and the dimensions it stipulated (18'6" high, one ell thick) make an interesting standard by which to assess such walls as survive. Unfortunately almost none stand to their original height. Let us begin with the Act itself and try to work out on what basis its specifications were formulated. Two aspects immediately invite question: first, the thickness of only one ell (0.94 metres) is much thinner than most contemporary walls. The dimensions recorded in figure 8.4 show a spread from 0.8 to 1.8 metres with most around 1.3 - 1.4. Secondly, the height is interesting in that it is not expressed in whole feet. In building contracts half feet are occasionally specified but rarely for an *overall structural* dimension. The specific use of an irrational number of feet in an Act with such a generalized application as this is to be wondered at. Such a precise dimension as 18'6" surely cannot have been the *starting point* for the form of these intended barmkins, although something *around* that dimension may have been considered as providing adequate protection, or at least deterrent against the surprise raids which characterised border reiving. Given that border reivers would usually have been lightly armed and not equipped for battering walls, relying mainly on surprise, height would be a much more visible deterrent than thick walls. The latter dimension of course could not be gauged from outside. Theoretically the minimum would suffice, hence perhaps the recommended one ell (which, granted is not as thin as the exceptional 0.8 metres at Seafield, Fife). Now it so happens that 18'6" is exactly six times one ell, and the possibility has to be considered that the authors of the Act were consciously working to a slenderness ratio of 1: 6. This is potentially very significant, given the apparent non-conformity by builders in previous periods to any particular ratio. It is possible that masons were now beginning to work out building practices which, more than previously, were taking greater account of economy or even structural sufficiency, albeit at a very basic level, and this obvious use of a slenderness ratio based on a wall thickness dimension as the starting point, in order to arrive at the specified height, may well be evidence of this. Interestingly, this was probably within a few decades of the time that Rodrigo Gil in Spain was drawing up his theories on vault abutment to similar purpose of structural sufficiency. This interpretation of the Barmkin Act would be a very tenuous conclusion if not for one further piece of evidence which may or may not turn out to be coincidental. Edinburgh, where the Act was passed, was itself by 1535 surrounded by the Flodden Wall, parts of which survive with a thickness of 1.2 metres (4 feet) and height of 7.3 metres (24 feet) - a ratio of 1: 6.

So much for the Barmkin Act. The extent of its application is difficult to assess, given that no barmkins in the Borders of this period survive to their original wall head. Nevertheless an assessment of wall thickness at least is possible. It has already been noted that the defensive requirements of borders barmkins that were subject more to lightly armed surprise raids probably differed from those of other establishments, and this may account for the relatively insubstantial specification in the Act of one ell (0.94 metres), when the trend was for walls of 1.3 - 1.4 metres. However, even that dimension is less than those of contemporary tower houses and courtyard ranges which commonly exceed 1.5, and are often nearer 2 metres where security is obviously an issue. It appears that fewer property owners were putting their faith in thick barmkin walls for their security, but those for whom security was still important were continuing to build their towers or courtyards with similar levels of protection as previous generations. It is difficult to generalize further here precisely what was going on, but these developments may be connected with changes in patterns of property ownership in this period. It could be that these property-owning households were smaller than previously and the importance of the barmkin wall as an enclosure of ancillary accommodation was generally declining as a result. A wide-ranging study of the owners, their households and wealth would be required to corroborate this.

8.7 THE POST-REFORMATION PERIOD c.1560 -

Again, we are thwarted by a sparsity of examples from which it is difficult to generalize. Nevertheless, it is interesting to note the absence now of anything thicker than 1.3 metres, and that there is some concentration round 0.8 and 1.1 metres, just over 2'6" and 3'6" respectively. It appears that a degree of standardisation has finally been adopted at these dimensions, a final choice between the two possibly being dependent on height, but that cannot be affirmed without a good number of examples which survive to the wallhead. Again, it is noticeable that attitudes to security where it is seriously intended (not including artillery fortifications) have not actually changed much: although examples of 'security conscious' towers and courtyard ranges in this period are few in number and difficult to discern, there is an unmistakable continuation of the trend for some such walls to be over 1.5 metres thick (e.g. Crichton, Huntly, Noltland).

8.8 CONCLUSIONS

This chapter set out to ascertain to what extent wall thickness was based on height, or contemporary perceptions of stability of any wall, possibly regardless of height, or contemporary perceptions of security, or a combination of these. First, however, some comment is appropriate on the more basic trends in wall dimensions. In each period there does seem to have been a number of very general preferences for certain wall thicknesses, often in what appear to have been round numbers of feet, or ells. Surviving documentary evidence (Appendix III) confirms that this was characteristic of contemporary practice of building specification. These preferred dimensions decrease over time in the increasing number of walls that appear not to be designed with serious defence as a primary consideration, or where greater reliance is placed on height as a deterrent.

However, by reference to the figures for lightly fortified courtyard ranges and tower houses it has been ascertained that, for the purposes of defence against lightly armed attack, the conception of a defensive wall did not alter appreciably throughout the entire period, remaining above 1.5, and more commonly 1.8 or 2 metres or more.

Minimum wall thickness is impossible to assess conclusively, since so many smaller examples have been lost. However the likely figure of about 2'3", (c.0.7m.) is found consistently since the fifteenth century, and simply becomes increasingly common in the later periods.

The predominant trend (excepting later artillery fortifications) is obviously for walls to be built thinner through to the late sixteenth century. However, this of course ignores the probability that there were many more relatively thin walls in the early periods which have been lost. Thus the trend is possibly not so much towards thinner walls in the later periods, as away from thicker walls, at least from the fifteenth century.

Maximum height increased slightly from the thirteenth century limit of about 10 - 11 metres, (ignoring the exceptional I4 metres of Mingary), to 13 metres in the fifteenth century in response to the requirements of fashion, or security, or both, and thereafter is reduced again to nearer 6 metres (minimum 4) as curtain walls give way to barmkin walls encompassing tower houses, variously fortified. Again, height was important because it was *visible*, from the aspects of both security and possibly fashion.

Of the relationship of wall thickness to height, whilst the sample fell into a range of slenderness ratios, the average of which increased marginally until the transitional period, the breadth of the range suggested that this may not have been a relationship used much, if at all by medieval builders, at least until around the time of the 1535 Barmkin Act. Until that time, and particularly during the thirteenth century, there may have been a notion that a curtain wall should be of a certain height appropriate to the needs of defence, or following contemporary received wisdom on the subject. There may also have been a similar notion concerning thickness, but the two do not necessarily appear to have been related. There does not even seem to be a regional division between those below around 1: 4 and those above. The Barmkin Act, however, appears to indicate that the Transitional period saw a change in practice towards the conscious and intentional use of slenderness ratio, but the lack of examples surviving to full height make it impossible to ascertain how generalized this change may have been.

The very broadness of the range in which slenderness ratios were found is perhaps reminiscent of Rondelet's prescription of three different ratios, 1: 8, 1: 10 and 1: 12 depending on the level of stability required; also the advice of Rodrigo Gil and Lorenz Lechler who, rather than rigidly adhering to any one rule, recommended a degree of flexibility in any given situation, depending more on the architect's accumulated knowledge and experience.

It is not intended to draw any more generalized conclusions concerning free-standing walls at this stage, but the above is simply intended to lay the foundations, as it were, for the studies on more specific building types which follow. The foregoing findings will be referred to in the ensuing sections and will be drawn together in the concluding chapter.

9 CENTRALLY PLANNED STRUCTURES

9.1 INTRODUCTION

Needless to say, this is a very small group, the Scottish building tradition being restricted almost entirely to rectilinear plan forms. Indeed it is quite pertinent to comment that all the examples in this category are based, to some extent or other, on imported ideas. For all that, some immensely interesting results emerge from analysis of each structure.

We are concerned here with circular structures, octagons and hexagons, and reference should now be made in this connection to the temple projects of Sebastiano Serlio which are analysed in Appendix I Section 4. In those cases the internal dimensions were invariably specified, together with the wall thickness, but no means of achieving the latter were explained. Invariably the internal geometric figure had been a polygon, even where shown as superficially circular. The wall thickness had been defined simply by extension of the lines of the internal wall planes, or by inscription of a smaller rotated polygon and extension of its sides, or both, the outside wall surface being defined where two such extended lines conveniently intersected. Such was the number of possible intersections of various lines that a wall could be thus designed with a wide variety of thickness options appropriate to its function and requirements. Most commonly the wall thickness had ended up in a proportional relationship with the vault span similar to that found in actual built works, and the practical recommendations of architects of that era: roughly between 1:4 and 1:5, occasionally more, as can be seen in the Span Ratio Summary in Section 7 of the appendix.

The aims of this chapter are to determine on what basis the centrally-planned structures forming the Scottish survey sample were designed, in particular what was the basis for calculation of the wall thickness? Does it appear that the design commenced, as in Serlio's temples, with an internal dimension, and from this the wall thickness and hence the external dimensions were formed? Was there a practice of geometrical manipulation in order to derive these dimensions? Was the same manipulation used in each case? Serlio's projects were all vaulted in a single span, whereas the vaults of some Scottish examples are supported by a central pier. However, this need not necessarily invalidate application of the same analytical methods used on Serlio's projects to the Scottish structures, and indeed such application was found to produce some very instructive results.

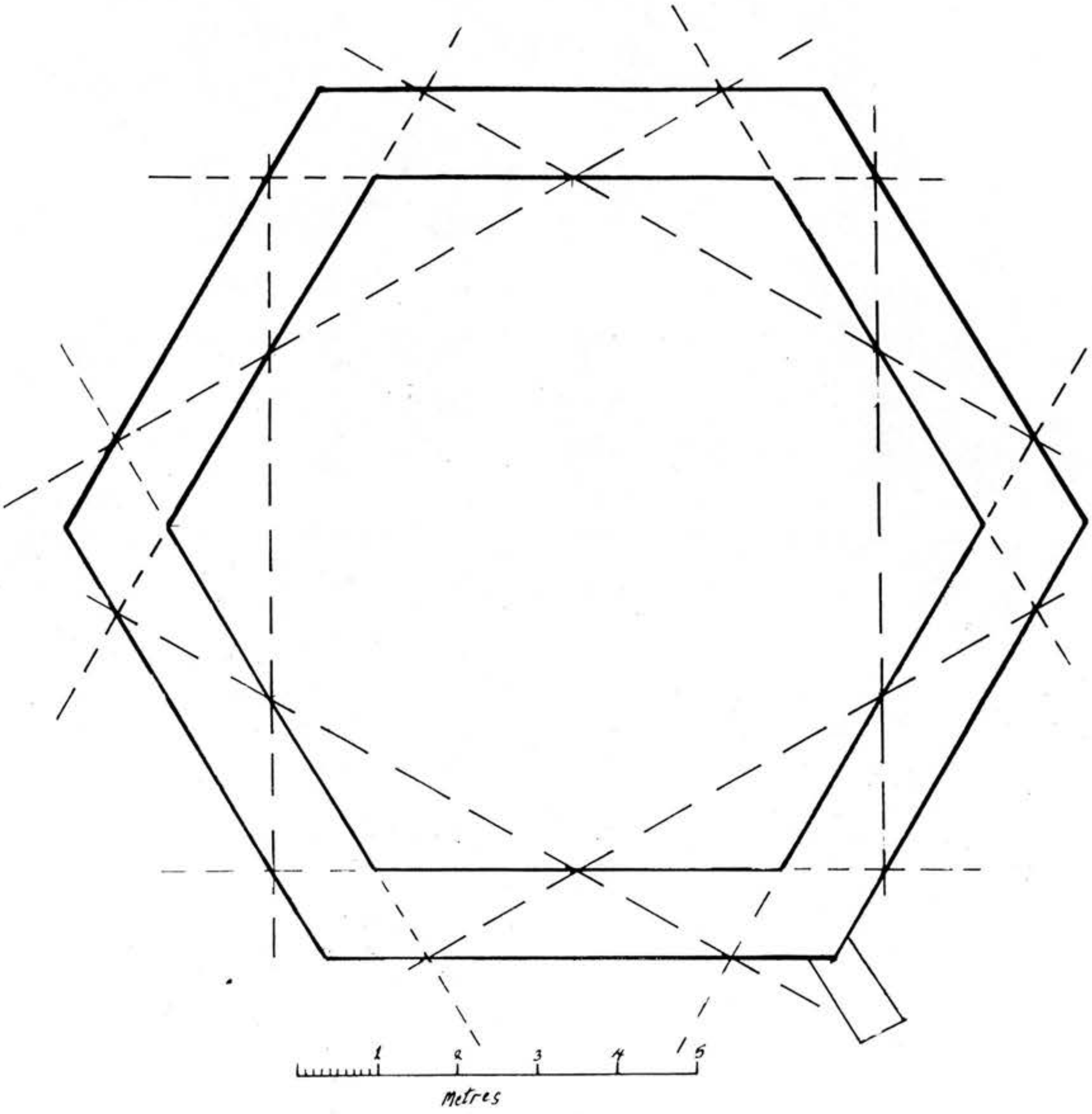
9.2 ECCLESIASTICAL STRUCTURES

9.2.1 *The Chapel of St. Triduana, Restalrig c.1480*

The structure is hexagonal in form and was originally of two vaulted storeys, the upper now being lost, the lower having a central pier. Buttresses lend additional support at the building's corners, although the present ones are replacements. The walls appear proportionately much thinner than those of Serlio's projects. The span ratio taking wall thickness alone at the vertices is 1: 7.8, but including the buttresses, 1: 4.4. Could they have been designed by similar methods?

Extension of the lines of inside wall surfaces produces no result on its own, neither does the inscription of a smaller rotated hexagon with extended sides. However, where the extensions of the former intersect with those of the latter does appear to fall exactly on the outer wall surface (Figure 9.1). On the same diagram is shown one of the buttresses. It is not intended to engage in a full investigation and discussion of these features and their relationship to wall thickness and fenestration in this section. That will be left to the sections on simple rectangular churches (chapters 10 and 12). However, in the case of this centrally-planned structure, it does appear that the buttress projection might have been achieved by geometric manipulation: the extended sides of the inscribed rotated hexagon do intersect roughly at the outer extremity of each buttress. It is noteworthy that the projection so defined gives a total abutment of the corners (i.e. wall thickness plus buttress projection) of about 2.3 metres. The total corner-to-corner roof span is 10.2 metres. The wall thickness to span ratio is therefore 1:4.4 and thus generally follows the recommendation of that time, according to Rodrigo Gil. One further point of interest concerning these buttresses is their width to projection ratio. It has already been noted that the original buttresses are lost but if we assume that their replacements are of similar size, an interesting observation may be made. At 61 centimetres, their width is exactly half their projection. This bears a very strong resemblance to one of the prescriptions for buttresses by Lorenz Lechler (Appendix I Section 5). Now it must be observed that buttresses of this proportion are actually quite rare in Scotland, and this fact, coupled with the possibly Greek origin of the hexagonal form (VII Campbell, 1995: 309),

Figure 9.1 The Chapel of St. Triduana, Restalrig. c.1480. Schematic plan



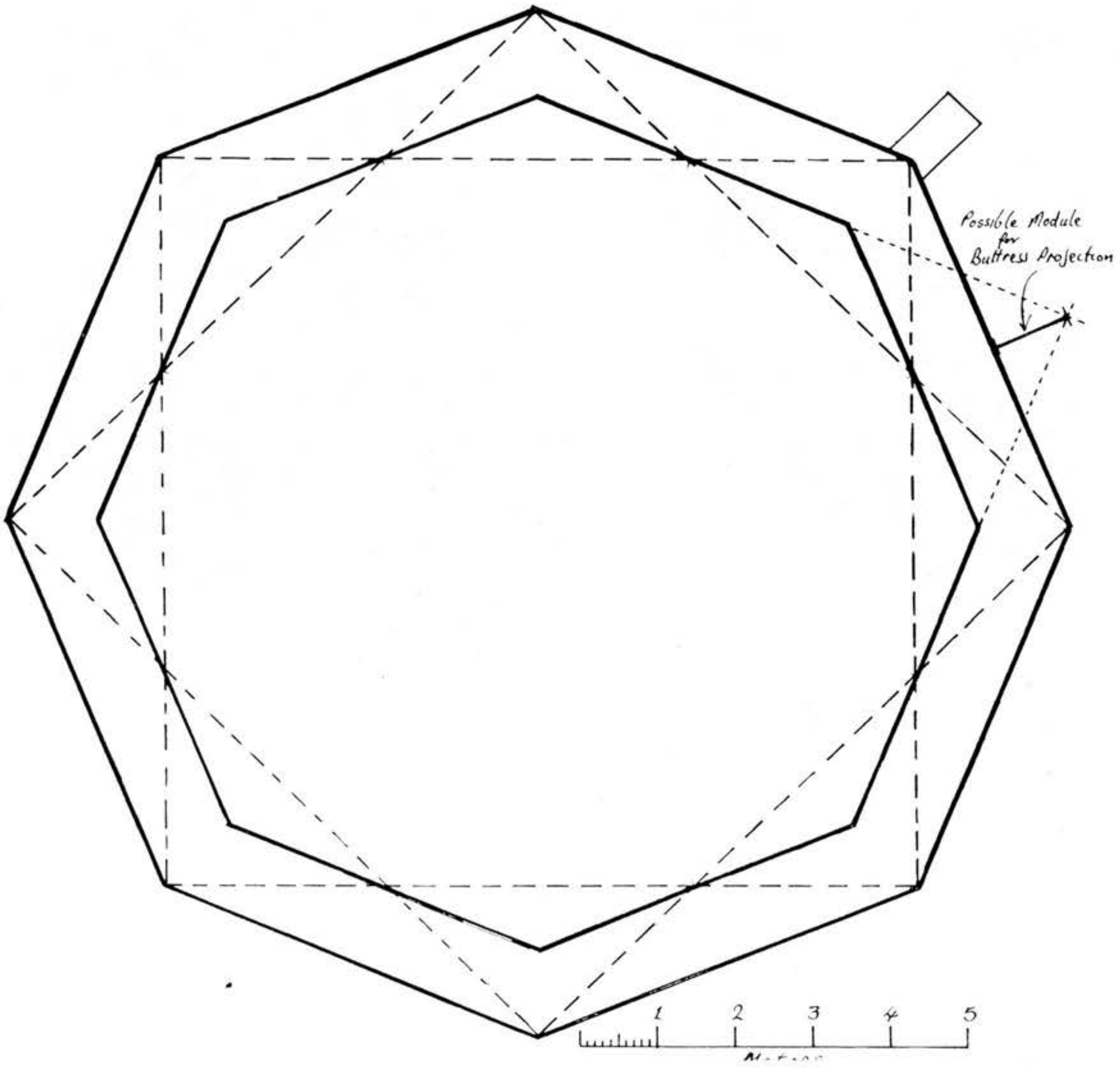
9.2.2 *Elgin Cathedral Chapter House*

An octagonal structure with central pier and buttresses of the late thirteenth century, the Elgin chapter house was remodelled to a limited extent sometime around the end of the fifteenth century. Despite some wall thickening from window level upwards, sufficient remains of the original structure to assess the origins of its plan. Again, it quickly becomes clear (Figure 9.2) that a further rotated octagon has been inscribed inside the internal figure, and the extended sides of this smaller octagon intersect at the external corners of the walls.

From here, definition of the buttress size is not so straightforward. To begin with, the buttresses are all of slightly different sizes; whilst approaching the 'ideal' of projection being double the width, none actually conform, the average being about 57 centimetres by 99 centimetres. The only convenient intersection of lines at a point about one metre from the outside wall occurs at the junction of two extended alternate inside wall faces mid-way along each of the external wall faces rather than at the corners. If this manipulation does define the buttress projection then it is unusual in that it takes the specified dimension from one location and moves it to where it is required. It has to be said that any assumption that the origin of the chapter house buttress projection is based on this manoeuvre should be regarded with caution. The dimensional similarity may simply be coincidental. It would be useful, and possibly decisive, to conduct a similar analysis of related structures such as the chapter houses of Lincoln, Salisbury, Southwell, Wells, Westminster, Worcester and York.

In any event, the span ratio resulting from this design process taking the wall thickness alone is 1: 9.5, higher even than that of St. Triduana's. Taking the buttresses into account brings the figure down to 1: 5.2. The inclusion of the buttresses for both examples analysed so far produces a figure much more comparable to those commonly found in the models examined in Appendix I, collated in the Span Ratio Summary (Section 7). However, both Elgin and St. Triduana's have a central pier and some account should be taken of that, but at this stage it is difficult to see quite how.

Figure 9.2 Elgin Cathedral, Chapter House. Late 13th century. Schematic plan



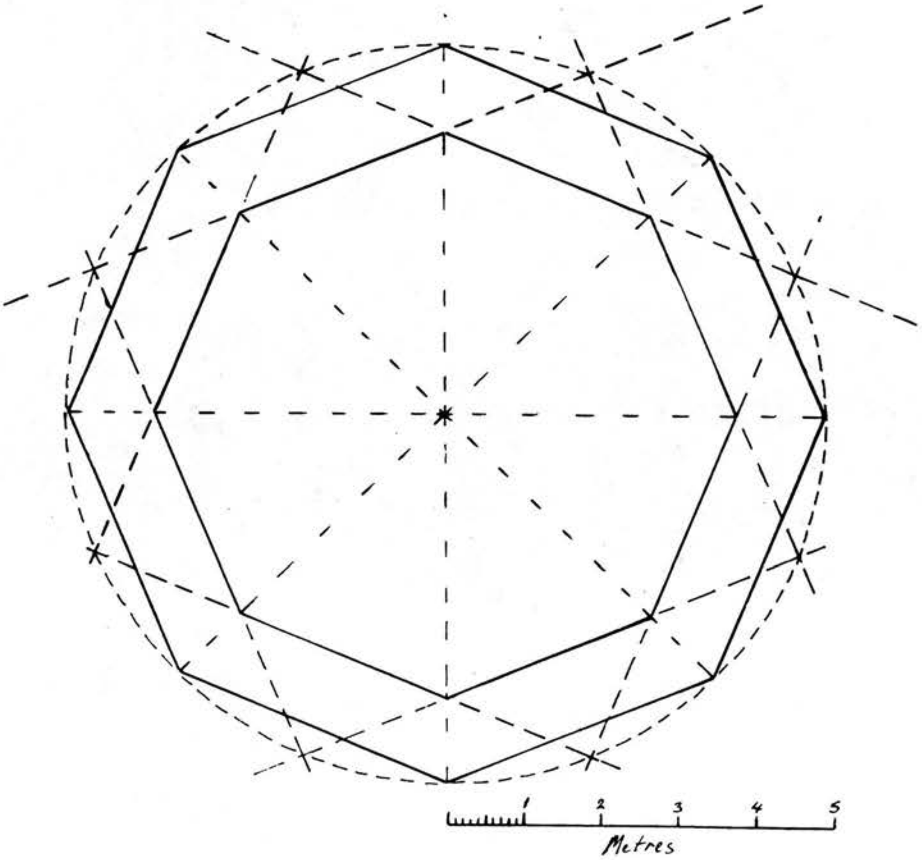
9.2.3 *Inchcolm Abbey Chapter House*

Originally this was a single storey structure, built in the early thirteenth century, of octagonal form and roofed with a ribbed vault of single span, unlike Elgin and St. Triduana which have a central pier. However, in common with these others, the corners are reinforced with buttresses. Thus a comparison of span ratios across these three examples may prove instructive. In the fifteenth century a room was added above the chapter house and roofed with a barrel vault.

For a geometric basis for the structural design of the thirteenth century chapter house, we look at first in vain. There are no convenient intersections which directly indicate either the wall thickness or the buttress projection. If the method used at Elgin is applied here, walls of a mere 0.75 metre thickness would result, giving a span ratio (walls only) of 1:10. For a vaulted building of this size such walls would surely be dangerously thin, even if strengthened with buttresses. Perseverance with geometric manipulation was justified: extension of the lines of the internal side walls results in their intersection at a point half way along each external wall surface but well outside it, by about 0.45 metres. These points in themselves appear meaningless at first but, if joined up, form another octagon which, if rotated 22½°, fits exactly the exterior wall surface of the chapter house (Figure 9.3). Geometry, it would appear, was used after all, but a different pattern of manipulation from that employed elsewhere: the 'Elgin method' would produce too thin a wall, so another set of convenient intersections was sought. The intersections of extended sides of a smaller inscribed and rotated octagon with those of the actual internal wall planes produce points of either even thinner (0.4 metre) or much thicker than necessary dimensions (1.9 metres). The architect has sought a solution somewhere between these extremes but he has still sought it within the geometrical method, and a practical solution has been decided on that is reasonably simple to achieve. A question that remains is whether or not he was guided by some rule of thumb or convention governing a vital relationship such as span ratio. The result here is 1: 6.8 walls only; 1: 3.75 including buttresses.

Buttresses for the chapter house measure 1 metre projection at the sides, by 0.66 metre width. No simple geometric source can be found for these and it is assumed that the former dimension has possibly been chosen simply for its uniformity with the wall thickness. The tidy 2:3 relationship of width to projection may itself be of significance.

Figure 9.3 Inchcolm Abbey, Chapter House. Early 13th century



9.2.4 *Conclusion*

In conclusion it does appear that the medieval architect used constructive geometry in this building type to achieve structural as well as spatial solutions, and that he worked from the basis of the required *internal* dimensions. At the same time he would be mindful of what proportionality of abutment to span would be appropriate and structurally sound for the particular problem under consideration. As we have seen, for any given internal architectural space, there were any number of possible solutions achievable by geometric manipulation, but training and experience would have guided as to which one or ones were structurally sound yet reasonably economical. Perhaps there were rules of thumb or certain conventions by which he would have been guided. From only three examples at our disposal in Scotland we still have something of a problem in finding out what these might have been. The evidence bears restating in tabular form.

Span Ratio	St. Triduana's (with central pier)	Elgin (with central pier)	Inchcolm
walls only	1: 7.8	1: 9.5	1: 6.8
walls + buttresses	1: 4.4	1: 5.2	1: 3.75
walls + ½ buttresses	1: 5.6	1: 6.7	1: 4.9

There is obviously a fairly wide disparity between the ratios, however much buttress is allowed for. Logically some additional allowance should be made to differentiate Inchcolm which lacks a central pier. If we take the last row of figures above which relate to walls plus half the buttress projection, and for St. Triduana's and Elgin recalculate the figures based on only *half* the span, that is from the central pier to the inside wall surface, there is no greater parity:

1: 2.8   1: 3.35   1: 4.9

If, however, *three quarters* of the span is used in the cases of St. Triduana's and Elgin, then there is some convergence of the ratios:

1: 4.2   1: 5.0   1: 4.9

Whilst this might produce figures which roughly equate, and also approximately conform to the range found in built examples listed in the Span Ratio Summary (appendix I section 7), this is not a particularly logical basis for calculation where central piers occur. Moreover, we are in sore danger of manufacturing methods to suit the ends, where there may actually be none. Also, a sample of only three is utterly insufficient on which to formulate a theory, let alone a conclusion. However, it may be seen perhaps as a basis for future experiment with a more widely based sample.

Whatever the guiding conventions might have been, and there must have been *some*, even if they differed slightly between architects, we begin perhaps to glimpse an idea of Lechler's meaning when advising his son:

> "Give to this writing careful attention, just as I have written it for you. However, it is not written in such a way that you should follow it in all things. For in whatever seems to you that it can be better, then it is better, according to your own good thinking. ... ... if there is a design decision to be made; make it, and if the building does not fall, then you know you made the right decision."
> (quoted in II Shelby and Mark, 1979:115).

The design decision, it would seem, was at least partly a matter of judging which set of constructive intersections or other manipulations to choose as appropriate for the building in question. As we have seen from the few Scottish examples, there were two principle criteria by which to judge which solution was appropriate: stability and economy. For ecclesiastical buildings simple structural stability was paramount, but our explorations into the use of constructive geometry show us that there was an element of choice between various geometric methods, and that this enabled moves towards an element of structural sufficiency; that is the design of structure that is *just sufficient* to provide stability, but within the constraints of the constructive geometry method. In the light of all this, Bucher's (II 1972: 48) theory that, until the collapse of Beauvais, design was purely by geometric manipulation and thereafter such method was augmented by the use of numerical and/or proportional rules-of-thumb, whilst probably still fundamentally correct, may now require some revision, at least for Scotland. By his thesis, Bucher implied that geometric manipulation only produced *one* structural design solution for a given building, whereas there were, as we have seen, several alternatives, and this was a considerable time before the collapse of Beauvais.

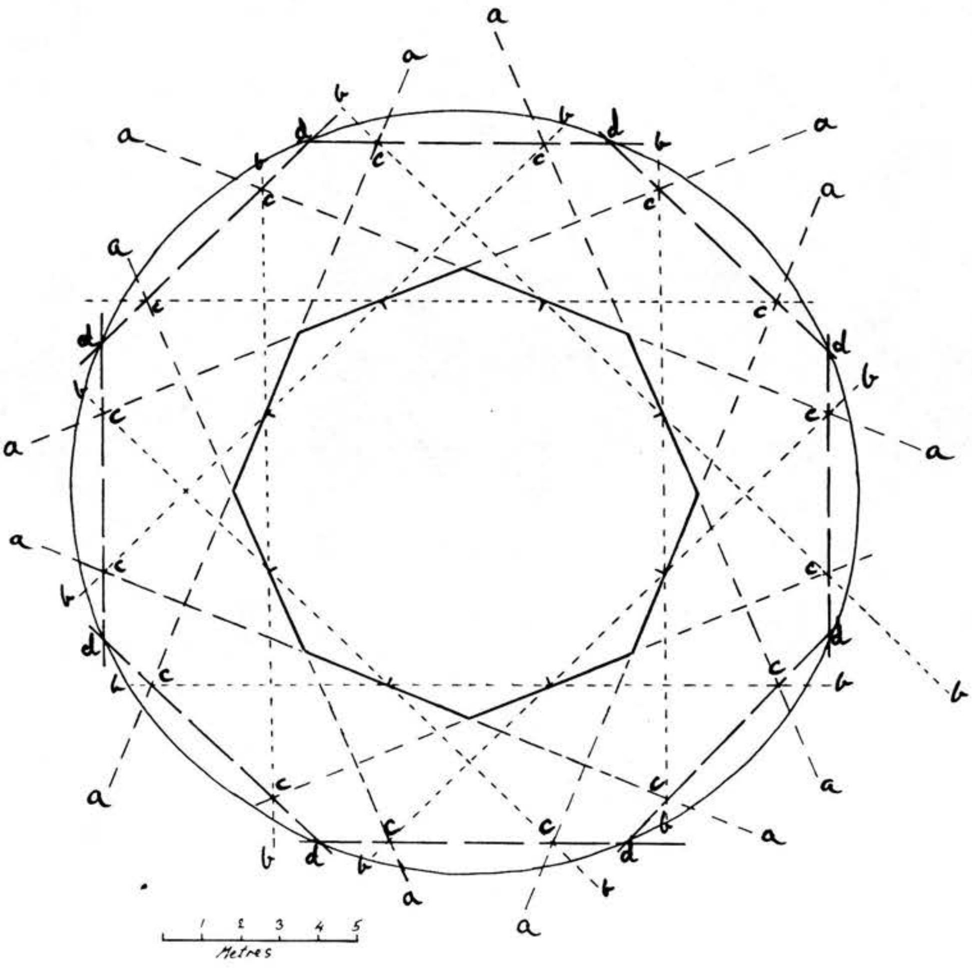
9.3 MILITARY AND DOMESTIC WITH POLYGONAL INTERIOR

9.3.1 *Bothwell Castle Donjon Tower*

Whilst externally the Bothwell donjon is a typical round fortified tower, having very thick walls, its internal figure is an octagon, and hence we recall Serlio's first temple project, of essentially similar form (Appendix I Section 4.2.2). However, in vain do we look for the outer wall surface by constructive geometry. It simply does not immediately appear from the usual plethora of extended lines and their intersections, and it is tempting to settle for one apparently remarkable coincidence which does not involve the geometric technique but bears more relation to the 'module transfer' principle which may have been at the basis of the Elgin chapter house buttress size. The walls are 4.6 metres thick, that is 15 feet, and this is identical to the length of each internal wall surface.

A niggling suspicion that such an apparent coincidence was not characteristic of medieval practice prompted further experimentation. Perseverance was justified (Figure 9.4). Just as at St. Triduana's where the outer wall surface was found to be defined by the intersection of extended lines of, firstly, the internal figure (shown as *a-a* medium broken lines), and, secondly, the smaller inscribed rotated hexagon (*b-b* shorter broken lines), so at Bothwell the same combination is used to create a larger outer rotated octagon. The intersections do not define the corners of this new figure, but rather two points along each outer wall surface (*c*). The outer octagon is then formed by drawing in these outer wall surfaces, and where these intersect (*d*) form points on the diameter of the outer circle of the Bothwell tower. It is a long process and it is easy for inaccuracies to creep in along the way. To draw it up with precision, even with the aid of graph paper, is no simple matter. Realistically, we still have very little idea whether the wall thickness was defined by this method or by a straightforward use of the dimension of each internal wall surface. Either seems possible. Even if the answer to this problem was to be found, another question immediately presents itself: why did the architect of Bothwell alight on this particular wall thickness dimension? There are other intersections of line extensions which could have been used, resulting in thicker or thinner walls: a very wide range of possibilities emerges, just as in the ecclesiastical examples. Was there a general consensus of optimum wall thickness for defensive purposes at that time for this type of structure?

Figure 9.4 Bothwell Castle, Donjon tower. Late 13th century. Schematic plan



Comparison with the thickness of curtain walls and bastion and other donjon towers of the thirteenth century in Scotland shows unmistakably that, at 15 feet (4.6 metres), the Bothwell donjon is in a substantially larger class, most contemporary curtain walls being half that or less, and it bears more relation to that mentioned in the French poem of that era quoted by MacKay MacKenzie. *Le Roman de la Manekine* is set partly in Scotland and in one section a king instructs his builder to "...make me here a great tower of stone and good mortar, completely round and with good thick walls fifteen feet thick or more." (VII 1927: 93). The similarity of Bothwell donjon with French work has been noticed by many. The coincidence of wall thickness may be just that, but it may also constitute a real connection. Again, such is not to be found anywhere else in Scotland at this date. The possibility of it being designed by a Frenchman or someone acquainted with French standards cannot be ruled out. Before leaving this subject, one further enquiry is worthy of pursuit.

Much has been made of the general similarity and possible influence of the donjon at the Château de Coucy. Certainly the overall form of the structure is not dissimilar, but it is much larger than Bothwell. Based on some figures given by MacGibbon and Ross, the two structures compare as follows:

	Overall diameter	Height	Wall thickness	Internal span wall-to-wall	Wall thickness: span	Wall thickness: height
Coucy	95'(28.96m)	215'(65.53m)	25'(7.6m)	13.7	1:1.8	1:8.6
Bothwell	65'(19.81m)	90'(27.44m)	15'(4.6m)	11.2	1:2.4	1:6

Coucy, for all its massive bulk of masonry boasted little extra living space over that of Bothwell, whose walls are relatively thin in relation to its internal diameter, but also relatively thick in relation to its height. The comparison is of little assistance, except that it demonstrates that the French, and Coucy is not alone in this, did build castles at that time with generally much thicker walls than in Scotland, and indeed also than in most English structures.

The donjon at Bothwell is also sometimes compared with that of Dirleton Castle, East Lothian. Here the interior is a seven-sided room but, as a geometric figure, is very irregular and, furthermore, it is not even set centrally in the tower structure as a whole. From the Lord's Hall on the first floor the wall thicknesses vary round the four great window embrasures 1.95, 2.13, 2.26 and 2.44 metres. Clearly it was not designed by geometric means. Perhaps it is at this point that we re-examine the status of these buildings and draw a distinction in geometric terms between what can justifiably be described as architecture at Bothwell and the vernacular, in relative terms, of Dirleton.

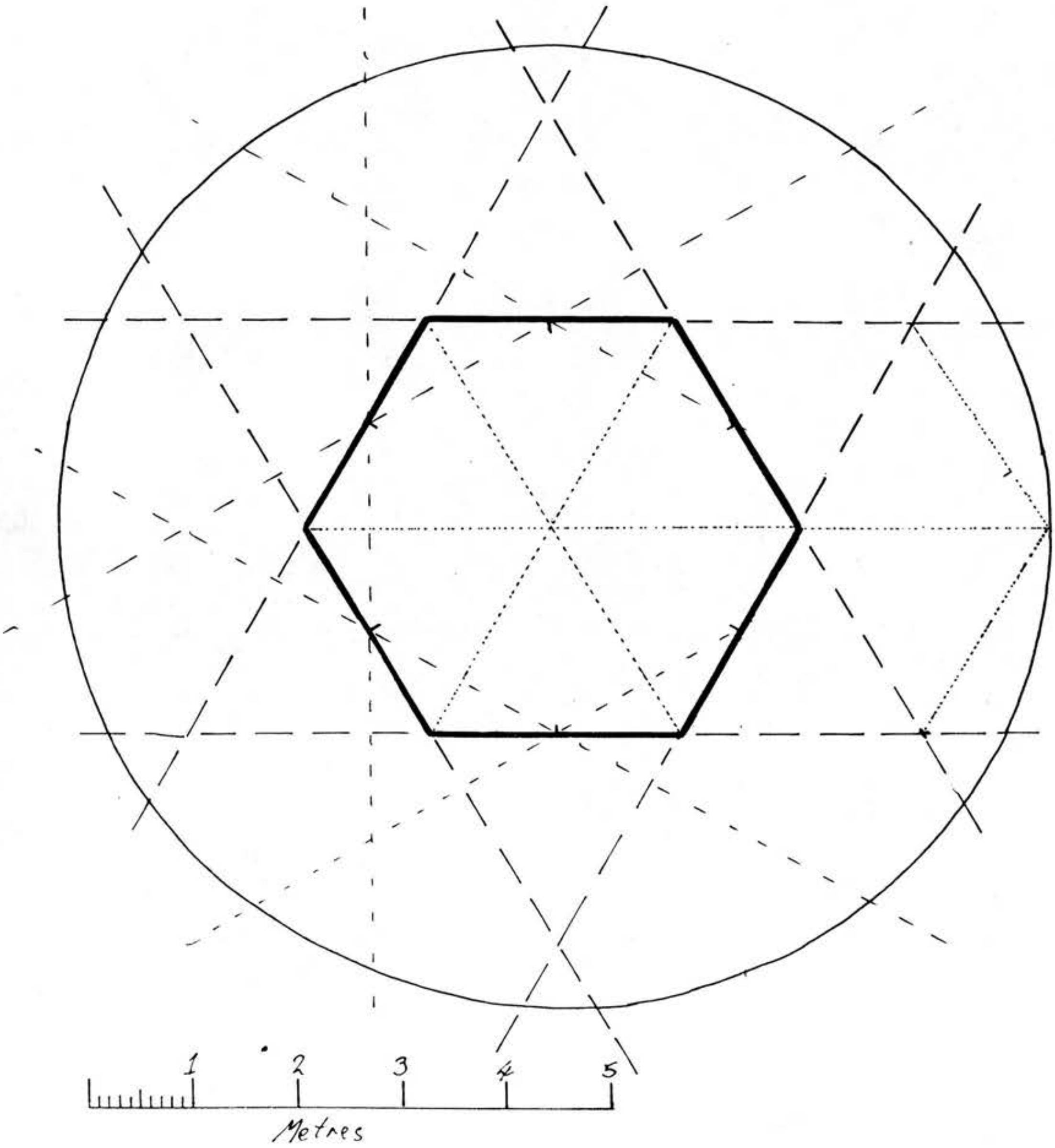
9.3.2 *Bothwell South-East Tower (Fifteenth Century)*

Although the foundations of this structure may have been set out in the thirteenth century, together with those of the rest of the proposed curtain wall and its other bastion and gatehouse towers, it was not actually built until the fifteenth century.

In the light of this it is perhaps not surprising that the tower, whose interior is a hexagon, displays an almost identical system to that found elsewhere in the castle but with one significant difference: the wall thickness of 2.4 metres is again identical to the length of each side of the internal hexagon (the sides all differ slightly but average 2.37 metres) but instead of being found to be projected from the mid-point of the hexagon side, it is measured from the vertices (Figure 9.5). Using pegs and string, this method could have been developed by starting the design with a circle, inside which the internal hexagon was then inscribed. Indeed the hexagon construction itself can only have begun with this circle. The radius of the circle is then simply extended by its own length outside the circumference to determine the wall thickness.

Finally let it be noted that the wall thickness falls comfortably within the range conventionally used for ordinary fortified walls of this period.

Figure 9.5 Bothwell Castle South East Tower. 15th century. Schematic plan



9.4 MILITARY AND DOMESTIC, ROUND INSIDE AND OUT

9.4.1 *Borthwick Gatehouse Tower*

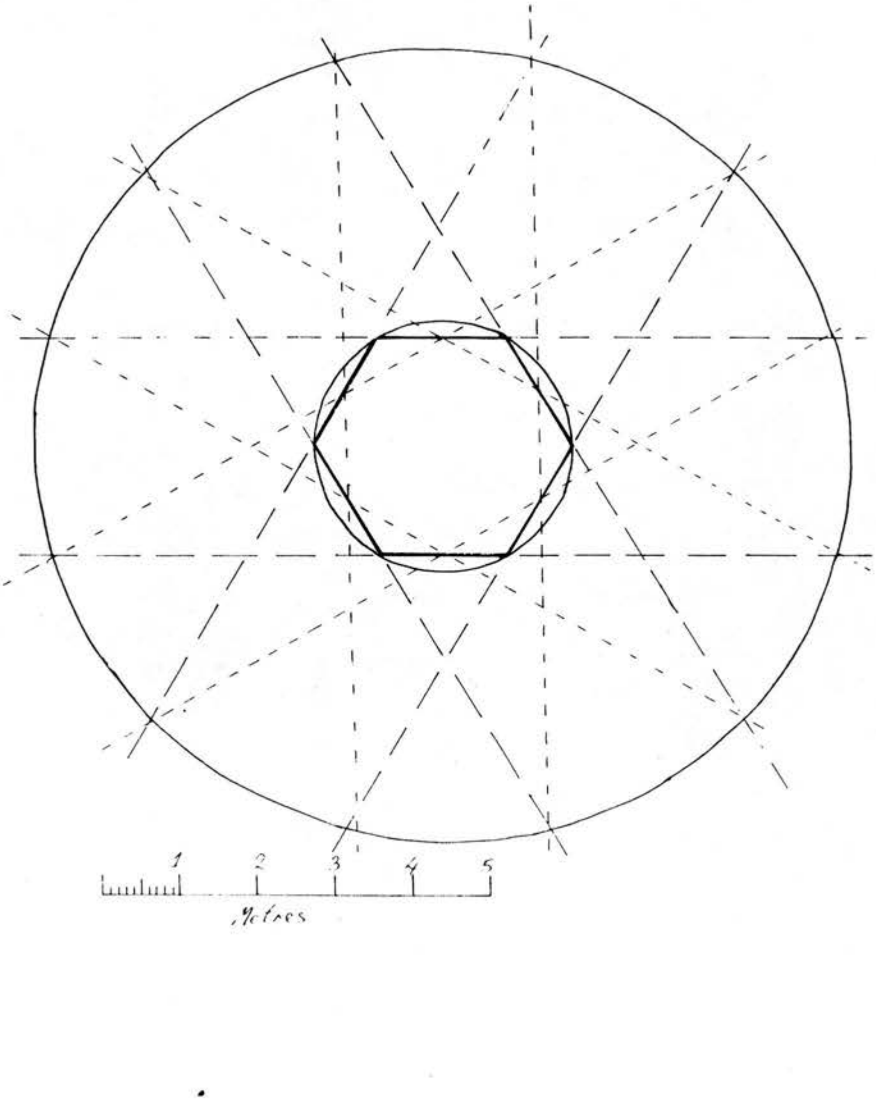
The scale and quality of the tower house of Borthwick Castle itself has always attracted more attention than the round tower by the entrance through its barmkin wall. Little of the latter survives, most of the present wall being of the late nineteenth century as is the upper section of the round tower. However, its base is original and possibly dates to sometime in the sixteenth century, having wide-mouthed gun loops typical of that time. In common with the latter, its walls are massively thick, at 3.66 metres, almost as much as those of the tower house. The overall diameter is 10.67 metres leaving only 3.35 metres internally. How were these derived? Here for the first time we confront a structure that is round both inside and outside (though of course this is not the earliest structure in Scotland to be so). Is there any element of constructive geometry? There are no convenient polygons here whose sides can be extended, but only circles.

With circles the only simple geometry that springs to mind is the use of π and herein it seems lies an answer. The internal diameter 3.35 metres is multiplied by π to find the approximate internal circumference, 10.52 metres. There is nothing extraordinary or helpful about that on its own, but for the fact that the overall diameter is 10.67 metres, a mere 15 centimetres difference. Now it must be said here that this structure is extremely difficult to measure accurately and an error could push the diameter either way so this solution is proposed with that *caveat*. It does seem that there is a meaningful relationship between the inner and outer circles. Whether this was achieved by the use of π, or simply by more pegs and string is open to debate. The approximate value of π had certainly been known for centuries, possibly even millennia, and was certainly available to any master mason who had a reasonably good grounding in basic mathematics but then again, it is a very difficult calculation to make, with all those decimal points and no electronic calculator. There has to be a possibility that the discrepancy of about 15 centimetres was simply a fudge resulting from this.

Had the job been done with pegs and string, starting as usual with the inner diameter, the inner circumference would have to have been accurately measured. This is never an easy job as the measuring string or tape must be held taut against the inner surface of the circle, by which process there will be a natural tendency for it to flatten between points of support, creating a polygonal effect. Was there another way in which this structure was designed, that was simpler, more accurate and perhaps more in line with methods encountered previously?

The figures most readily formed from the construction of the initial, inner, circle are octagons and hexagons, particularly the latter since the points on the circumference are the same distance apart as the radius whose measure can therefore be used in one simple operation to create the new inner figure. The sides of this hexagon are extended, as in previous examples, and they intersect somewhere in the middle of the wall thickness. A smaller rotated hexagon is inscribed, whose vertices touch the sides of the first hexagon at their mid-points. The sides of this new figure are extended and they intersect with those of the first hexagon, interestingly, almost exactly on the line of the outer wall. Here is a possible alternative design methodology (Figure 9.6). Again we have no means of knowing just which of these methods might have been used. At this stage all that can be done is to identify the alternatives, although I would personally incline towards the latter method, as being proven in so many other cases, although this is obviously for a very different purpose - artillery defence. Did this new era of warfare have a bearing on fortification design methods? Is the geometric manipulation merely coincidental? A comforting crumb of evidence in support of its perpetuation comes from another quarter, from afar: the French were actively involved in experimenting with the design of both châteaux and curtain-walled castles in the fifteenth century that could be resistant to artillery. Their quest at first centred very much on round towers, a traditional approach and one which of course was echoed in Scotland most notably at Ravenscraig and St. Andrews' Castle. Borthwick's gate tower seems also to fit this category. One of the principal examples of this trend in France is the updated thirteenth century curtain-walled castle of Ham, Somme, of which the four corner towers boasted a massive 10.67 metres wall thickness. Interestingly, analysis shows that Ham has identical proportions of internal/external diameter as Borthwick, suggesting the same design method. Further comparisons with French and other European examples would be welcome but simply do not fall within the scope of this research.

Figure 9.6 Borthwick, Gatehouse round tower. Schematic plan



9.4.2 *Bothwell Prison Tower (thirteenth century)*

In the light of this notion, that the design of some structures which are completely circular may be based on polygonal forms, enquiry is extended to other similar towers in Scotland. A logical starting point are the remaining towers on the curtain wall at Bothwell and, in particular, the little prison tower next to the donjon, which were both built at roughly the same time.

The inscription of an octagon (the same figure used in the nearby contemporary donjon) into the inside perimeter of this space produces no answers at all. However, a hexagon produces more interesting results: the length of each side of this figure is equal to the distance from the mid-point of that side to the outside wall surface, giving a wall thickness of 1.4 metres. Interestingly this is less than the thickness of any contemporary curtain wall, and indicates an apparent idiosyncrasy in fortification design at that time, especially since the donjon walls were 4.6 metres thick.

9.4.3 *Bothwell Unbuilt Corner And Gatehouse Towers (thirteenth century)*

The question now arises whether the tower planned for the north-east corner of the enclosure might also follow the same pattern. Only the foundations were laid and taking dimensions from these does not inspire confidence, the wall thickness varying between 2.67 and 2.82 metres and the circle is not even complete, preventing an assessment of whether it is the inside or outside circle at fault.

An inscribed octagon has sides of only 2.2 metres and projection of that amount from anywhere along its sides is clearly insufficient for the wall thickness. However, if again a hexagon is inscribed, its side of 2.91 metres is much nearer the mark. But it does not actually hit the mark: the projected perpendicular from the mid-point of the hexagon's side is 3.1 metres when, if this system is to be used, it should be the same 2.91 metres as the side. There may be a reason for this: most bastion towers of this period are slightly splayed at the base. The difference of just 20 centimetres may be accounted for by this. Granted this is speculation, but it cannot be dismissed out of hand.

Similar problems of measurement are to be had with the towers of the gatehouse at Bothwell, but what analysis can be done indicates a strong possibility that the same hexagonal measuring device was used here also.

9.4.4 *Kildrummy Castle*

Following these findings at Bothwell, analysis of the principal structures at Kildrummy might be expected to tell a similar story. The so-called Snow Tower (the donjon), although round both inside and out, bears an implied internal hexagon whose sides of 3.97 metres compare with the 4.1 metres length of the perpendicular erected from the mid-point of one side. The north-east Warden's Tower also conforms to this pattern. Analysis of the Brux and Maule Towers is planned but, to date, insufficiently accurate dimensions are rendering this problematic. The rounded ends of their 'D-plan' have internal half hexagons or half octagons and it appears that the wall thickness may be similarly derived from the sides of these but this cannot be verified yet.

9.4.5 *Inverlochy*

The donjon tower here also could be said to bear an implied hexagon whose sides of 3.1 metres coincides with the wall thickness of this tower i.e. measured from the vertices of the hexagon rather than its sides or, in other words, the wall thickness is the same as the radius of the internal circle.

9.4.6 *Rait*

The round tower on the corner of this hall house also conforms to the hexagonal derivation, based on the perpendicular erected from the side of the hexagon.

9.4.7 *Orchardton*

The diminutive and unique mid-fifteenth century round tower house in Galloway presents some problems both in measurement and analysis: its vaulted ground floor is a somewhat irregular rectangle and each of the circular storeys above is progressively greater in diameter as the walls step back at each floor level. Above first floor level the timber floors have been lost so measurement and analysis of only this storey is possible. An inscribed hexagon brings no result at all. An octagon, however, looks more hopeful, the intersection of its extended sides, together with those of a further inscribed and rotated smaller octagon falling just ten centimetres short of the outer wall surface. This has to be a possibility, but no more than that. Regarded in circumspection, Orchardton looks in some ways very vernacular and, in the light of its dimensions, it must be acknowledged that constructive geometry might in some cases be applied only loosely or not at all. In other ways a quite sophisticated little structure with fine gothic arched sink in one wall, Orchardton will probably always leave students of Scottish architecture wondering.

9.4.8 *Conclusions*

It would seem that most surviving fortified and ecclesiastical centrally planned structures in Scotland from the thirteenth to the fifteenth centuries were derived by some geometrical means, and that they were based on *internal* dimensions. The basis of the hexagon especially was both simple and logical since the same measuring rod or tape with which the inner radius was laid out could then be used directly to mark out both the points of the hexagon, and the wall thickness, from either the vertices or the mid-points on the sides of that figure.

During the thirteenth century the latter was almost invariably employed for round towers, with a few exceptions. The result of this method was obviously wall thicknesses which were proportionately related to internal floor area, and independent of any other considerations. Whilst this left some structures relatively lightly protected, there was a certain logic in that the largest towers with the thickest walls were invariably the donjons which accommodated the owner and his family at times of extreme threat. At the other end of the scale, the least secure were those such as the prison tower at Bothwell, latrines or other less significant structures, although strangely gatehouses also were sometimes relatively thinly protected.

The consistent application of such a geometric approach has to be wondered at for its lack of logic in another respect. Granted, it assured the most important towers the maximum protection. But a curtain-walled castle really requires the same protection along *all* its perimeter - if one element, even an insignificant latrine tower, is breached, the whole edifice is in danger, if not as good as lost. In the light of this the question arises over the whole intention and purpose of thirteenth century castle builders: this was a peaceful and prosperous period with no threat of war, but also little experience of war, apart from any Scottish knights who had ventured out to the crusades. The round tower, the sloping talus and other new elements of military architecture were indeed learned from middle eastern experience, but was their re-interpretation in peaceful Scotland more a manifestation of fashion than fortification? Comparison with the latest structures appearing in Wales, particularly Beaumaris, Harlech, Caernarvon and Conway, at the hands of Edward I's professional military engineer Master James of St. George would be instructive. Certainly scale plans of these structures do not seem to respond to geometrical analysis in the same way. Perhaps their creator based his designs on a more rational foundation. Site measurement and closer analysis are really required, but that is beyond the scope of this thesis.

10 SMALL UNVAULTED CHURCHES

10.1 INTRODUCTION

Under examination in this section are several church types, but mainly small parish churches. What they all have in common is a simple barn-like structure, or conglomerate of more than one such structure, without any complications of nave arcades separating parallel aisles. Also they are all unvaulted, apart from the choirs of Dalmeny and Leuchars which have been included for reasons that will become clear in due course. Some are ruinous but many survive, mostly altered or extended, and in these cases can only be used in part for this survey. For instance, whilst the foundations of Tyninghame church survive, providing plan dimensions, the walls do not, and so any assessment of structure relating to height is impossible. The separate chancel of Kirkliston, if it ever existed, has disappeared in subsequent reconstruction, so its relationship to the nave is unknown. The dimensions of the nave on its own, however, are still of some use.

A total of 39 churches are included in this study but for analysis these have to be split down into the individual component 'units' of which they consist: separate chancels, choirs, naves, transepts, porches and aisles where these are independent structures set at right angles to the main body of the church. Transepts, it will be noted here and in later sections, present some problems in analysis since, for reasons of utility, they do not require to be as wide as the main body of the church, but for the sake of structural and often it seems aesthetic continuity, their height is often based on that of the main body. It is appropriate to analyse such parts of a church together, but in other instances where there is no such connection, separate examination is required. In all, the number of church 'units' included in this survey amounts to 53 and they are listed in figure 10.1.

The aim in this section is simply to find out if there was any identifiable common ground in the way or ways in which the medieval architect decided on wall thickness for the structure he was designing, whether this dimension was more dependent on the buildings' width (span ratio), or height (slenderness ratio), or some other influence, and particularly whether there was any geometric basis for such relationships. What complicates the issues, particularly in the middle chronological periods, is the use of buttresses, and also the proportion of wall structure voided by fenestration.

Figure 10.1
UNVAULTED CHURCHES
SURVEY SAMPLE

Norman 12th Century

1	Aberdour	chancel
2		nave
3	Dalmeny	apse
4		chancel
5		nave
6	Duddingston	chancel
7		nave
8	Gullane	chancel
9		nave
10	Inchcolm	nave
11	Kirkliston	nave
12	Leuchars	apse
13		chancel
14	Monymusk	chancel
15		nave
16	Ratho	chancel
17		nave
18	Rosyth	chancel
19	St. Rule's	nave
20	Stobo	chancel
21		nave
22	Tyninghame	apse
23		chancel
24		nave
25	Uphall	chancel
26		nave

Gothic 13th/14th Century

1	Abdie	nave/chancel
2		porch
3	Burntisland	chancel
4		nave
5	Carnock	nave/chancel
6	Cockpen	nave/chancel
7	Crossraguel	nave
8	Culross	nave (lay bros. choir)
9	Dalgety	nave/chancel
10	Dunblane	choir
11	Dunkeld	choir
12	Dunnottar	nave/chancel
13	Keith Marischall	nave/chancel
14	Ormiston	chancel
15	Peebles	nave
16	Temple	nave/chancel

Late Gothic 14th/15th Century

1	Crossraguel	choir
2	S. Queensferry	transept
3	Whitekirk	nave

Transitional 15th/16th Century

1	Aberdeen, King's	coll.
2	Biggar	choir/nave
3		transept
4	Pencaitland	nave/chancel
5	Stenton	chancel

Post Reformation 1560-1700

1	Abdie	aisle
2	Dirleton	nave
3	Gladsmuir	nave
4		aisle
5	Glencorse	nave
6	Pencaitland	ailse
7	Kemback	nave

10.2 A GENERAL STATISTICAL APPROACH

Initially a general idea of the answers was sought by a statistical approach, and various graphical and statistical methods follow which should theoretically throw up an overview, if not some specific answers. The problem with any attempt to achieve a generalised view is that there are so many variables - span, height, and wall thickness, in some cases complicated by buttresses - which may be at work against one another to varying degrees in each building. To set the scene, figures 10.2 and 10.3 show cluster charts of wall thickness against on the one hand span, on the other height. The former shows that as span is increased, very generally, wall thickness is also increased. The latter shows that wall thickness responds similarly to height. It also shows that generally there is slightly wider spread amongst the sample in height than there is in span. The bulk of the examples in the span chart show a relatively constant wall thickness in the range of spans between 4 and 7 metres, whereas in the height chart most fall within a slightly wider range from around 3 to 7½ metres. There is actually very little difference but the obvious implication of this is that wall thickness was more dependent on span than height. The span cluster is undoubtedly more tidy and compact than that on the height chart.

Fig. 10.2 Unvaulted Churches - Span:Wall Thickness

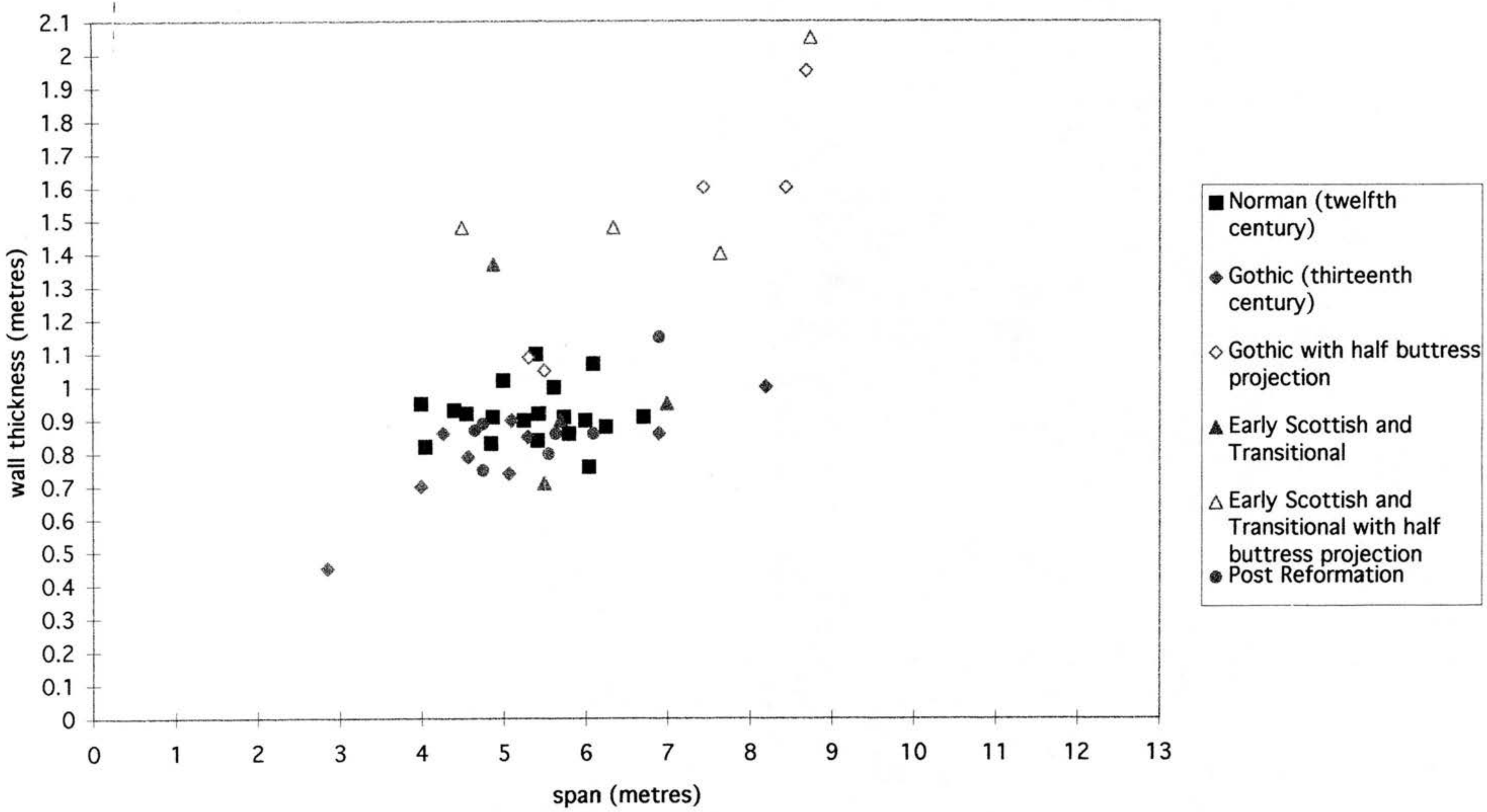
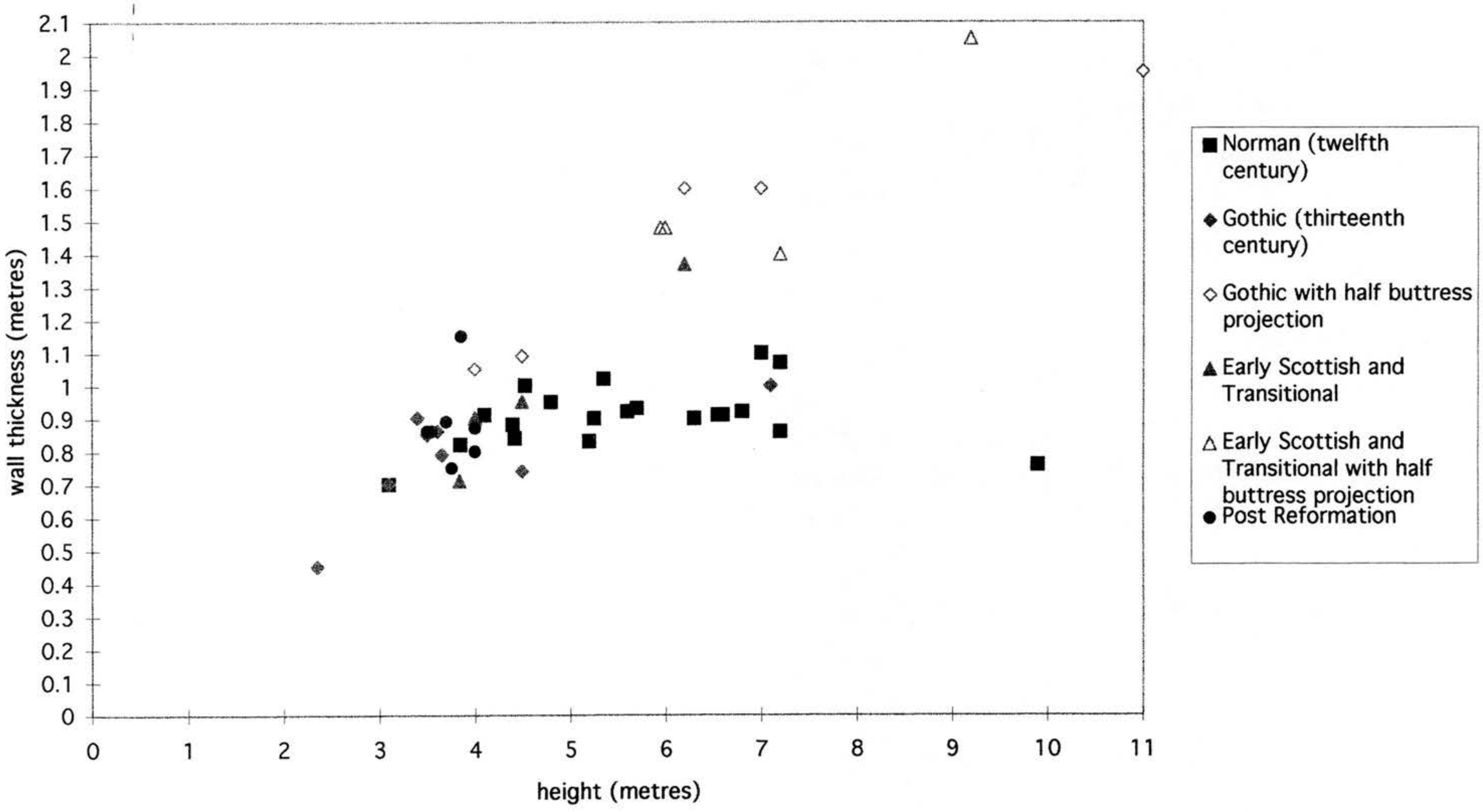


Fig. 10.3 Unvaulted Churches - Height:Wall Thickness



The upshot of this is, of course, that larger churches which generally have thicker walls are commonly both higher and wider than smaller churches, but a few tend to be disproportionately higher. The situation is complicated because their span to height ratio relationship changes over time. Figure 10.4 shows a breakdown of the span: height ratio for each church unit in each of the periods. It should be noted that examples up to the ratio 1: 0.9 are wider internally than their height to side wall-head. Those over 1: 1 are higher than their width.

Figure 10.4 UNVAULTED CHURCHES:- SPAN : HEIGHT RATIO

Ratio 1:	12th Cent. Norman	13th Cent. Gothic	Early Scottish	Transitional	Post-Reformation
0.1					
0.2					
0.3					
0.4					
0.5					
0.6	N		N		1 1 A
0.7	1 1	1 1		1	1
0.8	Q Q N	Q P 1 1 N	1		1 A
0.9	Q	1	Q 1	Q N	A
1	N N N			1	
1.1	Q N N N				
1.2	Q Q N N C				
1.3	Q Q N	Q	T	T	
1.4					
1.5	C	Q			
1.6	N				

N	nave
Q	choir/chancel
C	apsidal chancel
1	combined nave/choir/chancel in one unit
A	aisle
T	transept (these are invariably higher than their width, since their height is dictated by the rest of the church but their function does not require the same width as the nave or choir)
P	porch

The situation shown here is actually quite straightforward: whilst there are plenty of exceptions, churches in the Norman period tended to be higher to the side wall-head than their internal width. Thereafter the reverse is true. The two exceptions in the Gothic period (shown as 'Q') are the choirs of Dunkeld and Dunblane Cathedrals, and the latter may well have been built much taller than originally intended (VII Fawcett, 1979:50). In any event they are taller because, structurally, they are subsidiary units of larger, wider parent buildings, to whose height they must relate or conform. In the same way the transepts of South Queensferry and Biggar (shown as 'T' in the Early Scottish and Transitional periods respectively) are disproportionately tall because, as mentioned earlier, their use requires relatively little space but aesthetic or whatever other conventions dictate that their height should attempt to follow that of the main body.

Two other generalised representations follow: figures 10.5 and 10.6 show summaries of span ratio and slenderness ratio in each period. Attention is drawn to the diagrams' key which explains the inclusion of ratios of buttressed churches based on the wall thickness alone (bold & underlined), the same units shown with wall thickness *half* the buttress projection (b), and then again with full projection (B). Again, that which relates to height shows marginally greater variation but generally both charts are remarkable for the lack of clustering round any particular ratio and the evenness of their spread. Slenderness ratio in church building diminishes from the Gothic period onwards, principally because churches are built with lower walls than previously, but average wall thickness generally remains relatively constant. The spread of span ratio on the other hand remains remarkably constant for centuries, because, in contrast to height, the range of widths of churches remains very much the same and, as mentioned, so also does wall thickness, for the small church category at least.

Figure 10.5 UNVAULTED CHURCHES: SPAN RATIO SUMMARY

Span Ratio 1:	12th Cent. Norman	13/14th Cent. Gothic	Early Scottish	Transitional	Post-Ref
2.2				B	
2.3					
2.4					
2.5					
2.6					
2.7					
2.8				B	
2.9					
3					
3.1				B b	
3.2					
3.3		B			
3.4					
3.5	C				
3.6			T		
3.7					
3.8	C				
3.9		B B		b	
4					
4.1				b	
4.2	Q	B	B		
4.3					
4.4		B b			
4.5		1			
4.6	B				
4.7	Q	b			
4.8					
4.9	Q Q N	b B			
5	N	1		**T**	
5.1					
5.2		b b			
5.3	Q				A A
5.4	B	N			
5.5			b		
5.6	N				
5.7	N	Q 1 **N**			1
5.8	N **Q**	**1**			
5.9					
6	N N			**1**	1
6.1					
6.2		1			
6.3		P		1	
6.4	Q N				
6.5		**1 1**			A
6.6	1				
6.7	**N**				
6.8	N				
6.9		1		**Q/N**	1
7		**Q**			
7.1	N				1
7.2					
7.3	N	**Q**			
7.4			N		
7.5					
7.6			**Q**		
7.7				1	
7.8					
7.9					
8	N	N			
8.1					
8.2		N			

1	Church of nave & chancel/choir in single unit.
N	Nave (to which separate chancel/choir attached).
Q	Choir/chancel (to which separate nave attached).
C	Separate apsidal chancel (Norman only).
T	Transept.
A	Aisle, set at right angles to nave.
P	Porch.

Any of the above **emboldened** and underlined indicates that feature buttressed, but assessed on wall thickness alone.

B	The same assessed on wall thickness plus entire buttress projection.
b	As above, but with *half* buttress projection. (Not shown where only pilaster buttresses)

Figure 10.6 UNVAULTED CHURCHES: SLENDERNESS RATIO SUMMARY (Key as for fig.10.5)

Ratio 1:	12th Cent. Norman	13/14th Cent. Gothic	Early Scottish	Transitional	Post-Ref
3				B B	
3.1					
3.2		B		B	
3.3		B B			1
3.4					
3.5		1			
3.6					
3.7					
3.8		b 1			
3.9		b			
4		B	B	b	
4.1		B b 1		b	A A 1
4.2		1			
4.3				b	
4.4	1	Q		1	
4.5	Q N		T		
4.6	N	1			A
4.7	C Q	1	N		
4.8		N			
4.9	B				
5					1 1
5.1			b		
5.2		P			
5.3	Q Q				
5.4	C			1	
5.5		1			
5.6	B	b			
5.7	N				
5.8	N				
5.9					
6					
6.1					
6.2	Q	1			
6.3	Q	B		1	
6.4	Q			Q/N	
6.5					
6.6	Q			T	
6.7					
6.8					
6.9					
7	N N				
7.1		N			
7.2	N		Q		
7.3	N				
7.4					
7.5	N				
7.6					
7.7		b			
7.8					
7.9					
8					
8.1					
8.2					
8.3					
8.4	N				
8.5					
8.6					
8.7		N			
8.8					
8.9		Q			
9					
↕					
10.9		Q			
↕					
13	N				

Some of these generalisations really require to be quantified more specifically. Variations in wall thickness range from around 70 centimetres to about 1.1 metres, the vast majority falling within the 80 - 95 centimetre range, a difference of a mere 15 centimetres or 6 inches. It should perhaps be stressed here that in all the following deliberations on the derivation of wall thickness, it is a really very small variation that is being scrutinized. As for span, no part of a church, other than a porch, is less than 4 metres wide. Only a few, usually the higher quality parish, collegiate or abbey churches are more than 6.1 metres, or 20 feet, a difference of 2.1 metres or 7 feet. This contrasts with height, where the majority are spread between 3.4 and 6.4 metres, a much wider variation of about 3 metres or 10 feet. In percentage terms, all this can be summarized as follows:

Variation on average: wall thickness : 16.7%
span : 42%
height : 61%

Bearing in mind the relatively limited wall thickness variation over the whole period, here again is evidence that it was based principally on span - the other less variable factor - and responded proportionately less to changes in height. This would certainly be supported by the instructions of Lorenz Lechler to his son in 1516 when he set out the recommended wall thickness for a given span, although he was of course referring to vaulted churches (Appendix I Section 5). Whilst the graphs and charts amply reveal this to be a general statistical trend, they do not demonstrate that such a conclusion is actually applicable in each case. More specific evidence is necessary. Various ways of relating three variables, height, span and wall thickness were actually worked out in the nineteenth century by Jean Rondelet, and these simple building types are ideal for testing out Rondelet's formulae. They have been described in Appendix 1 and, in order to provide appropriate data for analysis, they needed to be slightly adapted. The first method applicable to the church situation was actually developed in connection with domestic houses one room deep with simple pitched roofs (Appendix 1, Section 2.1.2). Half the height to side wall-head was added to the span and the sum was then divided by the span dimension. Extra thickness could be added for extra stability, as required. This was a method to actually derive wall thickness from a combination of height and span and, according to Rondelet, it was found to be applicable in a considerable number of cases. In order to see the extent to which such a method might have applied to Scottish churches, the span and half height are added, as before, but then rather than dividing by span again to achieve a prescription for wall thickness, the sum of span and half height are divided by the wall thickness to find a coefficient figure. The amount by which this figure varies is thus an indication of the extent to which wall thickness conforms to such a 'system' of calculation.

If this process is applied to all the church units surveyed, the results are slightly different from those of slenderness ratio, and may be more useful. Figure 10.7 shows the range of coefficients which are just as widespread as in the previous figures. The fact that they may appear visually to be more tightly clustered than in figures 10.5 & 10.6 is due to the ratios having to be consolidated to even numbers only in order to fit them all on to the page. If wall thickness was consistently calculated by the architects of these churches from both height and span, it does not seem likely that this method was generally used.

Figure 10.7 UNVAULTED CHURCHES: RONDELET'S SPAN + HALF HEIGHT + WALL THICKNESS METHOD

(Appendix I Section 2.1.2)

Ratio up to:	12th Cent. Norman	13/14th Cent. Gothic	Early Scottish	Transitional	Post-Ref
3.6				B	
3.8					
4					
4.2				B	
4.4					
4.6					
4.8				B	
5					
5.2				b	
5.4	Q				
5.6		BBB		b	
5.8			T		
6		B			
6.2			B	b	
6.4					
6.6		b			
6.8		B			
7	QN	b			
7.2		1 b b			
7.4					A
7.6	Q	1			A
7.8	N	B			1
8	QQQNN	Q	b		
8.2		**N** **1**			
8.4		1		**T**	
8.6				1	A
8.8	Q	**1**			1
9	QQ	P			
9.2	N			**1**	1
9.4	N	**1**			1
9.6		b			
9.8	N		N		
10	N				
10.2	N			**Q/N**	
10.4		1			
10.6				1	
10.8					
11	N	**Q**			
11.2			**Q**		
11.4					
11.6					
11.8		1	1		
12					
12.2					
12.4		1			
12.6					
12.8		**Q**			
13					
13.2					
13.4					
13.6					
13.8					
14					
14.2					
14.4					
14.6	N				

1	Church of nave & chancel/choir in single unit.
N	Nave (to which separate chancel/choir attached).
Q	Choir/chancel (to which separate nave attached).
C	Separate apsidal chancel (Norman only).
T	Transept.
A	Aisle, set at right angles to nave.
P	Porch.

Any of the above **emboldened** and underlined indicates that feature buttressed, but assessed on wall thickness alone.

B	The same assessed on wall thickness plus entire buttress projection.
b	As above, but with *half* buttress projection. (Not shown where only pilaster buttresses)

Rondelet's other method was applicable to buildings where the roof structure provided some stiffening quality to the walls. Few Scottish roofs such as that shown in figure 10.8 survive from as early as the sixteenth century. They generally consisted of little more than couples of rafters joined at the ridge, and by a horizontal tie-beam, all jointed using pegs which have been commonly found to be a point of weakness: Ruddock found at 339-343 High Street, Kirkcaldy that the pegs had sheared and that this was "likely to have occurred soon after construction" (VII 1995: 304), as a result of which the wall, far from being stiffened by the roof, was actually bowed out by it. Similar distortion was found while surveying at a number of sites, particularly at Abdie Church, Pencaitland Church, both having later additional abutment, Whitekirk Church and James IV's great hall at Stirling castle. In spite of all this experimentation with Rondelet's method may not be inappropriate since the roof structures were obviously intended to be at least inherently self-supporting.

Rondelet's formula could be arithmetically calculated but it is unlikely that such complexities would have been unnecessarily engaged in by medieval architects. However, there was a simpler geometric method involving the erection of a diagonal in the section of a building, which could have been done in diagrammatic form on paper, or on the ground or a tracing floor, and this would have been within the capabilities of most masons. For analysis purposes, instead of extending the diagonal beyond the wall-head by a certain proportion of the height as Rondelet prescribes, it is necessary simply to measure the length of this extension as it is defined by the wall thickness of the church. The wall height is then divided by this dimension to find the coefficient for that church unit. The results are charted in figure 10.9 and, as can be seen, the range of coefficients is considerably reduced and there is even some 'clustering'. However, whilst this method does seem to be a more useful measurement tool for the job, it is still imprecise and only explains a vague range within which wall thicknesses fall, given the span and height. It does not tell us precisely which of these two were more influential over the wall thickness dimension.

Figure 10.8 Typical Scottish roof structure at the former Tithebarn, Whitekirk.

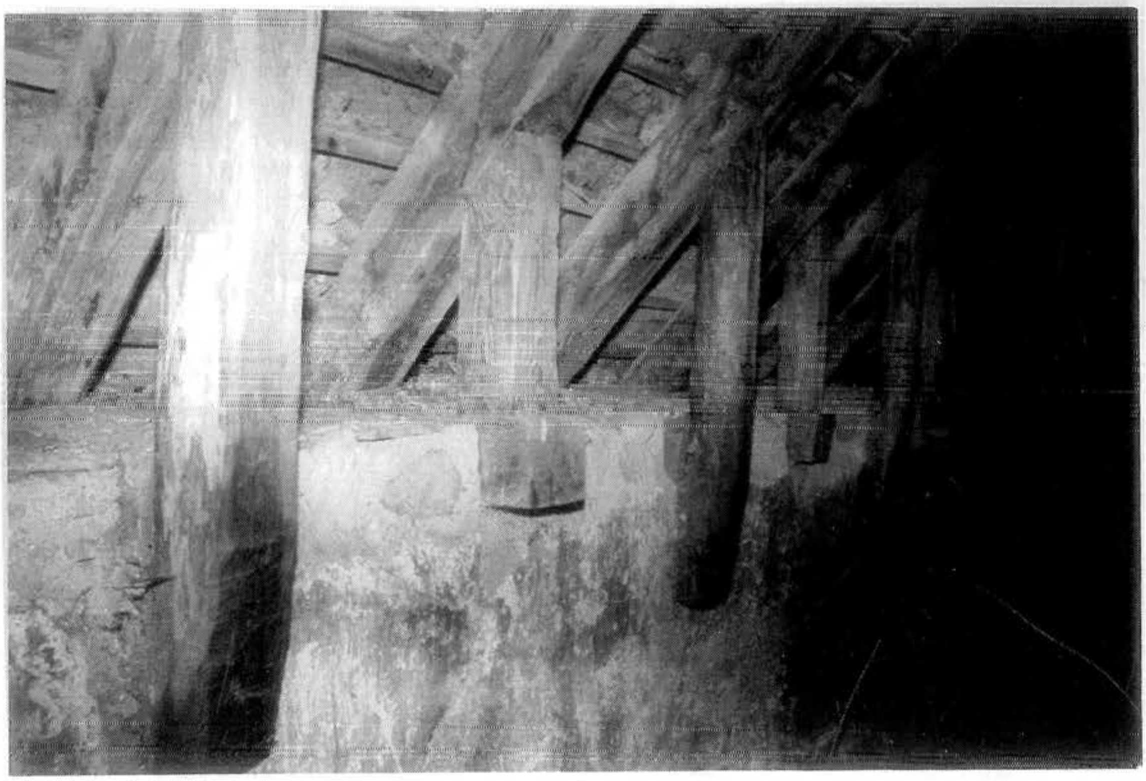


Figure 10.9 UNVAULTED CHURCHES: RONDELET'S DIAGONAL METHOD
(Appendix I Section 2.1.3)

Ratio	12th Cent. Norman	13/14th Cent. Gothic	Early Scottish	Transitional	Post-Ref
1.7					
1.8				B	
1.9				B	
2					
2.1					
2.2				B	
2.3					
2.4				b	
2.5		B B B			
2.6		B			
2.7					
2.8				b	
2.9		B	T B		
3		b b		b	1
3.1		1 1 b			
3.2					A
3.3	Q				A
3.4	Q	1			
3.5	Q	N **1** b Q			1 A
3.6	Q N N	**N**		1	
3.7		B			
3.8		**1**	b		1
3.9	N	P			
4	Q Q			**T**	1
4.1	Q	**1**	N		
4.2	N Q				
4.3				1	
4.4				**1**	
4.5	N	1			
4.6		b			
4.7	N				
4.8	N				
4.9	N			**Q/N**	
5	N				
5.1			**Q**		
5.2					
5.3	N				
5.4		**Q**			
5.5		1			
5.6					
5.7					
5.8					
5.9		N			
6					
6.1		**Q**			
6.2	N				

1	Church of nave & chancel/choir in single unit.
N	Nave (to which separate chancel/choir attached).
Q	Choir/chancel (to which separate nave attached).
C	Separate apsidal chancel (Norman only).
T	Transept.
A	Aisle, set at right angles to nave.
P	Porch.

Any of the above **emboldened** and underlined indicates that feature buttressed, but assessed on wall thickness alone.

B	The same assessed on wall thickness plus entire buttress projection.
b	As above, but with *half* buttress projection. (Not shown where only pilaster buttresses)

Where statistical generalities could not provide any firm answers, the only alternative appeared to be a building by building examination and comparison, and this is entirely consistent with the spirit of this research, much more so in fact than looking at generalised trends in the ways hitherto shown. The architect, after all, would have learnt lessons from his own previous designs as well as those of his peers, and would probably have made one-to-one comparisons when engaged in his latest commission. To follow such an approach to analysis will, it is hoped, be a step towards the initially

stated aim of getting into "the mind of the designer". For such an approach to produce meaningful results it was necessary to compare buildings that are roughly contemporary. Logically, therefore, examples in each period had first to be examined in relative isolation to discover whatever relationships there might be.
In the absence of any firm conclusions from the analysis carried out up to this point, this seemed to be a way forward.

10.3 ANGLO-SCOTTISH TO 1296

For the purposes of analysing this period, further notional subdivision is really necessary in order to highlight adequately the differences between the largely transitional Anglo-Saxon and Norman buildings of the twelfth century on the one hand, and on the other, the early gothic of mainly the thirteenth century.

In this group are fourteen loosely Norman style, and fourteen later Gothic churches (see figure 10.1), all built before the dilution of English influence from the beginning of the Wars of Independence. The Anglo-Saxon Transitional and Norman buildings, (to which I will henceforth refer simply as 'Norman' for the sake of convenience, since only St. Rule's fits the former category) are by far the most numerous generally over Scotland since they represent the initial church-building campaign when much of the structure of the present parish system was established under David I. They were characterised by separate structural units of nave and choir/chancel, whereas the later Gothic were more often of one single integrated unit. Unfortunately the majority of the Norman structures are now hardly recognizable as such, having been altered in various ways, extended or partly rebuilt. Nevertheless their basic dimensions usually remain.

10.3.1 *Overall Dimensions*

The Norman buildings all tend on average to be both slightly wider in the nave than later examples (average internal width 5.94 metres against the later 4.8 metres), but also proportionately much higher to the side wall-head (6.2 metres against only 3.7 metres). Most are slightly higher than their internal width, whilst the opposite is so for later examples. The average Norman wall thickness at 0.97 metres is greater than that of the smaller later churches at 0.81 metres, but their average slenderness ratio is much greater at 1: 6.5 compared with 1: 4.56. A comparison with that of curtain-walled castles here is interesting. Castle Sween, the only Norman style example whilst not the most slender structure at 1: 5, is certainly amongst those of higher ratio in the twelfth and thirteenth centuries.

The other comparison which is also significant is with St. Rule's Church nave. It is immediately obvious how the slenderness of St. Rule's, dating from sometime in the early twelfth century, compares at 1: 13. The preference for very thin walls in the Anglo-Saxon building tradition is already well known, but what is perhaps fascinating is the legacy of this tradition long into the Norman period, which is generally thought to have been characterized by ponderous volumes of masonry. The slenderness ratio chart (figure 10.6) illustrates the strength of this trend. Note that St. Rule's could not actually fit onto the page.

The thickness of most Norman church walls varies relatively little, most being between 80 and 110 centimetres and, within that range most being 3 standard English feet, or plus or minus some binary fraction thereof, that is 2¾ or 3¼ or 3½ feet. As for the concept of a *minimum* wall thickness beyond which masons would not venture for a given structure, it would seem, logically enough, that this depended very much on the overall size of the church. Around 0.8 metres was the average minimum wall thickness for most church building, but only 0.7 metres (c.2¼ feet) was used at the diminutive Rosyth Church. These figures compare with the minimum found for free-standing walls. for very small structures such as the porch of Abdie Church, Fife, as little as 0.45 metres (c.1½ feet) sufficed. This of course should be seen in the context of its height: its slenderness ratio of 1: 5.2 is very comparable with the average, but then so is its span ratio of 1: 6.3. We come back to the same problem. Before we examine and compare the buildings individually, let us examine more closely how the ground plan of these early churches was worked out.

10.3.2 *Geometric planning*

Analysis of the smaller Norman churches in Scotland was a highly complicated process and, although several possible approaches to structural design have been identified, it must be stressed that without some form of documentary supporting evidence (which is highly unlikely to ever be found) these will have to be regarded as a range of possibilities, maybe even probabilities, but there are very few certainties.

The churches surveyed are in some cases problematic in that they have not survived complete, but some as ruins, some heavily altered. With the single exception of Rosyth, the examples listed are, or were, all of the type with separate nave and chancel, the latter narrower and often slightly lower than the nave, and separated from it by a chancel arch. Even Rosyth may have been of this type: only the chancel now survives, the original nave having probably been wider than the present one which has been built later to conform with the chancel width. In the cases of Dalmeny, Leuchars and Tyninghame there is also a semi-circular apse at the east end. This feature may also have been present in others where the east end has been lost, such as Gullane and Kirkliston. We may never know. Some had towers. None of these survive in their original form and, in any case, these will be dealt with separately later.

It is generally accepted that the building of most churches began at the east end, and it seems logical for the moment also to assume that it was with the chancel that the design process also began. On the basis that, amongst others, Lorenz Lechler specifically commenced his design process with the internal width of the eastern arm (quoted in II Shelby & Mark 1979: 117), it seemed logical for the purposes of analysis to follow that method. In most of the Norman examples it immediately became obvious that the internal figure of the chancel or choir is actually a square, or almost a square, not including the chancel arch. There are three exceptions to this: Stobo and Aberdour which are not squares, but aurons, that is golden section rectangles of 1:1.618, incorporating *part* of the chancel arch. Dalmeny chancel does not measure an exact square internally. However, on closer examination a true square is formed externally by the outer wall surfaces, the whole of the arch to the apse, and encroachment to a line half way through the chancel arch, the nave being measured up to the same line. Dalmeny will be the subject of further scrutiny later.

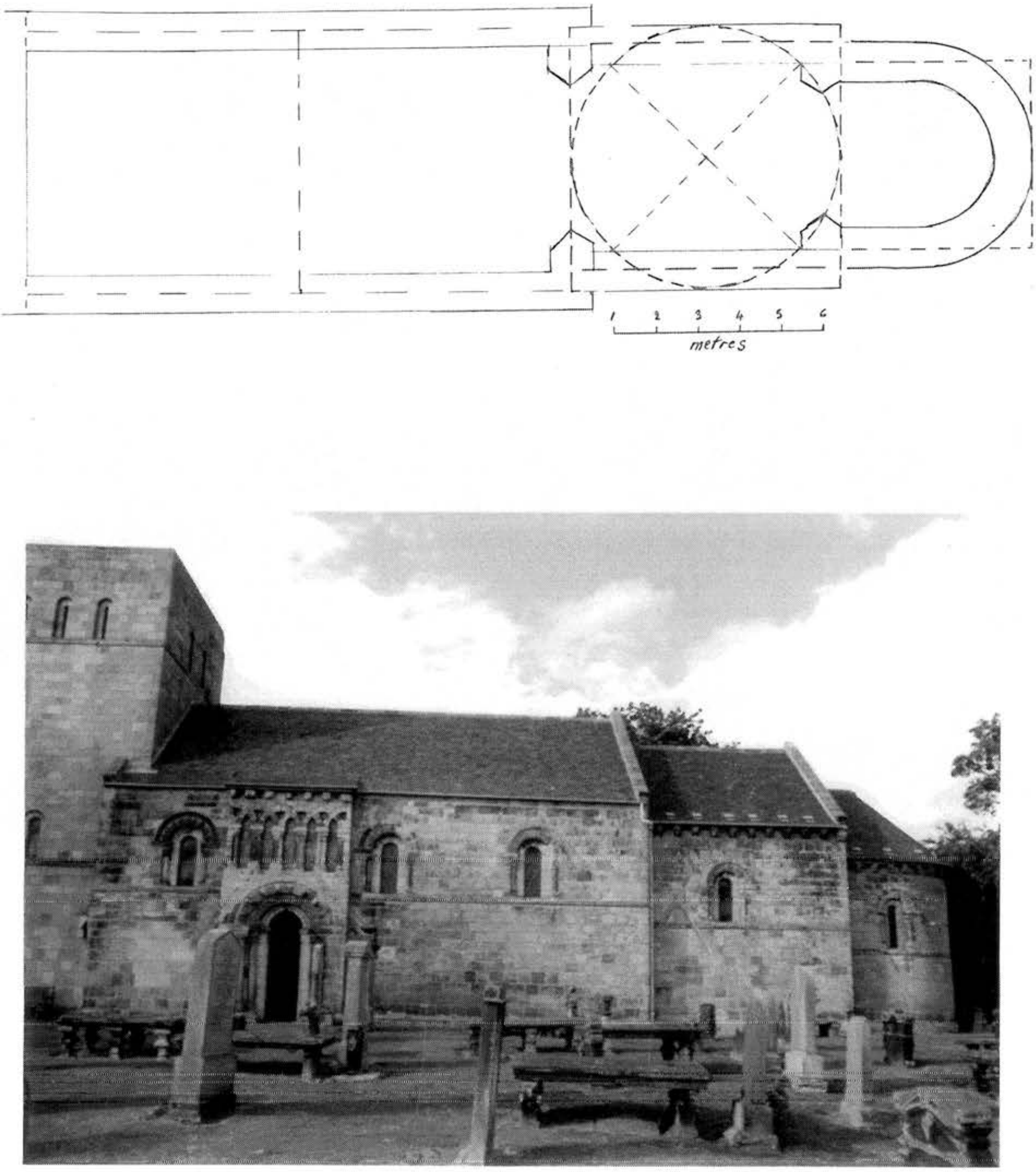
The wall thickness of most examples also appears to begin with the chancel. It seems in many cases to be loosely defined by rotation of the internal square of this structural unit or, in the cases of Stobo and Aberdour, the internal core square from which the aurons are derived. The internal width therefore relates to the external in the $1:\sqrt{2}$ proportion to within about two inches accuracy. The wall thickness actually used seems nearly always to have been a rounding to the nearest binary fraction of a foot, with the result that most are $2\frac{3}{4}$, 3 or 3 ¼ feet. The possible reasons for this will be discussed shortly. Rotation in this manner is probably used at Leuchars, Dalmeny, Duddingston, Stobo, Aberdour and Monymusk to within 3 centimetres, and these appear on the span ratio chart as between 1: 4.6 and 1: 5. It may well have been used at Tyninghame and Gullane, although precise measurement here was difficult. Only at Ratho and Uphall can it be categorically ruled out and we will return to these later.

So much for the chancel; what about the nave? How was this designed? Measurement of the internal proportions of most naves revealed almost no regular geometric figures at all. There are no double or treble squares or even binary fractions of squares, only near squares. The problem caused considerable disillusionment until it was realised how the nave and chancel proportions relate. Having defined the lines of the outer walls of the chancel by rotation, it appears that these lines were then simply extended westwards to form the basis of the geometric figure of the nave, somewhere within its wall thickness. Thus the whole church plan became a series of identical squares arranged in line and the identification of the number of whole and in some cases part squares becomes obvious.

That is all fairly straightforward, but it still does not answer the question: how was the wall thickness of the nave determined? As mentioned earlier, nave walls are almost invariably a little thicker than those of the chancel, and logic perhaps dictates that this should be so, considering that the nave is always a little wider and higher than the chancel. There are a few cases where an obvious possible solution presented itself, and these will be discussed first. Uphall was one of the exceptional churches where rotation had obviously not been used to determine wall thickness of the chancel. Instead, perhaps rather oddly, it has been used for the nave. This suggests that the nave might even have been designed first, though that cannot be proved. We shall return to Uphall again in another context.

Dalmeny is also exceptional in this respect: the walls of all three surviving parts of the building are of about the same thickness, three feet, which is unusual; in most churches the chancel walls are a little thinner than those of the nave. The most likely reason for this deviation is that the chancel and choir are both vaulted, requiring some extra support. This has given rise to the walls of the three separate elements of Dalmeny being arranged in a sort of telescopic manner (figure 10.10): the outer wall surface of the apsidal chancel is extended westwards to become the mid-wall axis of the choir, which is extended in turn to become the inner wall surface of the nave. Also the outer wall surface of the choir in turn becomes the mid-wall axis of the nave. The wall thicknesses are all fixed by their inter-relationship.

Figure 10.10 Dalmeny Church, West Lothian. 12th cent. Schematic Plan and Elevation



Apart from these it is very difficult to see evidence in any other churches of either the nave wall thickness itself, or of the siting of the inner and outer wall surfaces, being fixed by any obvious factor. There are a few rather vague connections or possibly just coincidences: at Stobo, as mentioned, the chancel interior is a golden section rectangle. It happens that the external length of this part, 8.55 metres, multiplied by 1.618 gives the external nave length. The external width of the nave, 7.62 metres, multiplied by 1.618 gives the nave internal length to the mid-chancel arch. Now this relationship only fixes the nave outer wall surface and as far as can be seen, there is nothing to fix the inner surface, so it amounts to little more than a mildly interesting observation, with no implication for the nave wall thickness itself. Similarly there is a root-2 relationship between nave external width and dimensions of the tower at Tyninghame and Monymusk but they are not significant for defining wall thickness. Geometric means appear to have been exhausted.

On reviewing the wall thickness of this whole group of churches three facts immediately present themselves: that in every case apart from Dalmeny and possibly Ratho, the thickness of the nave wall is slightly greater than that of the chancel; also that they are all, chancel and nave walls, between around $2\frac{3}{4}$ and $3\frac{1}{2}$ feet thick; and finally that nearly all of them are either three feet exactly or fall into one or other binary fraction either side of three feet. This would seem to indicate that the architects, whilst generally conforming to these round amounts, only made a nominal, rather than a more scientifically calculated distinction between the nave and chancel, and it usually amounted to about three inches. It would be nice to think that the different wall thicknesses chosen, and the difference between the height and/or width of the nave and chancel walls was of some consistent proportional relationship. Tidy patterns along these lines, however, are found wanting. Reference to the slenderness ratio graph (figure 10.3) emphasises how randomly wall thickness was chosen for a great variety of heights in the Norman period, invariably centring round the apparently convenient 3 feet mark. The exact wall thickness chosen in each case was, it seems, the individual choice of individual architects. All that can be said at a general level is that just as the ratio of height to span in any one church is merely *similar* in both nave and chancel, a difference in wall thickness was deemed appropriate in order that the slenderness and span ratios be kept *similar* also, but nothing more. Problematic calculation was avoided by simply making the difference a convenient three inches. This was found to be so in all cases where dimensions were known except Dalmeny (all walls 3 feet) and Monymusk, where the difference between choir and nave wall thickness was 6 inches.

10.3.3 *A Metrological Approach*

Perhaps a note should be added here about the apparent popularity of the three foot dimension of wall thickness. To be precise this is *around* three feet to within about two inches accuracy. There can be little in the way of explanation for this: whilst common, it was certainly not universally adhered to. Indeed it is only around this size of building (of around 20 feet span) that it seems to have been so popular. Perhaps it was a convenient and popular standard from which to work, in a similar way to the popularity of twenty units for other purposes. The origin of the yard as we know it is lost in the mists of time, the earliest recorded reference to it being by William of Malmesbury (1093-c.1143) (IX Connor, 1987:83) implying that it was in regular commercial use by then at least. It should not by any means be assumed that the three foot wall was some sort of common standard similarly inherited from previous generations. Anglo-Saxon building was often characterised by remarkable slenderness and walls of only two feet were not uncommon (I Fisher, 1969: 87-88). The lofty nave of St. Rule's Church is a mere two feet six inches thick. There may well have been some notion of three feet, or perhaps one ell, as a standard for wall thickness, just as it was for cloth measure originally, but in building it appears to have been a standard from which to work, by adding or subtracting ¼ feet as appropriate, rather than a standard of absolute authority.

In the light of all this, we must look again at Ratho, whose wall thickness was one of the few which were definitely not defined by rotation. Ratho's side wall height at 4.4 metres is relatively low, and they may of course have been higher originally, but the slenderness ratio is not so far off the average at 1: 5.3. Perhaps this is a case where the architect has taken a view that for such low walls there was no point in conforming to normal geometric derivation of wall thickness and instead opted for a solution based on relationship to height alone. Another instance of this is the diminutive and ruinous church of Rosyth. Little mention of this building has been made so far, the chancel alone surviving from the twelfth century, the rest being rebuilt in the later medieval period. Here the wall height is only 3.1 metres and rotation of the internal square would have given walls about 0.95 metres thick, resulting in an excessively cautious slenderness ratio of 1: 3.25. Around 1: 4.5 was the minimum found in churches of that period, and the chosen wall thickness of 0.7 metres (2¼ feet) gave a ratio that roughly conformed to that standard. It is perhaps worth recalling again that the ratio for Castle Sween, the only surviving free-standing wall of the twelfth century, was 1: 5, those of the thirteenth century averaged around 1: 4 and that the minimum wall thickness found in the ensuing period was also 0.7 metres.

It has been assumed until now that modern English units of measurement were commonly used in both overall and individual structural dimensions, but during the process of building measurement and analysis it began to appear that modern units, which theoretically have been used since at least Norman times, might not after all have been quite so universally employed. Of course many dimensions would not in any case be found in rational numbers of whole feet or in binary fractions thereof if they were all derived from the module of the internal chancel width in the ways previously described, the rotation of the chancel core square. The chancel width will have been the only predetermined dimension, everything else deriving from it in ways that do not result in whole rational numbers. But therein exactly lies an unexpected problem: not even the chancel width was found to be of a whole number of modern feet, except in two cases: Dalmeny at 15 feet, and Stobo at 16 feet. In the case of Monymusk, it is the nave that happened to be 20 feet wide, whilst at Duddingston there is an interesting phenomenon: the chancel is 16 feet, the nave 20 but the foot used is just slightly abnormal, being 303, rather than 305 millimetres. Here, the question must be asked, although masons may have conformed to official mensuration at least for wall thickness, were there variations on this? Application of all the hitherto known variants of foot possibly in use at that time - Roman, Northern/Drusian, Rhineland, etc. - all produce no convincing results at all, although it is acknowledged that Kidson found both the toise and Roman feet at Durham Cathedral of similar period (IX 1956: 67) and the builders of Durham were known to have moved on later into Scotland. Another approach to this apparent anomaly was to look for another variation on the standard foot. Assuming for a moment that the architect chose his overall dimensions in *whole* feet, we must determine what length of foot might 'fit' the overall building dimensions best. Firstly let us begin with a hypothetical but not uncharacteristic common building width for the period, given both the requirements of the buildings' utility, and the problems involved in economic roof construction. Many commentators have observed the frequency with which spans of 20 feet occur, well, *approximately* 20 feet to be precise. The popularity of twenty units in various other areas of mensuration has been highlighted by Connor (IX 1987: 43-44). The most commonly found width amongst the churches surveyed is c.5.4 metres, which is about 17$\frac{3}{4}$ modern feet - not a particularly obvious or convenient number for the medieval architect to have worked with. But suppose 5.4 metres was 20 feet, each of 271 millimetres, that is about

10.67 modern inches. This is not far off a man's size nine foot, which today is fairly common. Suddenly, where no tidy explanations seemed forthcoming a whole range open up: the chancels of Leuchars, Tyninghame, Ratho are all 20 such feet, Stobo 18, Aberdour 15. At Dalmeny, as noted, the starting point for the design was probably the choir mid-wall axis, which also formed the internal nave width and the apsidal chancel external width. This is also 20 feet of 271 millimetres. Perhaps this is an appropriate juncture to reiterate the fragment of what is thought to be King David I's Assize of Weights and Measures:

"The rude off lande in baronyis sal conten vj elne that is to say xviiij [18] fut off a mydlyn mane, the rude off the land in the burghe mesurit off a mydlyn mane sal be xx fut."

(X Acts of the Parliament of Scotland, I, 751: *Fragmenta... Collecta,* No.15.)

Whilst most of these churches today appear convincingly rural, they were of course originally built as burgh, or at least small town parish establishments, and hence may qualify for use of the 20 foot rood which formed the basis for the width of many building plots in the burghs of both Scotland and England. What is also significant about the wording of this assize is that the basis of the foot length implied little official uniformity. It must be recognised, however, that these rood measurements were principally for land survey. At least this is what has been thought until recently.

Now if the notion is correct that the medieval architect used an unofficial 'natural' or local foot for the overall dimensions of his plan design, or the initial chancel width at least, why would he then use 'official', (modern English) feet of 305 millimetres for the wall thicknesses? Until now it has been assumed that the dimensions approximating to 3 feet, and the binary fractions either side of it were standard modern feet. However, if slightly shorter feet were possibly being used for overall building dimensions, the same units might not unreasonably be expected throughout the rest of the building design, including wall thickness. However, finding a unit which fits all the key dimensions of a church unit was far from easy in most cases. Ratho was fairly straightforward. With a foot of 271mm. the choir span would be 20 feet and wall thickness 3 feet. In this case the latter was clearly not derived by rotation. The nave span is a round 23 such feet and its wall thickness 3 ¼ feet. At Leuchars the choir span is the same: 20 feet of 271mm. With a wall thickness of 3½ feet and 6 inches of attached colonnade. At Aberdour the chancel span is 15 feet of 271mm. And the wall thickness 3 of the same feet. These all seem clear enough. At some other churches such as Dalmeny and Stobo whole numbers of modern feet have been found in both overall and specific structural dimensions. However, at others such as Monymusk and Uphall no unit readily presents itself which provides a basis for both types of dimension. At such sites what appears to be a mixture is found: The larger overall dimensions being based on some unconventional or 'natural' foot, the smaller being of modern feet. At Monymusk, for instance, the chancel span is 15 feet of 293mm., the nave span is 21 of the same, while the wall thickness is 3 modern feet.

The idea of two separate systems of measurement in the same building seems absurd, at least to an observer today. How would it have been regarded then? The answers can only be guessed at and with some reference to what is known of later practice. The use of natural feet has already been noticed in some seventeenth century documentary sources. Their use is beyond doubt, but those sources do not make reference to the *simultaneous* employment of natural and also official 'English' feet. Perhaps some clue might be found in the sorts of tools that would have been employed by the architect, and here another look at the section on metrology (appendix II) is required. The measuring rod shown in the hands of Hugh Libergier on his tombstone is possibly of a toise (1.42 metres). Yardsticks and ellwands are mentioned occasionally and rigid measuring devices of this sort of length would have been useful for drawing out the patterns for individual features and moulds for the stone cutters, and measuring off smaller architectural elements such as stairs, doors, windows and perhaps also wall thickness. For most architects and master masons they would probably have been of high quality material, manufacture and calibration. They were highly prized tools of the profession whose status is attested by their appearance on tombstones. However, for the larger scale purposes of setting out the overall building dimensions, pegs and string, "pakthrede lyne" or ropes were probably used much as they are today, but calibrated with knots or some other tie. Whether the same string, so calibrated with feet or roods of 18 or 20 feet, that was used for land surveying purposes, was also used for the process of *measuring* out the church plan on the ground will probably never be known, but it has to be a possibility. There are also those documentary references to measuring poles, which would undoubtedly have been necessary for some vertical dimensions at least. The precise length of these is unclear but presumably the 'pole' or 'perch' of 16½ feet would be the longest that could be easily manhandled. Whilst such poles might well be useful for some aspects of the work, the flexibility and versatility of string, for both measuring and setting out at the same time, cannot be ignored. It is possible, of course, that there would have existed in any burgh or locality one or more such strings or tape calibrated with the feet and/or roods peculiar to that locality. If an architect had used the same string, based on a local version of the foot, for setting out the ground plan of the job in hand, but had reverted to his own personal yardstick of more official units for the items of smaller dimension (windows, doors, arcade mouldings, etc. and wall thickness) then we would expect to find the same variety of natural and official feet mixed in any one building, and indeed across a range of buildings. Alternatively he may, of course, have had a personal measuring string or tape based on his own foot for setting out. Either of these could have been the case at Leuchars, Dalmeny, Tyninghame, Stobo, Ratho and Aberdour which all share a module of 5.4 metres.

Reason suggests that where one architect has perhaps used his own or some local foot, there should be other variations elsewhere. At Monymusk in Aberdeenshire a foot of 293 millimetres may have been used. At Uphall in West Lothian where the nave, rather than the chancel, had been defined by rotation, a foot of 295 millimetres seems to have been used. This gives a nave width of 17 feet, and a mid-wall axis which becomes the chancel exterior width, of 20 feet. That is one possibility. However, if there is a danger that this subject can begin to appear all too easy to unravel, let us throw a few more wild cards onto the table! Another possibility at Uphall is that the internal nave width at 5 metres is a perch of 16½ modern feet and probably therefore measured by one of those "fir poles" described in building accounts. This is the only such case encountered. Interestingly, the most likely choice of foot for Gullane church is also 295 millimetres giving a chancel width of 16 feet. No other connection seems to be present, however, the nave wall thickness certainly not being defined by rotation. The module of 5.4 metres has been cited as the most common. However, Let us suppose for a moment that, instead of representing 20 feet of 271 millimetres each, it was a perch of 16½ feet, each of these feet being of 327 millimetres; or perhaps an 18 foot rood of 300 millimetres to the foot; or even an 18½ foot fall of 292 millimetres to the foot. Interestingly, if the latter were the case, and a similar foot was used in measuring out the chancel of Stobo, its width could be a Perch of 16½ feet, and so could that of Duddingston. It becomes evident that the possibilities, whilst not endless, are certainly numerous. The argument against the use of such land surveying units as architectural modules is simple, but at the same time unsafe. It is simply that widths were always quoted in building contracts in terms of feet, occasionally ells, but never roods or falls or perches, but this is unsafe because we do not have any contracts dating from this particular era.

The subject, then, is characterised by variety, but with plenty of features in common. We must conclude that, whilst the measurements of overall dimensions were not regarded as requiring adherence to any standardised system and were capable of being set out using a surveying tape or string calibrated with at least roods, at most whole feet, the thickness of walls was perceived to require greater accuracy and may therefore have been carried out with more finely calibrated yardsticks or rules, whose feet in some cases conformed to more universal or official standards. While a nominal attempt was made to size the walls in proportion to the size of the building they enclosed, this was most often done within the limitations of the binary fractions of a foot.

10.3.4 *Pilaster Buttresses*

It does not appear that the structural status, if any, of Norman pilaster buttresses has ever really been explained. There is only one instance of these in the survey sample, and indeed only one example where these are applied to a small church structure in Scotland: Duddingston. The chancel walls of this church are only about $2\frac{3}{4}$ feet thick and whilst that in itself is not unique (Aberdour and Ratho share this dimension) it is unusual, and, of greater significance, it is much thinner than the dimension that would have been defined by the rotation of the internal square, the method most commonly used to define wall thickness in other chancels of similar size. Indeed it is thinner by a full nine inches which, as it happens, is the same as the projection of the pilaster buttresses. Here, if it is needed, is evidence that these features were not merely elements of visual articulation or decoration, but genuine attempts to relieve the wall of some volume of masonry in a manner that is both calculated (by medieval standards) and aesthetically sophisticated. Indeed, there is a possibility that something even more significant has been revealed here. Perhaps the Norman pilaster buttress was not so much a reinforcement applied to a wall whose thickness was calculated by conventional means, but more a vestigial strip of a calculated wall thickness, the panels between which had been thinned to a more economical standard. This may be an indicator of a more widespread concept that permeated medieval and later thinking. Here it is appropriate also to recall the relatively high slenderness ratio of the curtain walls of Castle Sween in Argyll. If the pilaster buttresses here are taken to represent the actual wall thickness, then the resultant slenderness ratio of about 1: 4.5 is much more in line with other contemporary curtain walls. Alberti's concept of a colonnade was the vestigial remains of a wall that had been pierced through (X Book 1 Ch.10), an understanding that has been treated with respectful but patronising politeness by posterity. In the light of this, and of what has been found at Duddingston, the question has now to be asked, was Alberti alone in his understanding? Was he simply reflecting a commonly held conception throughout large parts of medieval Europe that the column and pilaster should be sized according to whatever formulae were generally used also for wall thickness, because in effect that is all that they constituted? Here may lie an issue of very considerable significance in the history of structural design generally, and also in our understanding of Alberti in relation to the building culture of his age. Time and space did not permit further investigation into this question, but the possible ramifications from following up such a line of enquiry may be far reaching.

Unfortunately there are relatively few examples in Scotland of pilaster buttresses, particularly on buildings where their structural function can be effectively assessed. To make these claims on the basis of Duddingston alone is dangerous, but it should invite further investigation into the many examples in England and western Europe generally.

10.3.5 *Geometric Planning and the Chancel Arch*

A word of explanation is required concerning the status of the thickness of the chancel arch in the geometrical planning process. This feature is nearly always solely encompassed within the larger square of the external dimensions of the chancel, while the easternmost 'square' of the nave adjoins, but does not overlap it. There are exceptions to this general rule. At Stobo the auron of the chancel overlaps about half the depth of the arch while the nave totally overlaps it. At Aberdour the auron similarly overlaps to about half the depth, but in this case the nave only overlaps up to the same line. At Ratho both chancel and nave totally overlap the arch so that its thickness is counted twice in the geometric planning of the church. This brings to mind Eric Fernie's analysis of St. Margaret's Chapel in Edinburgh Castle (VII 1986:400-3, 409 n.3. see Appendix I) where in the dimensional congruity of the entire composition, the chancel arch thickness has also to be counted twice. At Duddingston the chancel incorporates the whole arch, while the nave overlaps about one third of it. In all the others the arch is solely part of the chancel, with the notable exception of Dalmeny, and this church is worthy of further mention since it shows us just one case where the structure is of a more or less totally integrated geometric and dimensional system.

Several aspects of Dalmeny have been mentioned already, its 'telescopic' arrangement of nave, choir and chancel; its use of the 271 millimetre foot giving a width to the 'core' rectangle of 20 feet; the use of the same three foot wall thickness for all three parts of the building. There are many other dimensional and geometric relationships within this building which are worthy of note, but it is not within the scope of this research to hunt them all down. What is so significant about it for our purposes is this: that it is a rarity, that such geometric and dimensional interrelationships are not commonly found all together, St. Margaret's Chapel being the only other identifiable one of this period so far found in Scotland, although some of the individual elements are quite common. The general pattern of stone building in Scotland in this early era is for relatively simple structures where geometrical methods have been simply utilised to assist in setting out an orderly plan, and wall thicknesses have been based on what appears to be a very practical convention, rotation of the core square, which is structurally rational to the extent that it reflects a requirement for the wall thickness to be in a constant relationship to the span of the whole building. Dalmeny is more a work of art where the structure has to a greater extent become a slave to geometric integrity. It is possibly noteworthy also that this building could be likened to Leuchars, Tyninghame, and even Kirkliston, Ratho and Stobo by the apparent use of a 271 millimetre foot. If indeed this was the case and the same architect was responsible for all, it may tell us something of that architect's career: a pattern of development as he moved from one site to the next, developing his technique, or it may tell us something of the constraints of time and economy under which he worked for some projects and not others, or it may reflect differing levels of interest and interference by the patron. All these aspects are of course the common experience of architects in any age, but nevertheless, further study of this group of churches might well repay closer scrutiny in future, taking account of other aspects where connections might be made, such as masons' marks, style of decorative carving and moulding.

10.3.6 *Summary and Conclusions*

A picture begins to emerge of some possible medieval building practices. They will be difficult to prove conclusively, but equally difficult to disprove. Before proceeding to the next period, let us draw up a brief summary of what has been ascertained so far:

- the geometric and structural design appears to have frequently begun with the chancel width, which is set out either with an irrational dimension or, more likely, using a non-standard foot;
- the chancel itself is usually based on a square, occasionally an auron;
- the chancel wall thickness is usually obtained by rotating the diagonal of the square, giving a 1:√2 relationship of internal to external width, but this is often rounded to the nearest binary fraction of a foot, which may be the same non-standard as that used in the chancel width dimension, or may be the standard (modern) foot;
- the lines of the chancel external wall surfaces are extended westwards to form interstitial axes in the thickness of the nave walls, and it is on this width that is based the number of squares which will form the nave up to the chancel arch;
- the nave walls are drawn in, usually about three inches thicker than the chancel walls;

The question that still requires addressing is whether or not the architect of the Norman period took any account of height in his 'calculation' of wall thickness. The data reviewed so far seems to indicate very little consistency in either span or slenderness ratio. Perhaps he used a combination of both which would constitute a most problematic riddle, for it involves three variables. A relatively simple way to unravel this was used which seemed commonsensical enough but which is certainly not assumed to be infallible or final. If for a selection of churches of a given internal span, there are a range of wall thicknesses, then it might follow that where walls were thicker in this selection it may be for a logical reason, such as to support greater height. Listed below are a group of church units from the sample. Their internal span falls within the relatively narrow range of 5.25 and 5.8 metres in each case, a total variation of 57.5 centimetres or just over 22½ inches, and this dimension is therefore reasonably read as a constant. Wall thickness is shown in ascending order of magnitude. From this we can see at a glance whether or not additional wall thickness is intended to bear extra height.

Site	Span (M)	Wall Thickness (M)	Height (M)
Inchcolm nave	5.8	0.86	7.2
Ratho chancel	5.42	0.84	4.4
Gullane nave	5.74	0.9	6.6
Aberdour nave	5.25	0.9	5.25
Dalmeny nave	5.43	0.91	6.8
Stobo nave	5.6	1.0	4.5

Curiously, with the exception of Ratho, the sequence is almost in the reverse order of what was expected. The churches with the highest span ratio are also the tallest. Furthermore, the height of Ratho is regarded with suspicion, it possibly having been reduced at some time. It appears that either height was hardly an issue at all in this era, or it was taken account of in different ways by different masons. If that was the case, the pattern seems to indicate a widely diverse range of practices, some who are striving after greater economy, structural sufficiency, engineering perfection or whatever, while others who were content to 'play safe', not to experiment or seek to achieve more cost-efficient standards of structural design. Of course this is simplistic and does not take account of the wide variety of circumstances, demands, limitations, etc. imposed on each commission. Also, with differences in wall thickness between most of these buildings of little more than about nine inches, we are hardly drawing monumental comparisons. Of course also, it is often quite obvious from the mere appearance of a building to what standards it has been designed and built. Moreover, attempts to achieve structural sufficiency and logic might have been just one hallmark of professionalism in architecture; there were no doubt plenty of other areas in which the architect could aspire to achieve superior quality: for instance in integrated geometric or numerical proportions, or in quality of stone cutting and carving. Nonetheless the illustration of perceived attempts to achieve structural efficiency or sufficiency does provide us with another basis for assessment of quality in these buildings.

10.4 THIRTEENTH CENTURY GOTHIC

Moving into the thirteenth century, to what extent do these practices continue or change? Very quickly the two part church layout is dropped in favour of a single rectangular unit. Fawcett suggests that this waning interest in separate chancels was at least partly due to the granting of parish churches to relatively distant and uninterested monastic proprietors who were less concerned with the embellishment and general upkeep of separate chancels than had been the earlier resident rectors (VII Medieval Abbeys and Churches of Fife, undated: 8).

One surviving structure of separate nave and chancel from this period is the diminutive and ruined church of Burntisland, and it inherits some earlier features, but not all. The chancel interior is formed of two squares which overlap all but about three inches of the chancel arch. As to metrological explanation, the internal width is four metres which is an irrational number of modern feet: 13.12. Using a foot of 308 millimetres would give 13 feet; of 296 millimetres (the Roman foot) 13½ feet; of 286 millimetres 14 feet. Rotation of the internal square would have resulted in a wall thickness of nearly 2¾ modern feet whereas they are actually only 2¼ feet (0.7 metres). Again, it is noteworthy that this was the minimum thickness found in free-standing walls and it is reminiscent of the situation found at Rosyth. The design of the chancel walls is evidently based on simple structural pragmatism.

However, there is one question mark which hangs over the design of the chancel: was it really designed from the internal width? The external dimension teases: it is 5.4 metres. Is this coincidence or is it another 20 foot of 271 millimetres, or 18½ feet of 292 millimetres or whatever? Burntisland appears in a record of 1242 and if it indeed dates to around that time, then it cannot be the work of the same architect as the Norman examples discussed earlier, but could there have been after all a 'natural' foot of 271 millimetres commonly in use at least in the south-east of Scotland over this entire period? Alternatively, does the appearance of a foot of 271 millimetres indicate a much earlier date for this church? Clearly there is another task here, beyond the scope of this research, to ascertain just what units and methods of measurement were employed in this era. Many of the buildings surveyed require the benefit of another visit to in order to take many more measurements to try and piece together the metrological puzzle.

Derivation of the nave dimensions is not so clear as in the previous period. Continuation of the lines of the chancel exterior wall surfaces through and along the nave walls as a basis for the geometry of the nave results in a figure of two squares which fall about six inches short of the chancel arch. Straightforward use of the nave internal dimensions gives two and a half squares overlapping just over half the chancel arch which seems to be a more likely solution. If these two and a half squares are shunted westwards until they fit neatly up against the arch, they then overlap the west end wall, which for some reason is about one foot thicker than the side walls. It really is very difficult to know for certain what design methodology was in the mind of the architect. All that seems to be conclusive is that some change of approach has taken place, and if this is the case for the geometry of the overall plan, then is the derivation of wall thickness also similarly affected?

The lines of the chancel external wall surfaces are still extended to neatly form the mid-wall axis of the nave walls but, instead of then going on to themselves being used to define the squares of the nave length and breadth, it may be that the wall thickness is drawn in first, and then the nave squares derive from this *internal* dimension. The nave now appears to be treated structurally as a more separate geometric entity from that of the chancel. Although they still appear superficially to be, and indeed still are, of the same overall format as their Norman forebears, the design method has moved on and is directed towards a separateness, or unitisation that becomes ever more pronounced in Scottish building through the later medieval period. Now it is readily admitted that to base a thesis to this effect purely on the evidence of one church, and at that one where some assumptions have been made, is tenuous to say the least. Some more examples are really needed but unfortunately the numbers of this church type of this period surviving in Scotland are few and could not be accessed with the limited resources available.

All the other thirteenth century churches in the survey sample are of combined nave and chancel within a single rectangular unit. The internal plan dimensions of these simple structures again are all of whole squares or with binary fractions, but it is difficult to discern precisely what units of measurement have been used in the overall dimensions. If the internal width was still the primary module and was still measured in whole feet then those were certainly not modern feet of 305 millimetres, possibly excepting one church, Cockpen. What about the external width? Could that form the module in the same way that it possibly did for Burntisland? The same problem is encountered, again with the exception of Cockpen. In order to 'obtain' a whole number dimension for any width, a different foot measurement has to be used for each church. This of course has two possible implications: either whole feet are not being used at all, or each architect is using a different foot. Either is possible in any of the churches, though bearing in mind that contracts rarely specified any dimension other than in whole feet, the latter situation seems more likely.

For all that diversity, there remains, however, considerable homogeneity in choice of measurement for wall thickness. Almost as if most of the architects working in Scotland in this period trained under the same master, seven out of the ten examples have identical wall thicknesses of around 85 centimetres, or $2\frac{3}{4}$ modern feet. Perhaps the twelfth century characteristic of sometimes using two different systems of measurement still applied.

How was this wall thickness decided? Perhaps this had become a standard dimension for *any* building of around that size. It is difficult to make a case for relationship to either height or span: in isolation the buildings concerned, although similar in these proportions, were certainly not identical. There was no constant slenderness ratio or other relationship by Rondelet's methods. In only two cases, Keith Marischal and nearby Ormiston in East Lothian, does it appear that the wall thickness was defined by rotation. The fact that in these two cases it happens also to be $2\frac{3}{4}$ feet arouses suspicion that this may just be coincidence.

The other example where rotation has been used, but not to define wall thickness, is Cockpen, mentioned before as being exceptional in respect of dimensions and units of measure. In passing, it is worth enlarging on this sadly ruinous and partly rebuilt, yet very high quality little church (figure 10.11). Firstly, it is the only church in this group whose geometry consists only of whole squares - four to be specific. Internally it measures 60 feet by 15 feet and these are accurate modern feet. The wall thickness is 2½ feet. Now rotation would result in much thicker walls than that. It would give total external width of just over 21 feet. At this point rotation might seem to be irrelevant were it not for the fact that 21 feet is precisely the dimension at the east end where there are two Norman style clasping pilaster corner buttresses, each protruding six inches from the actual external width of the rest of the church of 20 feet. It is interesting to find this latter dimension measured in modern feet, whereas we have seen so many that are possibly of the same dimension but measured in shorter natural feet. It is a pity that only at the east end do the original walls of Cockpen survive with their pilaster buttresses, but what is left agrees significantly with findings at Duddingston (and not forgetting Castle Sween), and possibly therefore with the much wider concepts which may be at the heart of Alberti's thinking on the origins of the colonnade in the pierced wall, mentioned earlier.

The east gable wall of Cockpen echoes the geometry of the interior, having a 15 foot square east wall, with triangular gable above, pierced by twin lancets and fine quality rose window. It is only when comparing the measurements of such structures with others that the quality of the design is fully realised and one can begin to set apart such buildings with greater conviction as 'architecture'. Cockpen is also an interesting example of a transitional design: Norman in its use of rotation incorporating pilaster buttresses, but more typical in its generally squat proportions of the incoming smaller Gothic parish church.

Figure 10.11 Cockpen Church, Midlothian

To return to the definition of wall thickness in this group of churches, there seems to be only the most generalised correlation with height and internal width, the charts showing a marginally greater influence of span than height. Comparing slenderness ratios and Rondelet's methods of analysis show little more than a general trend towards less slender walls, which is of course principally due to the fact that many smaller churches are being built whose walls are much less high than in the previous century, but are only marginally thinner. Now in order to get to the crux of the matter, it would have been ideal if the same process could have been used as for the Norman church sample: setting a range of churches of similar span in ascending order of wall thickness to assess what relationship there may be to height. Unfortunately however, there were not in this group sufficient structures of similar span to enable a meaningful comparison. So instead some pairs of churches were taken with at least one dimension in common and compared as individuals against each other. This particular period made an ideal starting point for an approach of this nature, so many of the smaller churches being of roughly similar size, and yet with just sufficient differences to enable meaningful comparison. Only three dimensions are examined in each case: internal width, height to side wall-head and side wall thickness. Carnock

Church in particular is singled out as a basis for some initial comparisons given its conformity to average dimensions in most respects. It is first placed alongside the chancel of Burntisland. In each case the dimensions quoted will simply be as follows:

	Span (m)	Height (m)	Wall Thickness (m)
Carnock	5.3	3.5	0.85
Burntisland chancel	4	3.1	0.7

The difference in wall thickness here could be attributed either to the difference in height or span, but the latter is quite clearly the greater possibility, given the differential of 1.3 metres as against only 0.4 metres in height.

Carnock	5.3	3.5	0.85
Keith Marischall	4.27	3.6	0.86

Here the difference in span of about one metre has no effect on wall thickness. By default it is possible therefore that height would have been a deciding factor.

Carnock	5.3	3.5	0.85
Ormiston	3.86	3	0.85

The situation here is similar, with no effect on wall thickness by the considerable span difference.

Carnock	5.3	3.5	0.85
Temple	5.3	4.5	0.81+ buttresses = 1.37

It appears that it is a difference in height that is responsible for a considerably thicker wall if buttress projection is taken into account. It should be noted that Temple Church's walls are perforated by large and elegant windows with fine tracery (figure 10.12). These may to some extent may be responsible for, and offset the effect of the buttresses. However, they do not by any means fill the spaces between the buttresses whose design may therefore only be partially concerned with the reinforcement required by their presence.

	Span (m)	Height (m)	Wall Thickness (m)
Dalgety	5.1	3.4	0.9
Temple	5.3	4.5	0.81+ buttresses = 1.37

A similar story, although in this case there is also a span difference, but it is not nearly so marked as that of height.

Carnock	5.3	3.5	0.85
Abdie	5.5	4	0.85 + buttresses = 1.25

Here there is negligible difference in both span and height and yet substantial abutment. However, Abdie's buttresses appear to be for a very different purpose from the elegantly capped examples at Temple (figure 10.13). Here are no fine Gothic windows regularly disposed between the relatively clumsy buttresses which only reach half-way up the walls. These, it is suspected, are designed not to augment wall thickness against the overturning stresses imposed by the roof, or to enable the opening of the masonry wall to fine windows, but rather to spread the load of the building on an unsound foundation and subsoil. That may be why they are not full height. That is possibly why also, in comparison with Carnock, they are superfluous in view of the negligible difference in height and span. The dimensionally almost identical Abdie and Temple are juxtaposed below:

Temple	5.3	4.5	0.81+ buttresses = 1.37
Abdie	5.5	4	0.85+ buttresses = 1.25

Figure 10.12 Temple Church, Midlothian

Figure 10.13 Abdie Church, Fife. Original buttresses

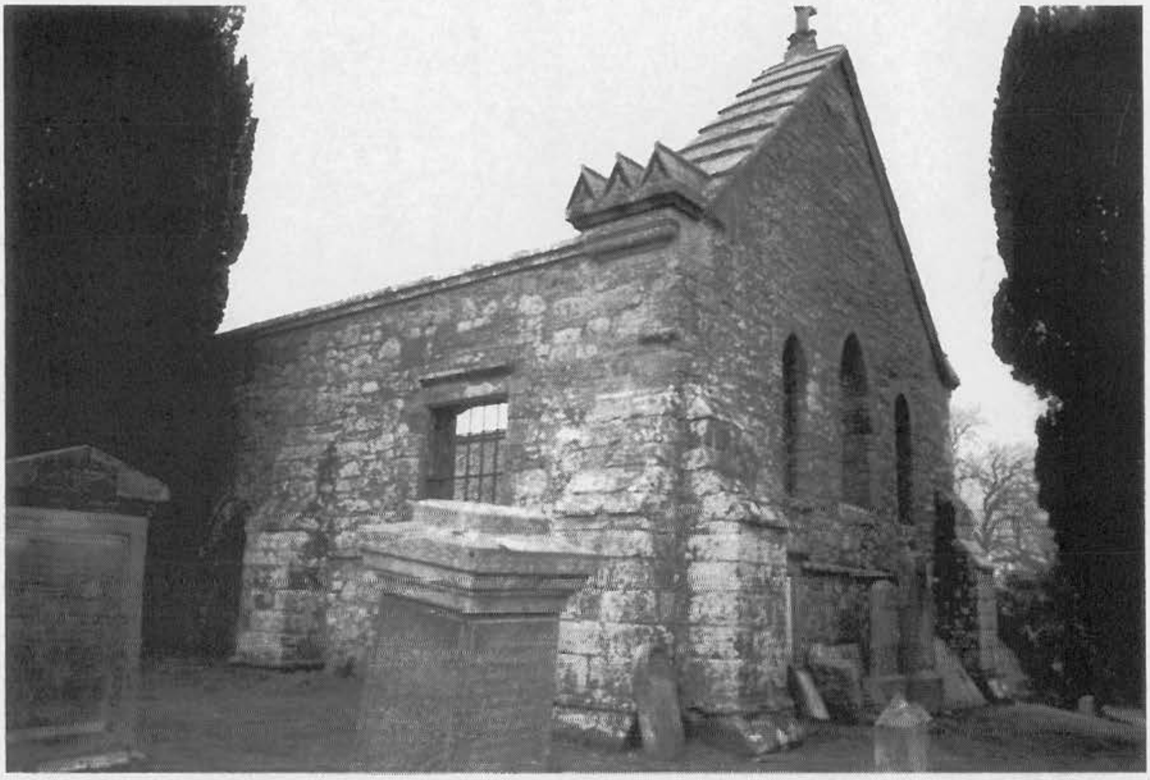


Figure 10.14 Abdie Church. Buttresses added in the 17th century

As a final note of irony, even the buttresses from which Abdie did benefit were insufficient for the task and by the seventeenth century extra abutment was required and clumsily applied (figure 10.14).

Now here are some larger buttressed examples:

	Span (m)	Height (m)		Wall Thickness (m)
Dunkeld Cathedral choir	8.7	11	North	1.2 + buttresses = 2.8
			South	1.28 + buttresses = 2.56
Crossraguel Abbey nave	7.45	6.2		1.3 + buttresses = 1.9

The extra buttressing at Dunkeld is obviously in response to considerably greater differential in height than in span. Both these structures have large scale regularly disposed fenestration. Dunkeld choir is a rare example of a church unit of this period being taller than its width, obviously because it is part of a larger structure whose width is actually greater than height. In this context, the proportions of such choirs should perhaps be regarded as more comparable with those of transepts in their similar relationship with the main, wider body of the church. Hence, in a later section Dunkeld will be compared with the transepts of Biggar and South Queensferry.

Temple	5.3	4.5	0.81 + buttresses = 1.37
Crossraguel Abbey nave	7.45	6.2	1.3 + buttresses = 1.9

Here is a case where the height and span at Crossraguel are proportionately larger than those of Temple by about 1.4 times. It so happens that total wall thickness, including abutment is greater also by the same amount.

Dunblane Cathedral choir	8.45	12.5	1.15 + buttresses = 2.1 lower, 1.9 upper.
Crossraguel Abbey nave	7.45	6.2	1.3 + buttresses 1.9

This is potentially a most instructive comparison. Dunblane (figure 10.15) is just one metre wider, but twice as high as Crossraguel (figure 10.16) and yet shares roughly the same level of abutment. This would seem to fly in the face of all the evidence so far from these paired comparisons that height seems to be the crucial determinant of wall thickness. But the situation at Dunblane might not be so straightforward as first appears. Fawcett has pointed out that windows in the upper part of the east wall of the

Figure 10.15 Dunblane Cathedral Choir

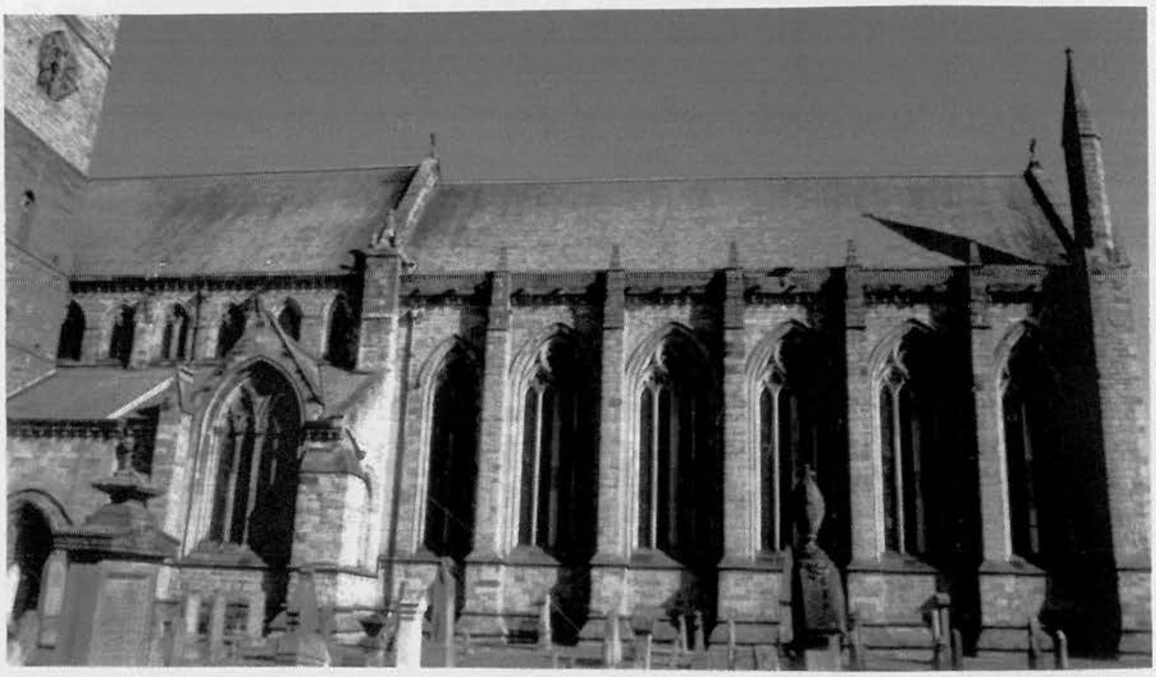


Figure10.16 Crossraguel Abbey Nave (foreground), Choir (beyond gable wall)

nave, which was rebuilt before the choir, simply look through into the choir rather than to the outside world and he has suggested that the choir may have been constructed much higher than originally intended (VII 1997: 50). To conjecturally reconstruct the choir as it might have been envisaged when the foundations were laid is a task still to be done, but a height of around 6 or 7 metres to the wall-head would probably have left these east nave windows free, and would also account for the approximate parity with the abutment on the nave of Crossraguel.

There are many more comparisons which could be made. Most either only repeat the patterns set by the above selection or are entirely inconclusive for the purposes of this project because the proportional differences in height, span and wall thickness are all negligible. No attempt has been made to choose comparisons which follow a preordained agenda. Those explained are entirely representative, and indicate that wall thickness in these buildings was determined primarily by the height of the side walls. In claiming this, it should be remembered that there seem to have been some general conventions in church design on the approximate proportional relationship between height and span, as shown in figure 10.4. It should also be noted that wall thickness was often rounded to the nearest binary fraction of an English foot. Before leaving the thirteenth century, there is one church which is exceptional to the point of defying all attempts at explanation: the Cross Kirk at Peebles was originally a parish church and shrine which passed to the Trinitarians in 1474. It has an abnormally wide span at 8.2 metres, and the walls at only 1 metre thick were very slender for their height of 7.1 metres. This is all the more remarkable in view of the rough rubble build. The church was burnt by the English in 1549 but survived in use as a parish church until 1784. Apparently the nave south wall fell in 1811 and this is hardly surprising in view of its slenderness, (1: 8.7) and the span (1: 8.2) of the roof it once bore.

It has now become evident that an enormous paradox has appeared in our analysis of unvaulted churches. The trend indicated by the cluster charts 10.3 and 10.4, and the ratio tables 10.5 and 10.6 was that *span* seemed to be most influential over wall thickness, whereas these paired comparisons indicate otherwise. How can such a contradiction occur, and how can it be reconciled? A clue perhaps lies in the fact that the method of defining wall thickness has obviously changed since the Norman era when it was based in quadrature and nominal increments of binary fractions of a foot, to some other system in the early gothic period. If we return to the original cluster charts (10. 2 and 10.3) and then delete the Norman examples (shown as black squares) a rather different picture begins to appear (figures 10.17 and 10.18).

Fig. 10.17 Unvaulted Churches (omitting Norman)
- Span:Wall Thickness

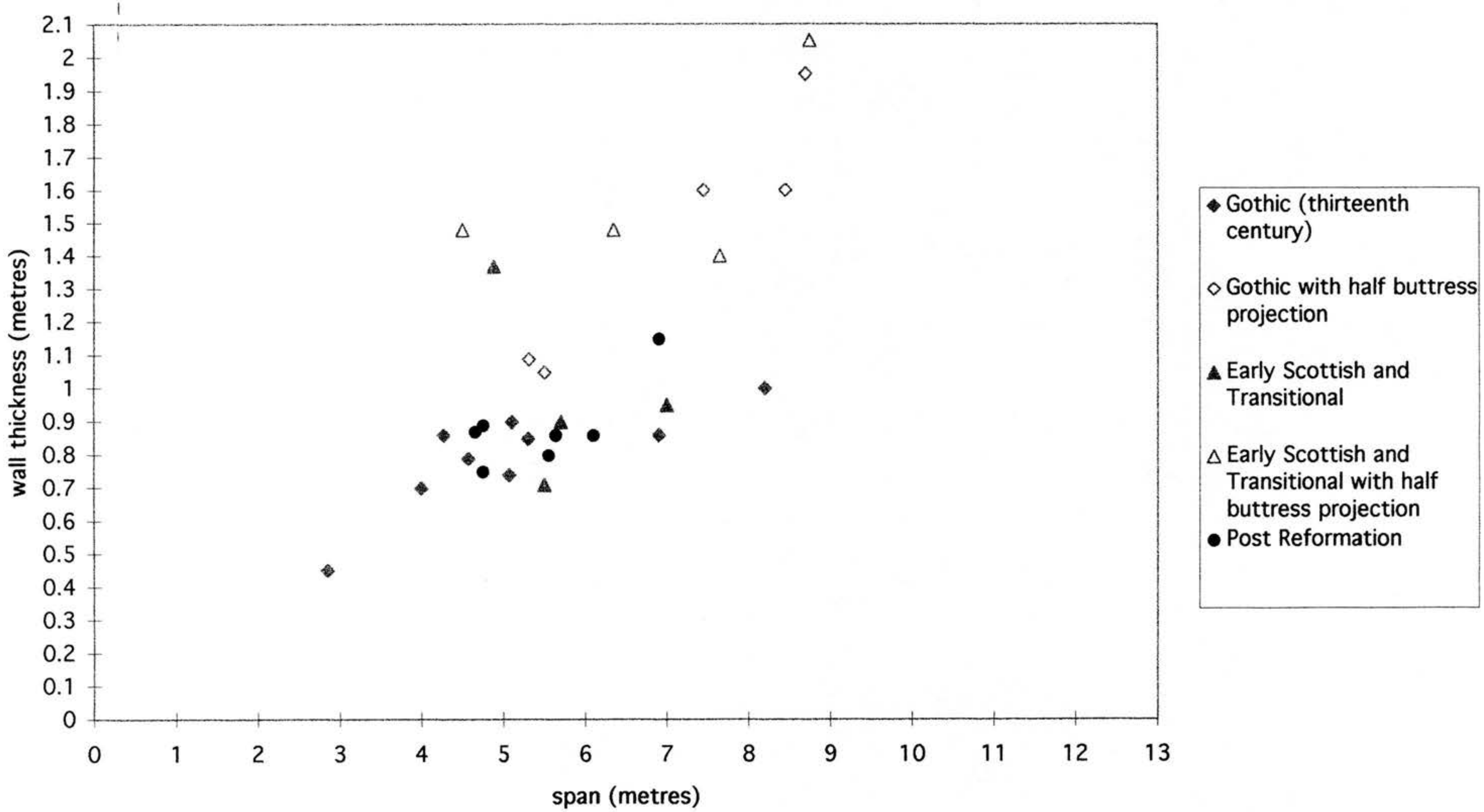
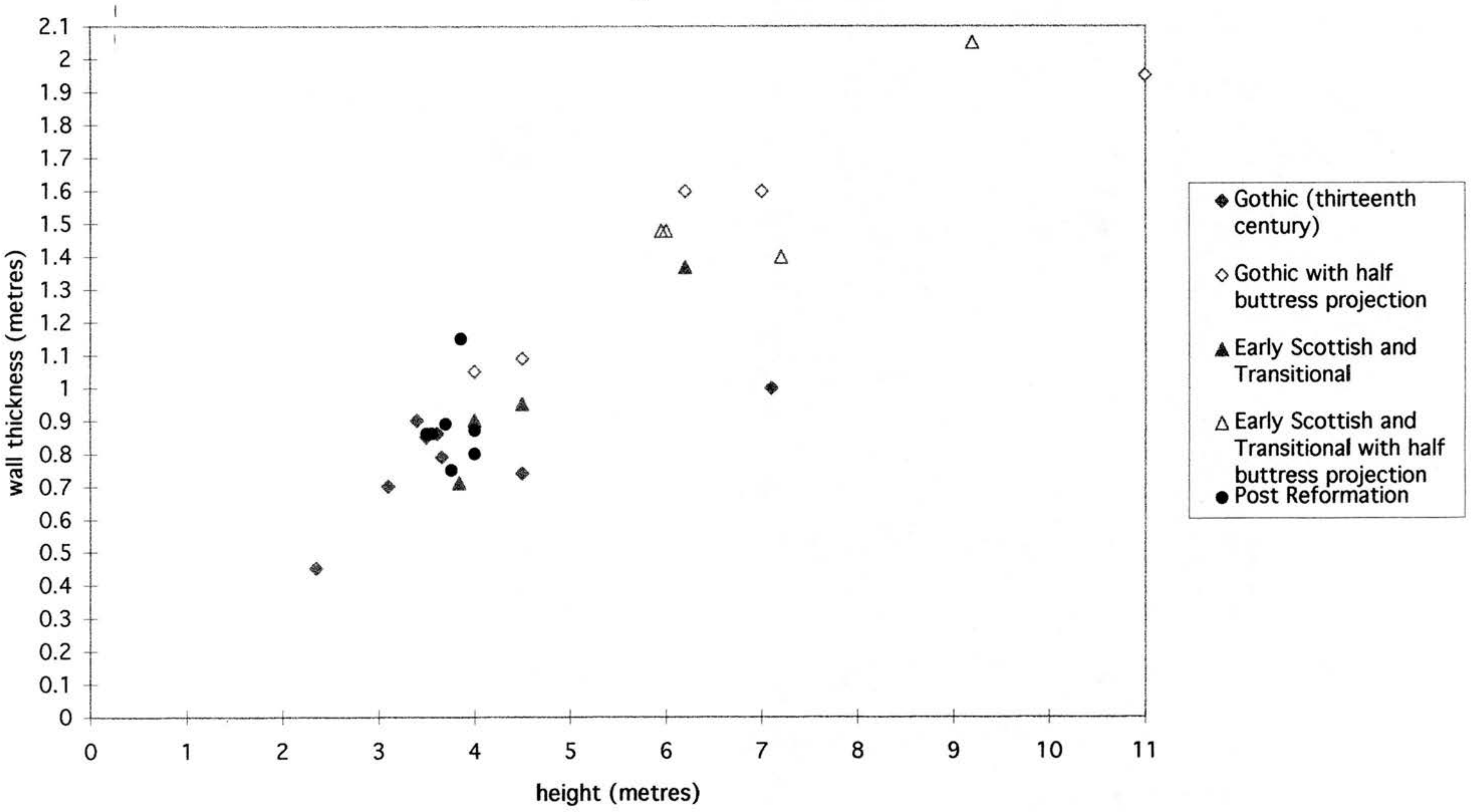


Fig. 10.18 Unvaulted Churches (omitting Norman) - Height:Wall Thickness



In the height chart particularly a definite pattern emerges with a more tightly defined cluster at the lower ends of the scales, loosening progressively at the larger dimensions. The span chart, whilst indicating a vaguely similar trend, does not have quite the same clarity. It begins to appear that height was indeed the generally more dominant influence over wall thickness, and that the presence of the Norman examples in the original charts was confounding the overall picture.

10.5 EARLY SCOTTISH: 14TH AND 15TH CENTURIES TO C.1480 AND TRANSITIONAL: C.1480 - 1560

After the Wars of Independence much new church building centred around the larger aisled parish churches and many of the new smaller single cell structures were privately endowed collegiate foundations which were vaulted. The former category is not dealt with in this research and the latter are the subject of a later chapter. Because of the relatively small number of examples surveyed in these two periods, and their diversity of size and structural form, they have been combined for the purposes of analysis.

Buttresses became more commonly used making comparison of structural design difficult if not impossible, especially when trying to reconcile that of a highly prestigious structure like King's College Chapel Aberdeen with the relatively humble nave of Whitekirk Church in East Lothian. Yet in practice there is no reason why they may not share the same principles in their structural design.

The general preference for width over height in sectional proportion continued in this period except in the case of transepts, as explained earlier. In laying out ground plans, the practice of using multiple squares, with or without binary fractions, to make up the dimensions of the internal plan continued, but it becomes harder to decipher precisely how this has been done because of increasing complexity of plan forms. Also in setting out, the use of exact geometrical forms seems to have become more arbitrary, or less consistent. For instance, the near-square becomes more common, and the canted apse is incorporated in the exact geometric figure or whole squares in the case of Crossraguel but not in the case of King's College, Aberdeen, or Biggar. However, that is not the subject with which we are so specifically concerned.

As far as is possible to discern, many wall thickness measurements continue to be in whole modern feet or binary fractions thereof. Predictably, with the greater variety of structures in this group, wall thickness varies more than in earlier groups. No longer can it be pinned down to within inches of three feet. Now the question must be addressed, to what influence was it most responsive? Will the same importance be attached to height as was apparent as in the last group? Firstly, rotation of the internal square can be ruled out. In not one church in this period does this method appear to have been used. The thickness that would have resulted varies from 0.2 to 1.4 metres thicker than walls that were actually built.

Next to be examined is slenderness ratio and figure 10.6 is again referred to. The situation is complicated by the presence in most examples of buttresses. The church units with these are shown emboldened and underlined where slenderness ratio has been calculated as if the church had none, that is purely based on the wall height and thickness alone. Further calculation where the relationship of the wall height to the combined dimension of wall thickness and entire buttress projection is shown as 'B'. Where half the buttress projection is used, the ratio is shown as 'b'.

What is immediately obvious is the appearance in both Early Scottish and Transitional periods of most, but not all, the walls alone of buttressed churches as amongst the most slender, not only in their own periods but in all but the Norman period. It would appear from this that a principal purpose of buttresses was to enable walls to be thinner, an obvious and elementary statement perhaps, but one that nonetheless needs to be tested. The alternative reason for their use may of course be to enable the opening up of wall masonry for larger regularly disposed windows. These do, after all, appear in most cases where buttresses have been employed.

Let us attempt a few comparisons in the same way as for the previous period, firstly amongst the unbuttressed churches:

	Span (m)	Height (m)	Wall Thickness (m)
Stenton	5.5	3	0.7
Pencaitland	5.7	4	0.9

Again, it would appear that the slightly greater height differential that determined the thicker walls at Pencaitland.

	Span (m)	Height (m)	Wall Thickness (m)
Whitekirk nave	7	4.5	0.9
Pencaitland	5.7	4	0.95

A considerable difference in span has no apparent effect on wall thickness, implying that height is again the determinant. These buildings also make interesting comparisons with some of the buttressed structures:

Whitekirk nave	7	4.5	0.95
Biggar choir	6.4	6.0	0.93 + buttresses = 2.03

Obviously again height is the determinant but it should also be noted that the walls of Biggar are opened up to some relatively large windows. It is noteworthy that in this case, as in some others when comparing buttressed and unbuttressed churches, that it is the buttresses themselves which make up the required wall thickness to accommodate the extra height.

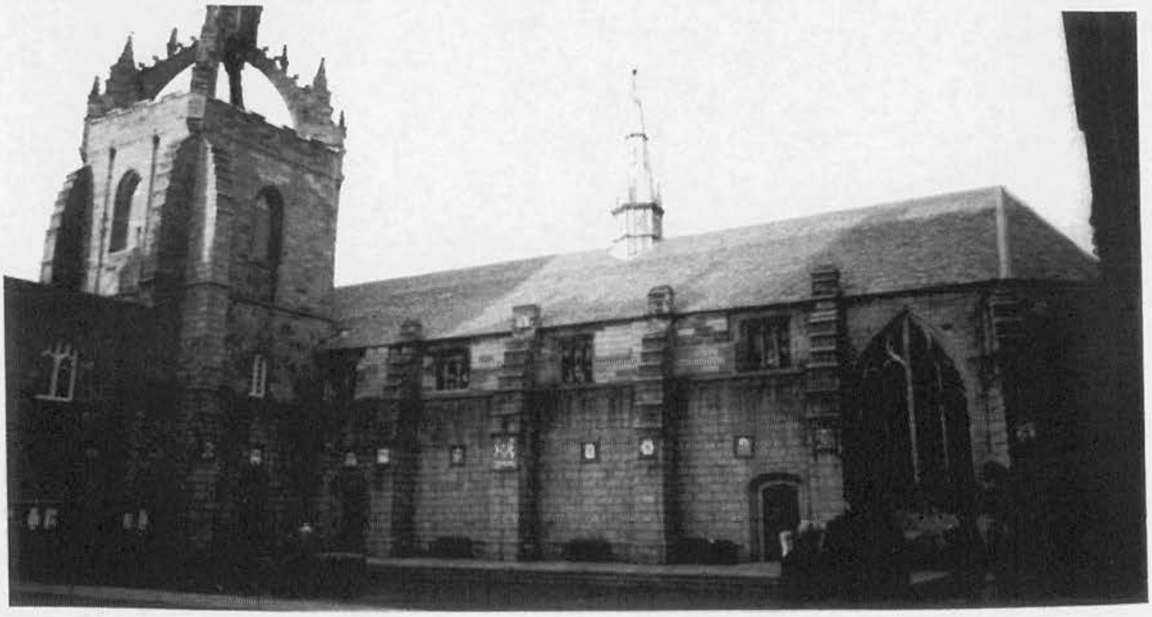
Pencaitland	5.7	4	0.95
Biggar choir	6.4	6.0	0.93 + buttresses = 2.03

Another illustration of the previous point. The height differential is more than double that of the spans. Again also Biggar boasts considerably grander fenestration than Pencaitland.

Whitekirk nave	7	4.5	0.95
Crossraguel Abbey choir	7.65	7.2	1.0 + buttresses = 1.8

The same applies here also.

On the basis of these comparisons the connection between height and the use of buttresses is possible, but nevertheless it is unlikely that it was height *alone* that necessitated their use. The almost universal coexistence of buttresses and large, regularly disposed windows on the bigger more prestigious buildings will always cloud the issue. Perhaps the only example which may throw some light on the subject is King's College Chapel, Aberdeen (figure 10.19). Here the north wall (which is used in the following comparisons) has full fenestration and buttresses which project 1.4 metres. The south wall, however, faces a courtyard which was originally cloistered, and hence it has only relatively small high level windows. The wall thickness is the same, but the buttresses project only 1.2 metres. If this small difference of only 20 centimetres has indeed been consciously calculated, then it probably represents the extent of the effect of full fenestration. By most standards this is not an effect of great magnitude. A generalized conclusion on the basis of just one example is of course unwise, but at the same time it should be realized that buildings are very hard to find where such comparisons are possible.



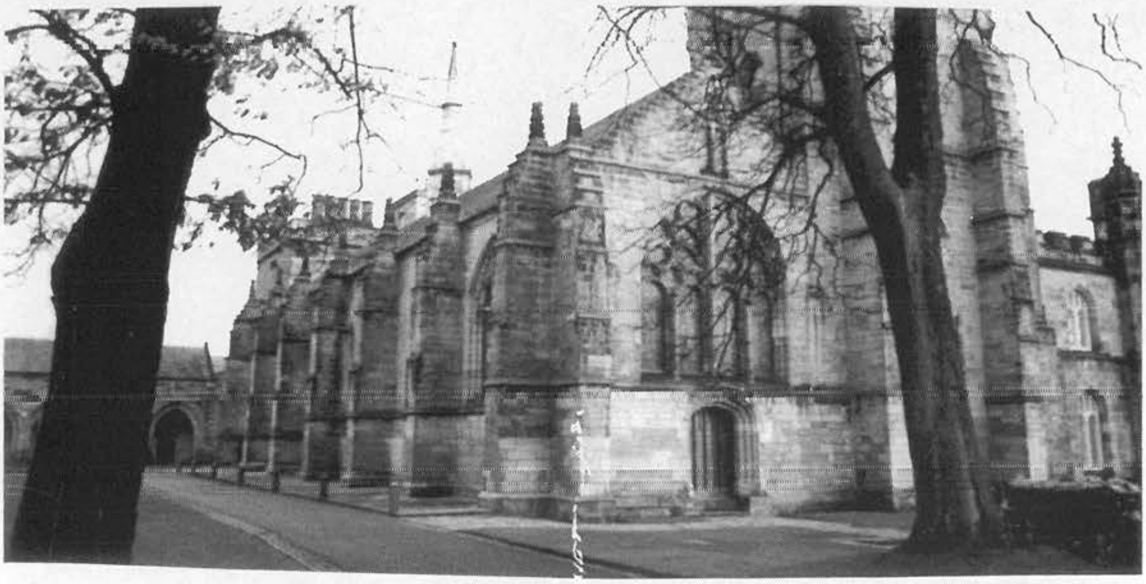


Figure 10.19 King's College Chapel, Aberdeen: top: south cloister elevation
bottom: north and west three-quarter view

Next some of the buttressed structures are compared with each other to see if there is any common approach to the calculation of abutment.

	Span (m)	Height (m)	Wall Thickness (m)
King's, Aberdeen	8.75	9.2	1.45 + buttresses = 2.85
Crossraguel Abbey choir	7.65	7.2	1.0 + buttresses = 1.8

Again the predominant influence on overall thickness seems to be height, although comparing these two, the abutment of King's does seem a little overdone, or alternatively Crossraguel is somewhat adventurous. If the choir of Biggar is added to the enquiry, it becomes evident which is the more likely case:

Biggar choir	6.4	6	0.93 + buttresses = 2.03

Biggar works out as being proportionately very similar to King's, which is consistently larger in each dimension by around 1.4 to 1.5 times. In comparison Crossraguel is obviously uncharacteristically economical in wall structure for its period, at least when measured against these other two. Next it is compared alongside the earlier nave, originally built in the thirteenth century, damaged in the wars of independence, and rebuilt to basically the same dimensions in the fourteenth century:

Crossraguel Abbey nave	7.45	6.2	1.3 + buttresses = 1.9
Crossraguel Abbey choir	7.65	7.2	1.0 + buttresses = 1.8

The earlier nave represents relative profligacy in the use of stone, showing a slenderness ratio of only 1: 4.8 for walls alone, 1: 3.2 including whole buttresses and 1: 3.9 with half the buttress projection. The choir shows a healthy reaction by its later architect, trimming the slenderness ratios down to 1: 7.2, 1: 4 and 1: 5.1 respectively. Interestingly, the net result, a total abutment of 1.8 - 1.9 metres is virtually the same but in the choir has been achieved with great strides towards a more scientific method and structural sufficiency. This does not reveal much about the determinant of wall thickness, but it is nevertheless highly significant in terms of progress in structural design in a building which superficially appears to be of the same form throughout (figure 10.16).

Now a comparison of the abbey church nave directly alongside King's: similarly prestigious structures from different periods:

	Span (m)	Height (m)	Wall Thickness (m)
13th C. Crossraguel nave	7.45	6.2	1.3 + buttresses = 1.9
c.1500 King's Aberdeen	8.75	9.2	1.45 + buttresses = 2.85

This again shows King's height and total wall thickness including abutment as proportionately greater by 1.5 times. In thickness of walls alone, however, King's is only 1.1 times greater, confirming the earlier conclusion that Crossraguel's nave walls are uncommonly thick.

Next is a comparison of the three subsidiary church units, the transepts and Dunkeld choir, which are all higher than their width because, whilst conforming to the height of their parent structures, do not require the same floor area:

late 13th C Dunkeld choir	8.7	11	South 1.28 + buttresses = 2.56 (North 1.2 + buttresses = 2.8)
c.1545 Biggar transept	4.5	6	0.9 + buttresses = 2
c.1440 S.Queensferry transept	4.9	6.25	1.37

Dunkeld (south wall) is about 1.8 times *all* the South Queensferry dimensions. The height and span of Dunkeld are also about 1.8 times those of Biggar, but its total wall thickness is only 1.4 times. This may presumably be because Biggar's walls, at 90 centimetres, had already reached what was perceived as a minimum for this size of structure. This comparison shows a remarkable continuity of principles of structural design in this class of structure, but it also raises a question about the validity of comparing solid unbuttressed walls with the *total* abutment (wall and buttress combined) of buttressed walls. This will be addressed shortly, and with reference to these same three examples.

It seems reasonable for the moment to conclude that, very generally, as height increases so too does wall thickness, that is including abutment. There are of course exceptions and variations. On the face of it though, slenderness ratio appears usually to be the decisive factor. But before settling confidently with this conclusion, let us look a little further at the implications of its use, particularly in cases where buttresses are employed.

10.5.1 *Slenderness Ratio and Buttresses*

Referring back to the slenderness ratio summary chart (figure 10.6) a simple comparison of the average slenderness ratio of side-walls of unvaulted churches with buttresses, against those without of this period produces the results shown below. Incidentally, since the number of examples from the period surveyed is admittedly rather small, statistics for the thirteenth and fourteenth centuries are also shown incorporated in the second line for comparison. Two unbuttressed buildings may be classed as outliers, Peebles Crosskirk, which is an exceptional structure as will become evident, and Culross Lay Brothers choir which no longer exists, but whose sectional dimensions are clear from its ghost on the wall of the church tower to which it was once attached. However, what is not clear is whether or not it had buttresses. If Peebles and Culross are omitted, the averages are almost identical in every respect. Our survey sample is therefore taken to be representative.

SLENDERNESS RATIO

	Unbuttressed (1)	Buttressed Wall only (X)	Buttressed Wall + whole butt. (B)	Buttressed Wall + ½ butt. (b)
15 + 16 cents only	1: 4.75	1: 6.36	1: 3.26	1: 4.26
13, 14, 15, 16 cents	1: 5.22 with Peebles & Culross otherwise 1: 4.78	1: 6	1: 3.26	1: 4.17

Generally, for post-Norman structures, buttressed churches tended to be among the larger examples, and with more slender walls, commonly above 1: 6 ignoring abutment altogether. These churches are nearly all characterised also by large regularly disposed windows.

Comparison of the ratios of walls alone of unbuttressed churches with those of buttressed churches, 1: 4.75 and 1: 6.36 respectively, imply that the use of the buttress is most definitely structural rather than merely stylistic. They produce a saving in wall thickness but, on the other hand, buttresses are more expensive to manufacture in terms of cut, shaped stone than a flat, plain and relatively thick wall, whose extra bulk is made up of relatively cheap unshaped rubble and quarry spoil. Their presence must therefore be regarded to some extent in terms of style, sophistication and expense, rather than of economy. Buttresses do also allow the opening of larger windows. (No research has been done on comparative costings but it would be interesting to ascertain just how much would have to be spent on a large pointed arch window with decorative tracery and glass of whatever sort, compared with a smaller simpler opening plus greater volume of masonry.)

The next question to demand attention is how was the size and strength of a buttress determined for a given structure, particularly in relation not just to the height, but also the thickness of the wall abutted? Was there a commonly used formula, in the broadest sense of the word? There survives in Lorenz Lechler's book of instruction to his son written in 1516 some ideas on the subject, but they are very unclear and, worse, the two different versions of the book vary in their instructions. Also the instructions are for vaulted churches. Nevertheless, they make a useful point of departure.

A summary of Lechler's guidelines are set out in Appendix I, and Shelby & Mark's comments on interpretation are accepted. For instance, the choir heights given by Lechler are taken as reaching the vault apex rather than the *tas de charge*. In order to adjust the height from that of the apex to that of the springing of the vault, and thus to make it equivalent to that of the side walls of the unvaulted churches under review in this section, an assumption is made that the vaults will have been equivalent to an equilateral triangle. The height has then been reduced by that amount. Thus for a hypothetical church by Lechler with choir width of twenty feet, the side wall height should be approximately seventeen feet, the wall thickness two feet and buttress projection four feet. The slenderness ratios for wall thickness alone will be 1: 8.5; for wall thickness plus entire buttress projection, 1: 2.8.

It cannot be pretended that these figures are anything but very approximate. They bear the vaguest correlation with the averages found in Scottish churches of similar width: 1: 6.36, and of side walls plus entire buttress projection, 1: 3.26. However, it will be recalled that the slenderness ratio of the side walls of Scottish unbuttressed churches averaged 1: 4.75. Now if there were a method of achieving some sort of structural equivalence between buttressed and unbuttressed buildings, it would probably have been of a simple geometric or whole number manipulation of existing dimensions. Let it be assumed for a moment that this was the way in which medieval builders worked. Perhaps the most obvious solution would be to take a slenderness ratio based on the wall thickness plus *one half* of the buttress projection. Masons may have used this as a basis for abutment calculation, or they may have used a smaller fraction, perhaps one third, depending on other factors such as distance between buttresses, volume of masonry lost to fenestration, quality of stone, quality of masonry build (i.e. random rubble or coursed ashlar). What would be the results of such an adjustment? For Lechler's hypothetical church: 1: 4.25 and for the average Scottish buttressed church of this period: 1: 4.26, an interesting coincidence, and neither are too far removed from the Scottish unbuttressed average of 1: 4.75. The average figures for free-standing walls are worth recalling here for comparison:

13th century:	1: 4.1
14th century to 1370	1: 4.7
1370 - 1480	1: 5.3
1480 - 1560	1: 6.4
1560 -	1: 5.1

Before leaving this subject, a useful comparison can be drawn between three structures highlighted in the previous section:

	Span (m)	Height (m)		Wall Thickness (m)
late 13th C Dunkeld choir	8.7	11	South	1.28 + buttresses = 2.56
			North	1.2 + buttresses = 2.8
c.1545 Biggar transept	4.5	6		0.9 + buttresses = 2
c.1440 S.Queensferry transept	4.9	6.25		1.37

It was mentioned that all the dimensions of Dunkeld (using the *total* abutment figures, and using only the *south* wall at Dunkeld) were about 1.8 times all those of South Queensferry. However only the height and span of Dunkeld were 1.8 times those of Biggar. The total wall thickness with buttress was only 1.4 times. If in each case the walls plus *half* the buttress projection are now substituted, the following results:

late 13th C Dunkeld choir	8.7	11	South	1.28 + ½butts = 1.92
			(North	1.2 + ½butts = 2)
c.1545 Biggar transept	4.5	6		0.9 + ½butts = 1.45
c.1440 S.Queensferry transept	4.9	6.25		1.37

Immediately an approximate equivalence appears between Biggar and South Queensferry and while the overall dimensional relationship between them and Dunkeld obviously remains at 1.8 times, the abutment relationship is now more consistently 1.3 -1.4 times.

There is some logic in this approach of measuring to *half* the buttress projection, or some other fraction, since each buttress is only directly stiffening the short stretch of wall to which it is directly joined. Only a proportion of its projection can therefore be said to have any such effect on the lengths of wall between them. Perhaps this is the rule of thumb that medieval builders used. Certainly if this hypothesis is applied to both the magnificently buttressed King's College Chapel and the relatively simple and unbuttressed nave of Whitekirk, the slenderness ratios compare at 1: 4.3 and 1: 4.7 respectively. This is a nice neat little comparison, but it is only one. One problem with this process is the level of contrived interpretation applied to Lechler's instructions. On the face of it , this does seem justified but the ambiguity of his writings will always cast doubt on their use for the creation of a model.

All this assumes that abutment was related to height, logically so since the comparisons drawn earlier nearly all point to the determination of wall thickness in relation to that dimension. There is, however, another aspect of this enquiry which is worth mentioning, and which may throw something of a masonic spanner into the works.

10.5.2 *Quadrature and Buttresses*

It was stated earlier that rotation of the internal square of any of these buildings could not have been the basis for the wall thickness dimension. The root-2 relationship that would result always overlaps the wall thickness to some extent or other. Figure 10.20 shows for unbuttressed churches a summary of the effect of rotating the diagonal of the internal core square - being in most cases, after the Norman period, the extent to which it overlaps the actual wall thickness. At only Ormiston and Keith Marischal does it appear to have been used thereafter to define the wall thickness. However, it will be recalled that there was a connection between the rotation method and the projection of the pilaster buttresses at Duddingston (choir) and also at the surviving east end of Cockpen in the thirteenth century. Because of this, it could possibly be claimed that Cockpen belongs typologically more in the Norman period. However, it indicates, along with Keith Marischall and Ormiston, that the principle was still being used in some building work at this later time, in both pilaster-buttressed and unbuttressed buildings. In the light of this, the question has to be asked, was rotation also used in any way for the sizing of buttress projection in other churches?

Figure 10.20 UNVAULTED UNBUTTRESSED CHURCHES :-
Results of rotation

Site	Underlaps each side by: (m)	Defines wall thickness	Overlaps each side by approx: (m.)
Norman 12th Century			
NB except Uphall, only chancels shown since rotation known to have been definitely used in these Norman two-part churches			
Aberdour chancel		x	
Dalmeny chancel		x	
Gullane chancel		x	
Leuchars chancel		x	
Monymusk chancel		x	
Ratho chancel			0.28
Rosyth chancel			0.25
Stobo chancel		x	
Tyninghame chancel		x	
Uphall nave		x	
Gothic 13th/14th Century			
Burntisland chancel			0.12
Carnock nave/chancel			0.25
Culross nave (lay bros. choir)			0.58
Dalgety nave/chancel			0.2
Dunnottar nave/chancel			0.33
Keith Marischall nave/chancel		x	
Ormiston chancel		x	
Peebles nave			0.7
Late Gothic 14th/15th Century			
S. Queensferry transept	0.35		
Whitekirk nave			0.5
Transitional 15th/16th Century			
Pencaitland nave/chancel			0.28
Stenton chancel			0.43
Post Reformation 1560-1700			
Abdie aisle			0.06
Dirleton nave			0.27
Gladsmuir nave			0.4
Glencorse nave			0.35
Pencaitland ailse			0.08

Figure 10.21 shows a list of the buttressed churches surveyed, with a note of the approximate extent to which the line of rotation overlaps the buttress projection. Having

already noted the very rough correlation in slenderness ratio between the walls alone of unbuttressed churches, and the walls plus *half* the buttress projection of buttressed structures, it perhaps comes as little surprise to find that the line of rotation overlaps with great precision half the buttress projection of the small churches of Temple and Abdie. These are the only cases, but the incidence of an approximately one *third* overlap at Dunkeld, Crossraguel nave, King's and Biggar does suggest that there may be some common element of purposeful design in these cases also, even separated as they are by a considerable timespan. If Dunblane is excluded because it was probably built higher than intended, and therefore its walls and buttress depth are also out of scale, then an even more consistent pattern emerges. In the light of all this, the basis for calculation of buttress projection may be entangled in both slenderness ratio and rotation of the internal core square, and it is difficult to justify choosing either of these in isolation as the determinant used, with the limited number of examples available as evidence.

Figure 10.21 UNVAULTED BUTTRESSED CHURCHES:
Results of rotation

Site	Span	Height	Overlaps buttress by approx:					
	(M)	(M)	1/4	1/3	1/2	2/3	3/4	Entire
Duddingston	4.85	5.2						x
Cockpen	4.57	3.7						x
Dunblane choir	8.45	12.5 (!)				x		
Abdie	5.5	4			x			
Temple	5.31	4.5			x			
Dunkeld choir	8.7	11		x				
Crossraguel nave	7.45	6.2		x				
Crossraguel choir	7.65	7.2					x	
King's Aberdeen	8.75	9.2		x				
Biggar nave / choir	6.35	6		x				

On the face of it, there is strong evidence to suggest that rotation was used to some extent, and that overlapping of one third of the buttress projection appears to have been a commonly applied practice in some larger buildings. What is perhaps significant here is that, whilst slenderness or span ratio might have been used to determine *total* abutment, the principle of rotation may have assisted in the determination of the ratio of wall thickness to buttress projection. Alternatively, perhaps the wall thickness plus one third of the buttress projection was actually more generally regarded as the equivalent of an unbuttressed wall, rather than one half as has been assumed until now. All would presumably depend on a myriad of factors in individual cases such as the scale of fenestration, distance between buttresses, amount of stepping or intake of buttresses at higher levels, and no two cases will be the same. In the final analysis, it has to be accepted that there will always be a number of exceptions and that any 'rules' or 'norms' will be very vague and open to different interpretations by different architects at different sites. A picture is beginning to emerge of just how widespread were the more commonly accepted norms and to what extent they were deviated from.

10.6 POST REFORMATION

The period from 1560 is characterised in church building by simple barn-like 'preaching boxes' of straightforward longitudinal plan or T-shaped types which continued to be built long after the seventeenth century, the roots of the former of course lying in the thirteenth century. There were also a few centralized plans such as Burntisland, which was unique, and Lauder which was much later, neither of which are dealt with here. It is hardly surprising that the slenderness ratio for the examples surveyed averaged 1: 4.25, not too far removed from that of the thirteenth century examples' average of 1: 4.8, the latter figure assuming inclusion of half the buttress projection on buildings where these features appear.

Adherence to regular geometrical forms is found in three examples and, of these, only Dirleton is a whole number of squares - four to be precise. Three examples, however, are only aisles and these are never quite a square or any other recognisable figure. Ideally, a few more post-Reformation churches built from new are required to make up a more convincing sample but it is doubtful that any more would actually change the picture appreciably.

Only at Gladsmuir church was the modern foot in evidence for the width, a convenient 20 feet. All the other churches were of internal widths of odd numbers of feet and inches, and their external widths were similarly irregular, indicating either a lack of attention to accuracy in setting out, or a variety of different local or natural feet which are difficult to identify and almost impossible to prove. But we can try: Dirleton, the only church with a whole number of squares in its plan, has a width of 6.9 metres, 22 feet exactly of Scots feet of 3.3 millimetres, that is one third of a 37 inch ell as found in the plans of Holyrood Palace by Bruce and Mylne (Appendix II Section 2). Here is possibly an indication of the early use of this foot.

The wall thickness at Dirleton is very difficult to measure, being well endowed by the plasterer, and it would be rash to try and make any hard and fast claims but it would seem to be just in excess of three and a half feet which may indicate that the same Scots foot was used for this dimension. If indeed it was then we can perhaps chart for this building at least a change from the old practice of using different units for the walls and the overall dimensions.

At Glencorse, similarly, a foot of 291 millimetres gives an internal width of 19 feet and a wall thickness of the almost standard two and three quarter feet. At Abdie a foot of 296 millimetres gives a width of 16 feet and wall thickness of three feet exactly. One could go on to guess at the units used in all these and other buildings and the answers found might well be correct, but without the corroborative evidence of building contracts, they can never be proved.

The similarity in concept of many post-Reformation churches to those simple barn-like antecedents of the thirteenth century has already been mentioned. The similarity is more than just superficially apparent: overall dimensions of width and height are very similar generally and so is the preference for side walls of, mainly, $2\frac{3}{4}$ feet thickness. Perhaps this is an indicator that ideas and 'rules', if there were any, had not actually changed in three centuries and more, for the building of these simple structures. For other recognizable influences over wall thickness calculation we look in vain. There is little difference in size or proportion of any of these buildings, and the groupings on the cluster charts only perhaps tell us that wall thickness for such structures had now become a matter of rough standardisation, if indeed it had not always been so.

10.7 GABLE END WALLS

There was one other concern or influence in choosing wall thickness for some churches which may have absolutely nothing to do with structural strength. The study so far has concerned itself exclusively with the side walls of churches. These are of course longer than end walls and bear any overturning stresses imposed by the pitched roof or vault. The end gable wall by comparison has a relatively benign structural role to play, simply having to bear the load of the end of a ridge pole and any purlins of a timber roof structure. According to Rondelet's theories this end wall could be thinner than the side walls and logic might support this view. Why then in numerous medieval churches in Scotland and possibly elsewhere do we find precisely the opposite: an end wall that is considerably *thicker* than the side walls.

The most likely answer is to be found in an aesthetic dimension. Ever since in Norman times a veritable art form was made out of the so-called 'ordered' or layered arch. It is generally believed that this phenomenon evolved out of the desire or need to economise on centring for arch construction - a simple arch of a single voussoir's depth could be constructed on a narrow timber formwork, and then this arch itself could serve as the centring for a thicker arch above, and so on until the thickness had been achieved that was adequate to support the wall above. Such a system provided a magnificent field of layers of increasing radius for sculptural or linear embellishment, such as can be found on nave arcades and windows but more especially on western portals. Such was the importance attached to this art form that on some structures such as Jedburgh Abbey, a specially thickened section of wall is to be found awkwardly protruding from the main structure at the western entrance in order to accommodate a finely sculpted and deeply splayed portal. This, in a word, can only the logic behind the thicker end gable walls. Unfortunately it is not always a dimension that is possible to measure, but where it was possible, this wall, particularly at the eastern end where there were finely cast windows over the altar such as at diminutive Cockpen, was found to be thicker than the side walls. The difference in many cases amounted to little more than a few inches but it was nevertheless a difference that was intentional and calculated.

10.8 CONCLUSIONS

10.8.1 *The height / span question*

Whilst for the Norman period a reasonably clear case emerged for a system based on quadrature in the building plan, both in the additive and the manipulative senses, with a perceived preference for working in multiples of binary fractions of a foot, whether natural or standard 'modern', the Gothic era presented a more elusive solution or range of solutions. There seem to be good arguments that wall thickness was based more on height, but equally convincing data suggesting that span was the dominant influence. Certainly consideration of height had by this time been brought into the design process, and was likely to have been considered of even greater significance after the collapse of Beauvais in 1284, although it may be unwise to attribute too much to this event alone. There were, after all, many disastrous collapses closer to home (I Braun 1985: 230-232). There seems to have been a level of experimentation, possibly diversity of practice in this period, although some commonality of approach is noticeable, particularly in the individual comparisons where some structures of differing overall size were found to share similar proportions. There is evidence to suggest that ideas on slenderness were common to both these simple church types and to free-standing walls, and it should be recalled that the 1535 Barmkin Act indicated a conscious awareness and use of slenderness ratio by that date, but span was undoubtedly also an issue. Any final judgement will always be against the background that there were certain accepted conventions of the relationship of height to span in church design, and these varied according to what status of church was proposed. Further variations might be made as final adjustments by eye to suit the particular project. We have evidence for all this in the *Lettere Sanesi* concerning Siena Cathedral, in Lechler's instructions, and in the survey measurements taken, which showed fairly constant trends for each church unit type (i.e. cathedral choir, collegiate/parish church choir, collegiate/parish church transept, etc.). Against this, there is always a possibility that some architects will have simply used a certain standardized wall thickness, probably around three feet or a binary fraction either side thereof, for certain building types. How can all these possibilities be reconciled or explained?

Let us return for a moment to the cluster charts. With the elimination of the Norman cohort these had begun to show more consistent patterns. However, are they even now revealing a true picture? Are they being corrupted by other outliers which could justifiably be removed or repositioned? The exceptional proportions of the Peebles Crosskirk have been noted and may justify removal. The same might apply to Dunblane, because it was probably built much higher than originally intended, but if so perhaps it would be fairer to move it to a position on the chart reflecting the 7 metre height that (approximately) would have allowed the nave east windows to look outside rather than into the choir roof. The wall thickness of Culross lay brothers' choir was based only on its ghost on the tower wall, and this did not account for the use of buttresses if there were any. Its abnormal slenderness would strongly suggest that buttresses did indeed augment the original wall thickness and perhaps because of this a conjectural 0.43 metres should be added to represent half a theoretical buttress projection. (This dimension has been chosen as it is the same depth as the wall thickness, a concept based on the situation at Dunkeld, whose walls are a similar slenderness ratio). What does the height chart look like now?

Figure 10.22 Unvaulted Churches (omitting Norman and Peebles and amending Dunblane and Culross) - Height:Wall Thickness

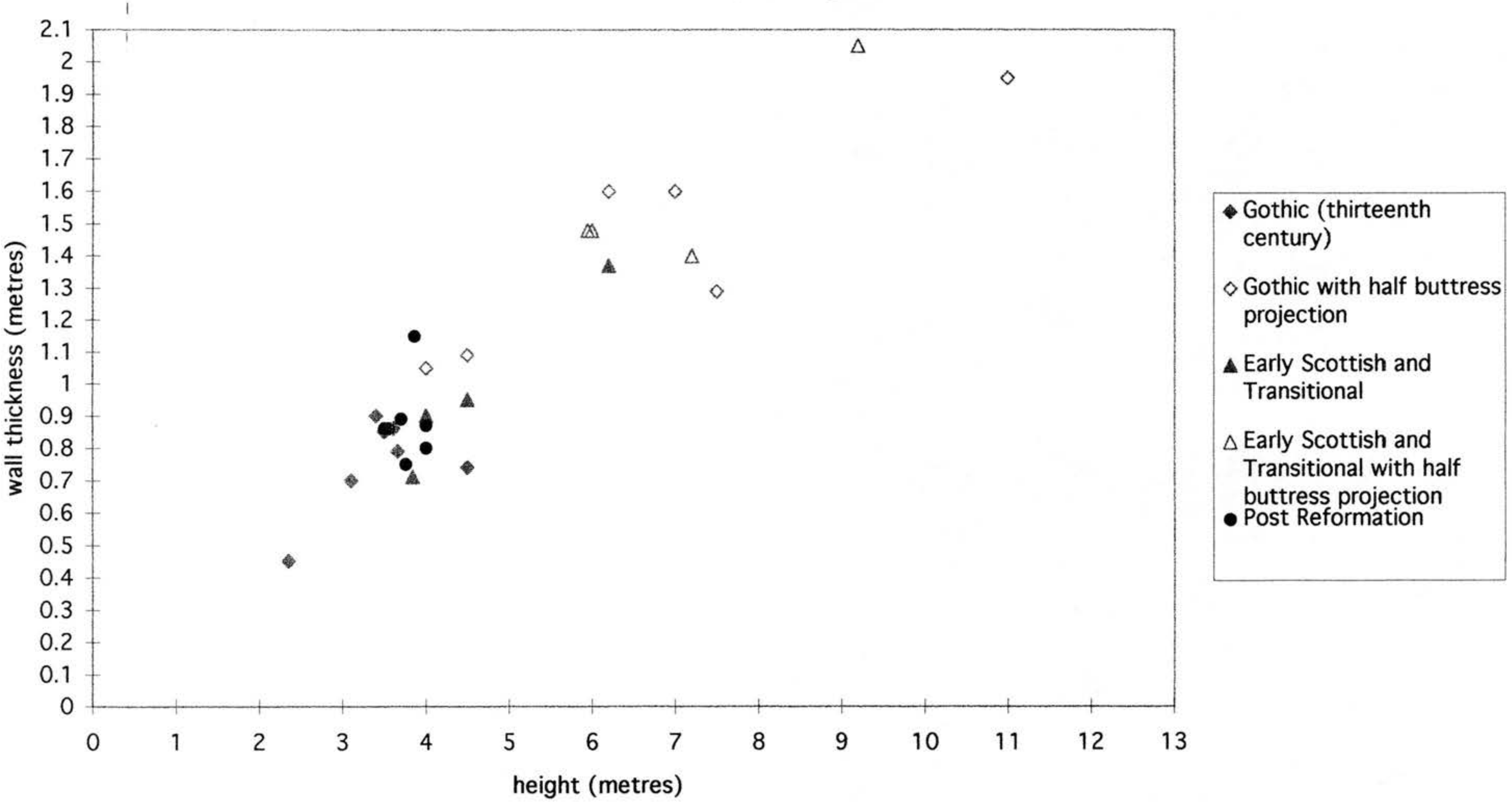
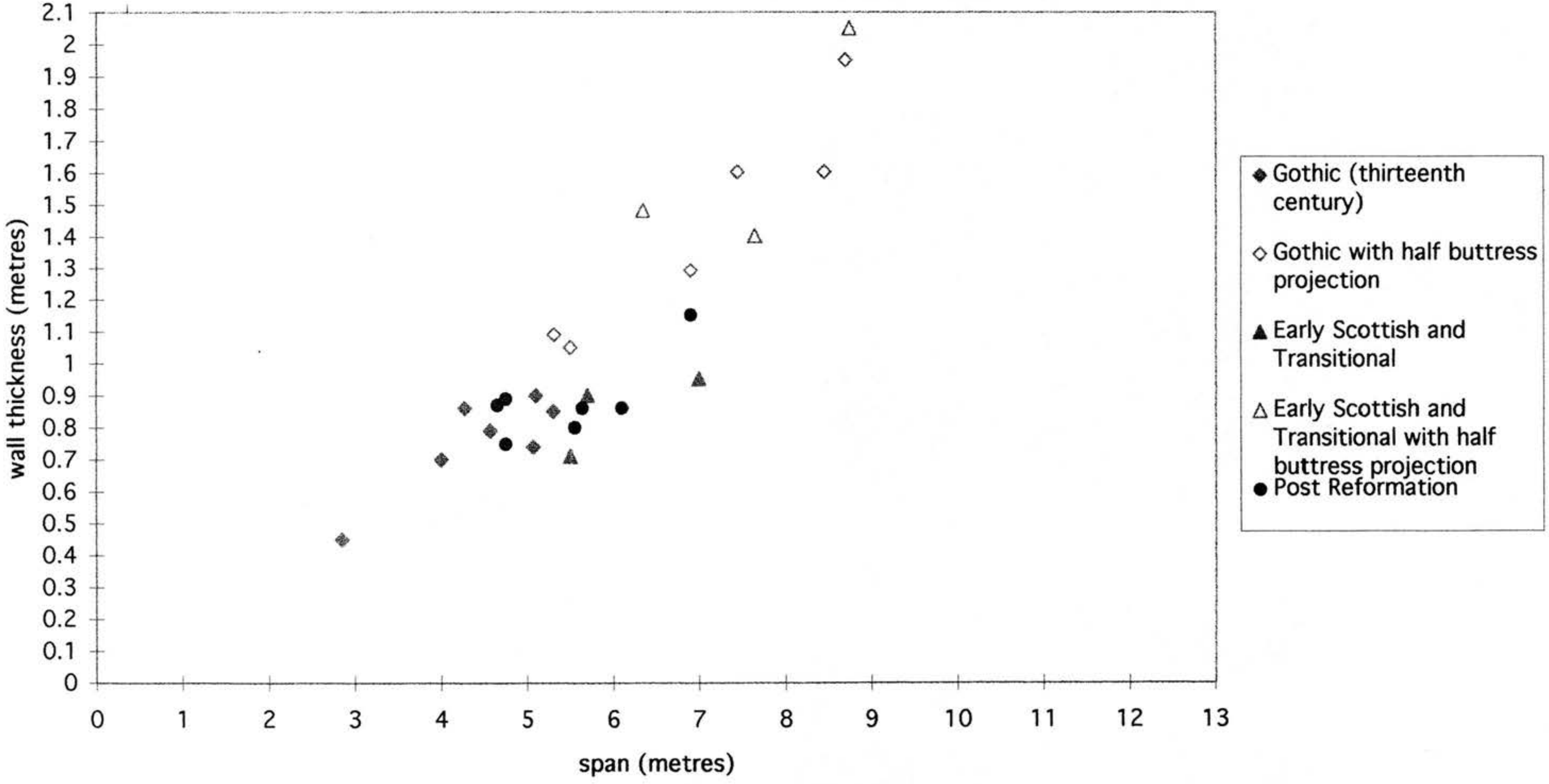


Figure 10.22 shows a remarkably tidy trend which might confirm height as the more significant influence over wall thickness. However, do similar adjustments have an equivalent effect on the span chart?

In the case of span relationships, different parameters and other conditions apply which require that the position or existence of other churches require some review. It has been noted already that transepts were uncharacteristically narrow in relation to their height and wall thickness because these dimensions were more commonly aligned with those of the main church body. Those of South Queensferry and Biggar Churches ought therefore to be either adjusted accordingly, or deleted from the chart. For the latter, the dimensions would simply become the same as those of the nave, which is already shown. For South Queensferry, it is very difficult to judge what adjustments to make since the choir is vaulted and the nave has been lost. From the thickness of its walls, it is conceivable that the transept itself was actually intended to be vaulted, but there is no way of proving this. It is safer to count it as an outlier and eliminate it from the chart. As in the height chart, the inexplicable proportions of Peebles Crosskirk make it a candidate for elimination, and the addition of the same nominal 0.43 metres is made for abutment to Culross. The result leaves little or nothing to choose between the trends in both height and the new span charts (figure 10.23), and the problem of distinguishing which of height or span was more influential over wall thickness is no nearer being solved, although perhaps the apparent dominance of height in the paired comparisons should be borne in mind. However, a lot of useful light has been shed on the question, perhaps enabling some educated guesswork. Let us try and piece together some elements of the design process.

Fig. 10.23 Unvaulted Churches (omitting Norman and outliers* & amending Culross) - Span:Wall Thickness



* Peebles, Biggar transept, South Queensferry transept

The initial proposal of building any church will have presumably brought with it some idea of the internal spatial requirements, just as Lechler's instructions began with the size, and specifically the width of the choir. From here various possibilities present themselves as forming the next steps in the design process:

1) Some architects may, as Lechler did, size the choir wall thickness in a directly proportional relationship with the choir width. But this takes no account of height.

2) There will have been some established convention of the height that a particular church unit should be in relation to its width, which will have varied dependant on what class or status or level of sophistication is required. Lechler mentioned various alternatives in his instructions concerning the choir.

3) If, in general terms, wall thickness was determined by both span and height equally, it is difficult to conceive any way in which this must have been achieved except one: use of some diagonal measure in the building's section. Such a method as proposed by Rondelet in the 19th century was mentioned from the outset in this chapter and, as a simple tool which required only pegs, string and measuring rod, has to be reconsidered as a possibility for the medieval architect's method of wall-sizing in this category of building at least. Although showing a degree of variation, the results of applying the method to the survey sample did show a stronger trend or pattern than either span or slenderness ratio in isolation. How do they look now, after taking into account the alterations made to the cluster charts?

Figure 10.24 shows the same table as that of figure 10.9, but omitting Peebles, adding buttresses to Culross and lowering Dunblane choir. This is the tidiest table yet formulated, and seems to confirm that some method or methods of wall thickness calculation using a diagonal manipulation was probably used.

Figure 10.24 UNVAULTED CHURCHES: RONDELET'S DIAGONAL METHOD with outliers amended or deleted

(Appendix I Section 2.1.3)

Ratio	12th Cent. Norman	13/14th Cent. Gothic	Early Scottish	Transitional	Post-Ref
1.7					
1.8				B	
1.9				B	
2					
2.1					
2.2				B	
2.3					
2.4				b	
2.5		B B B			
2.6		B			
2.7					
2.8				b	
2.9		B B B	T B		
3		b b		b	1
3.1		1 1 b			
3.2					A
3.3	Q				A
3.4	Q	1			
3.5	Q	N **1** b Q			1 A
3.6	Q N N	**N**		1	
3.7		b			
3.8		**1**	b		1
3.9	N	P b			
4	Q Q			**T**	1
4.1	Q	**1**	N		
4.2	N Q				
4.3				1	
4.4				**1**	
4.5	N	1			
4.6					
4.7	N				
4.8	N	**Q**			
4.9	N			**Q/N**	
5	N				
5.1			**Q**		
5.2					
5.3	N				
5.4		**Q**			
5.5					
5.6					
5.7					
5.8					
5.9		**N**			
6					
6.1					
6.2	N				

1	Church of nave & chancel/choir in single unit.
N	Nave (to which separate chancel/choir attached).
Q	Choir/chancel (to which separate nave attached).
C	Separate apsidal chancel (Norman only).
T	Transept.
A	Aisle, set at right angles to nave.
P	Porch.

Any of the above **emboldened** and underlined indicates that feature buttressed, but assessed on wall thickness alone.

B	The same assessed on wall thickness plus entire buttress projection.
b	As above, but with *half* buttress projection. (Not shown where only pilaster buttresses)

10.8.2 *The medieval concepts of 'wall' and of 'abutment'*

The clustering of figures with full buttress depth (B) in the 13/14th century is perhaps particularly instructive, and beggars the question, were the architects of that period thinking in terms of the *entire* abutment, rather than of separate entities of walls plus buttresses, rather in the same way that Rodrigo Gil wrote of "buttresses" when he actually meant "walls, plus buttresses"? Are we here perhaps looking at a development of the concept suggested by Norman pilaster buttresses, whose projection had been defined by quadrature? In such cases, (Duddingston, Cockpen and possibly corroborated by the walls of Castle Sween), it seemed as though the wall thickness itself was thought of as the total of wall and pilaster buttress combined. This was compared with Alberti's concept of a colonnade as being a wall with the masonry between the columns cut away, i.e. in the medieval mind pilaster buttresses represented the true wall thickness; they were the columns buried, as it were, and just protruding from the infill masonry mass between them. In the later Gothic period, are we perhaps seeing a natural progression from this, where the *entire* wall thickness plus buttress projection was actually regarded by some at least as simply *'the wall thickness'*, or by others as simply *'the buttress'* , or perhaps even in archaic terms, *'the column'*? At Crossraguel for instance the total abutment of the fourteenth century nave was 1.9 metres made up of 1.3 metres wall and 0.6 m. buttress, whereas in the fifteenth century choir the figures are respectively 1.8, almost the same, but made up of a thinner 1 metre wall and greater 0.8 metre buttress. Did the later architect believe he was achieving what he would have thought as an equivalent 'wall thickness', because his *total* abutment was almost the same as the earlier nave? Times had moved on and structural concepts will undoubtedly have changed or developed. Economy may have become a greater issue, and the masonry between the buttresses, effectively what Alberti and possibly many others might have considered to be expendable material that, in archaic terms, could be removed to form a colonnade, was indeed left thinner. There is a real possibility that our present historical conception of Norman and Gothic architecture does not accord with that of its creators, and requires some revision. However the medieval architect regarded structure, it will be hard to prove, and certainly would require a great many more examples.

Whether or not all these deliberations have cracked even part of the medieval architects' code for the design of simple roofed structure at a general level remains to be seen. Whilst the Norman and post-reformation periods appear relatively straightforward, the complexities of the gothic era require a great many more examples in order to define beyond doubt what general rules there may have been, particularly where buttresses are present. What has become clear is that the subject, as expected, is characterized by individual solutions, by experiment, by alterations after building has commenced to the original design, even by idiosyncrasy. Few generalisations hold good for the great number of examples. Unfortunately there are very few other buttressed single-cell churches in Scotland. The net must be spread wider, but that is for another day. In the meantime the surface of the subject has at least been scratched.

10.8.3 *Some individual 'revelations'*

Whilst certainties are still sought at a general level, the work so far has produced many individual discoveries of interest and possibly of importance:

1) the extent to which the walls of Peebles Crosskirk are exceptional;
2) that Culross Lay Brothers' choir probably had buttresses;
3) that the original design for Dunblane choir was probably considerably lower than the finished structure, as Fawcett has suggested;
4) that there may have been an intention to vault the transept of South Queensferry church;
5) that a number of structures were found to have been invested with considerable geometric sophistication, particularly Dalmeny and Cockpen, but that such quality was by no means commonplace;
6) that Rondelet's method of defining wall thickness by means of a diagonal seems to be a useful tool for the analysis of these buildings and suggests that medieval architects may also have used such a device, or another with similar effect;
7) that some other comparative means or methods have been posited, by which these buildings can be analysed, and such discoveries made.

It now remains to be seen whether similar practices are to be found in unvaulted domestic work, and also in vaulted structures, both ecclesiastical and domestic.

11 UNVAULTED DOMESTIC including MULTIPLE TRANSVERSE VAULTS

11.1 INTRODUCTION

This category of building is, at a general level, the first to be covered in which such issues as aesthetic proportionality and design are likely to have played less if any part in the creative process. With the exception of a handful of early stone hall houses, here are much more utilitarian buildings which may be generally classifiable as vernacular rather than of architectural merit. They comprise mainly ranges of buildings round a courtyard for the purposes of either accommodation or services. Many of this class were more commonly vaulted at ground floor level, sometimes with longitudinal vaults, which will be dealt with separately later, sometimes with multiple transverse vaults. In this latter category, because the long side walls merely close the end of each vault rather than providing abutment for its lateral stresses, they should theoretically be comparable with those of similarly sized unvaulted structures. They have therefore been included in this section.

The surveyed examples are listed in Figure 11.1, the buildings with multiple transverse vaults being distinguished by appearing in italics. Whilst some of the latter do have thicker walls at ground floor level, so also do some unvaulted structures. Perhaps less predictably, two of the vaulted examples actually have *thinner* side-walls at ground floor level than above.

Apart from the few stone hall houses, buildings of this category of earlier than the fourteenth century were less commonly constructed of stone than timber, and simply do not survive. The stone hall house group present some problem since their original height is uncertain. Of course there were stone domestic buildings in monastic ranges from the twelfth century, but more often than not these are too ruinous to be of use, or are unsuitable because they are either vaulted or they are not free-standing, or both.

Few structures from the fourteenth until the mid sixteenth centuries survive which are suitable for this research. The small number of sites included from this period are nearly all partly fortified. That is, each one is part of a group of buildings

Figure 11.1 DOMESTIC UNVAULTED and MULTIPLE TRANSVERSE VAULTS (*shown in italics*)

Date	Site	Height to wall-head	Internal width (m)	Wall thickness unfortified (m)	Wall thickness fortified (m)	Slenderness Ratio	Span Ratio
12C	Bishop's Pal. Kirkwall	?	6	1	-		
13C	Craigie hall ho.	?	7.4	-	1.8		
1200	Aberdour hall ho.	?	7.4	-	1.8		
13C	Skipness hall ho.	?	6.8	-	2.2		
13/14C	Rait hall ho.	c.7.8	6.6	1.2 end	1.8 sides		
M14C	Tantallon hall (W) Rg.	8.3	GF 6.15 1F 6.45	1.25 1.15	2.5 2.3	6.6	5.25
M14C	Tantallon gatehouse twr.	c.22.0	6.2	1.0 side	1.85 front 1.3 rear with fireplaces	22	6.2
14C	Balmbreich hall (S) Rg.	10+	5.3	1.3	1.8	7.7	4.1
14/15C	*Crossraguel Dorm.*	*6.1*	*5.55*	*1.15*	-	*5.3*	*4.8*
E15C	Bothwell hall Rg.	8.65	GF 9.18 1F 9.9	1.1 0.95	1.73 1.18	8.5	9.4
M15C	*Crichton Chlr. Crichton's (S) Rg.*	*13*	*8.1*	*1.7*	*2.05*	*7.6*	*4.8*
15C	Crichton (W) accom twr.	c.18.0	4.3	1.0	1.6 1.8 with fireplaces	18	4.3
15C	Caerlaverock (W) Rg.	7.4	4.83	0.94	2	7.9	5.1
1530s	Balmbreich 3.8 (NW) rg.	11.25	4.6	1.2	(1.85) (original 14C curtain)	9.4	
1553-	*Edzell Gatehouse Rg*	*8.7*	*GF 5.35* *1F 5.15*	*0.85* *1.0*	*1.05* *1.05*	*9.4*	*5.7*
16C	Huntly (W) Rg.	7.0	4.4	0.9	1.7	7.8	4.9
M16C	Brunstane	6.0	4.27	0.86	0.86	7	4.9
M16C	Dryburgh Abbey gateho.	6.3	3.5	0.72	-	8.75	4.9
L16C	*Edzell (N) Rg.*	*12.4*	*7.2*	*1.1*	-	*11.3*	*6.5*
L16C	*Balvenie Palace Rg.*	*11.5*	*GF 5.5* *1F 6.3* *2F 6.75*	*1.5* *1.4* *1.2*	*2.2* *1.5* *1.25*	*8.5*	*4.6*
L16C	*Musselburgh Tolbooth*	*9*	*GF 5.4* *1F 5.6*	*0.95* *0.85*	- -	*10*	*5.5*
L16C	*Tolquhon Dining Rm Rg.*	*9.25*	*5.5*	*0.9*	*1.1*	*10.3*	*6.1*
L16C	*Tolquhon Gallery Rg.*	*5.5*	*GF 4.6* *1F 4.25*	*0.85* *1.03*	- -	*5.85*	*4.7*
L16C	*Tolquhon Gatehouse Rg.*	*5.7*	*2.5*	*0.5*	-	*11.4*	*5*
L16C	*Newark (Pt Glasgow) Dining Hall Rg.*	*10.8*	*6.6*	*0.72*	*(1.0)* *(earlier hall range wall)*	*15*	*9.2*
1580's	Dunnottar Gallery Rg.	5.55	4.5	0.8	-	6.9	5.6
1580's	Dunnottar stables Rg.	4.5	4.1	0.84	-	5.4	4.9
1589-	Linhouse (S) Rg.	7.3	5.1	0.71	-	10.3	7.2
1597-	Culross Main Block	3.8	4.2	0.7	-	5.4	6
1597-	Culross Guest Block	4.2	3.9	0.8	-	5.2	4.9
L16/E17	Whitekirk Tithe Barn	5.95	4.5	0.7	-	8.5	6.4
1600-	Lamb's House, Leith	10	5.75	0.8	-	12.5	7.2
1611-	Culross Guest Block	6.8	5.5	0.8	-	8.5	6.8
E17C	Aberdour Stables/Gallery	6.6	4.5	0.93	-	7.1	4.8
1631-	Linhouse extension	7.3	4.9	0.8	-	9.1	6.1
1638-	Auchans extension	9	5.2	0.86	-	10.5	6
1660's	Craigmillar (W) Rg.	6.1	5.35	0.83	-	7.3	6.4

Dates:				
	E	early	1F	first floor;
	M	mid	GF	ground floor
	L	late	Rg.	range
	C	century	ho.	House

NB where dimensions differ on each storey, an average has been used to calculate slenderness and span ratios forming a fortified enclosure, or courtyard complex, and therefore in most cases the courtyard side of these buildings can reasonably be assumed not to be fortified. Comment has already been passed on the subject of fortification in connection with free-standing walls, when the examples discussed in this chapter were used for comparison with those structures.

As in the last chapter the question must now be addressed, on what basis was wall thickness calculated? Was it materially affected by either span or height? There are some notable differences in this building type, however, which affects the issue. The churches, it will be recalled, generally conformed to certain conventions of overall proportion, that is the ratio of the internal span to the height to the wall-head. These domestic structures of course do not share such characteristic and, in any event, they are of different numbers of storeys, though most are of two or three.

11.2 WALL THICKNESS

Figures 11.2 and 11.3 set out the slenderness and span ratios for the survey sample and it is immediately very obvious that neither height nor span seem to have been particularly consistent influences on wall thickness. There are, however, three trends which are worthy of note: firstly the very evenness of the level of inconsistency throughout, which is only broken by, secondly, a noticeable clustering in span ratio around 1: 4.8 which indicates the possible use of quadrature, the rotation of the diagonal of the core square. Thirdly, the number of thinner walls increases in the post reformation period. In order to set all this in context, a chronological appraisal is appropriate.

Figure 11.2 DOMESTIC: UNFORTIFIED, UNVAULTED, and MULTIPLE TRANSVERSE VAULTS

SLENDERNESS RATIO

Slenderness Ratio 1:	Anglo-Scot	Wartime	Early Scot	Transitional	Post Ref
5					
5.25			V		1
5.5					1 1
5.75					
6			1		V
6.25					
6.5		1			
6.75					
7		1		1	V 1 1
7.25					1
7.5					
7.75		1	V 1	1	
8					
8.25					
8.5					1 1
8.75				1	
9					1
9.25					
9.5				1 V	
9.75					
10					V
10.25					V 1
10.5					1
10.75					
11					
11.25					V
11.5					V
11.75					
12					
12.25					
12.5					1
12.75					
↕					
15					V
↕					
18			1		
↕					
22		1			

Ratios have been rounded to the nearest quarter point
Where wall thicknesses are different at each level, the *average* has been used to calculate slenderness ratio

1 Unvaulted building based on slenderness ratio with unfortified wall thickness
V Vaulted building based on slenderness ratio with unfortified wall thickness

Figure 11.3 DOMESTIC: UNFORTIFIED, UNVAULTED, and MULTIPLE TRANSVERSE VAULTS

SPAN RATIO

Span Ratio 1:	Anglo-Scot	Wartime	Early Scot	Transitional	Post Ref.
3.7					V
3.8				1	
3.9					
4					
4.1		1			1
4.2					
4.3			1		
4.4					
4.5					
4.6					
4.7					
4.8		1	V V		1
4.9		1		1	1 1
5				1	V
5.1			1		
5.2					
5.3					
5.4					V
5.5					
5.6					
5.7					V
5.8					
5.9					
6	1				1
6.1					1 V
6.2					
6.3				V	
6.4					1 1
6.5					
6.6					
6.7					
6.8					
6.9					1
7					
7.1					
7.2					1 1
7.3					
7.4					
7.5					
7.6					1
↕					
8.3			1		
↕					
9.3					V

Where wall thicknesses are different at each level, that of the ground floor only has been used to calculate span ratio

1 Unvaulted building based on span ratio with unfortified wall thickness
V Vaulted building based on span ratio with unfortified wall thickness

11.2.1 *Anglo-Scottish and Wartime*

Of the earlier examples surveyed, the internal span was generally wider than that of later structures, mainly falling into the range of 5 to 10 metres, perhaps reflecting the relatively public nature of life and society in the feudal period. Before the fifteenth century unfortified wall structure had been around 1.1 to 1.3 metres thick if the few examples shown can be said to be representative. The approach to security seems to consistently hover around a wall thickness of 1.8 metres (6 feet) in some cases, and 2.2 to 2.5 in others.

11.2.2 *Early Scottish and Transitional*

In the fifteenth century there is a perhaps surprising consistency in the thickness of 0.9 to 1 metre (around 3 feet) for an unfortified wall, and this continues right through the seventeenth century, with a few exceptions of taller structures. Fortification again seems to perpetuate the earlier perceived wisdom in requiring around 1.8 metres (6 feet). The instances where this is exceeded become fewer.

Before progressing to the sixteenth century there are two very tall buildings which are worth examination in closer detail. The 18 metre height of the mid fifteenth century Crichton accommodation tower (not to be confused with the fourteenth century tower house), and Tantallon gatehouse tower (22m.) make these structures of particular interest. Typologically they are difficult to categorize: they neither really fit in this chapter which is concerned mainly with two and three storey structures, but nor do they sit comfortably beside tower houses which are free-standing, vaulted and fortified on all sides. Again the 1.8 metre norm for fortification applies where appropriate, but a feature of particular interest in these two tall structures is the use of very thin walling (1 metre) where possible.

At Crichton the two adjacent unfortified walls are only one metre thick and possibly are so because of the use of quadrature, rotation of the diagonal of the core square, though this is only approximate to within about 9 centimetres. The two side walls of Tantallon are of similar dimension and the slenderness ratio of these walls roughly reflects the commonality of practice reflected in the treatises of Alberti and Stieglitz, the slenderness ratio of 1: 20. However, it must be borne in mind that both these Scottish examples were stiffened both by thicker adjacent walls, and by the other structures to which they were attached. They were not free-standing in the same way as those referred to by Alberti and the author of the Stieglitz treatise. Furthermore, it will be recalled from the section on free-standing walls, that a minimum thickness of only 0.7 metres was found in a variety of buildings back at least as far as the fifteenth century, where fortification was not required, and some earlier curtain walls were also only one metre thick. The similar dimension found in these situations at Crichton and Tantallon is not necessarily to be wondered at. It only appears to be uncharacteristically thin when juxtaposed with the adjoining walls.

One further complication arises with these two structures. Whilst having both obviously fortified and unfortified walls, there is evidently a third type of wall which is potentially significant.

11.2.3 *The Service Wall*

At Tantallon, whilst the side walls are whittled down to a mere 1 metre, the north wall facing into the courtyard is 1.3 metres. Now it is conceivable that it is stronger to face attack from that side should the curtain wall be breached. But it is also the wall which bears all the fireplaces, one on each level, and the chimney flues within its thickness. In view of its obvious 'service' function, such structures will henceforth be referred to as service walls. Significantly perhaps, a similar feature is to be found at Crichton. The two adjacent outer walls are obviously fortified but one is thicker than the other (1.8 metres against 1.6 metres) and it now comes as no surprise to see why: it bears two fireplaces. What is also significant about these two examples is that the *entire* wall is thicker; there is no thought in the fifteenth century of standardising the wall thickness at the required level and then adding some extra masonry specifically at the appropriate point to accommodate a particular 'service': in this period the norm is a complete all-embracing service wall.

11.2.4 *Later Economy and Fortification*

From the mid-sixteenth century what is immediately noticeable in these domestic buildings is the consistency with which almost *any* building has wall thickness of between 0.7 and 0.9 metres irrespective of height, right up to the 10 metres or so of Lamb's House, Leith. It is only in the cases of the slightly earlier

Balmbreich NW range, Edzell's north range and the Balvenie palace building that a thicker wall coincides with greater height. Apart from those three, perhaps it is significant that a similar thickness of 0.7 to 0.9 metres was consistently noted in small aisleless churches of this period, particularly around 0.86 metres ($2\frac{3}{4}$ feet). In common with that category, it should be noted that few of the examples surveyed exceeded 6 metres in internal width. There are a very few later buildings of wider span, Heriot's Hospital and Parliament Hall in Edinburgh, for instance, but generally the requirement for such span was now reduced - the age of big churches, and grand feudal halls was largely past. Life that had been relatively public and/or communal was increasingly becoming more private and familial. From the early seventeenth century the internal 'spine' wall, as at Culross Abbey House and Linlithgow Palace North range was increasingly used to divide up excessive spans. Furthermore, in the structural design of the latest generation of buildings from the mid sixteenth century, great or small, an increased tendency towards economy, even structural sufficiency, seems now to be an overriding factor in building, probably much more so than previously. This conclusion is, of course, open to some debate in the light of at least one other possibility: there may have been just as many structures of similarly thin walls of earlier periods, which have been the first to suffer decay, collapse or destruction, and are now therefore disproportionately rare. Notwithstanding this, it is perhaps significant that by this time the 1535 Barmkin Act had been passed, with an obvious awareness of the logic of slenderness ratios, the thinking behind which is very much in line with a more economical approach generally.

Where an extra level of security was required, it is noteworthy that greater thickness was occasionally deemed necessary well into the sixteenth century by some (e.g. Huntly, west range), and moreover it was around the same standard thickness as in earlier times. Worthy of individual mention in this respect are the walls of the late sixteenth century palace range at Balvenie which are stepped to become progressively thinner at each storey, having an obviously fortified thickness of 2.2 metres at ground level. The untypical occurrence of this dimension at that time, together with the very obvious tactical sighting of gun ports in the adjacent round tower which enfilade the main entrance, reveal all too clearly that security or perhaps even serious defence was actually of high priority in this particular instance, which flies in the face of claims to the contrary about Balvenie by McKean (VII 1995: 1). Meanwhile at other properties of similar date such as Brunstane, the owner either could not afford thicker walls, or felt quite secure without them, or realised that they offered little protection against medium to heavy firearms, or felt no threat from anyone who might possess such weaponry.

11.3 SUMMARY AND CONCLUSIONS

To summarize the few points of general significance arising from these figures: first, in a few cases throughout the entire period quadrature appears to have been used to derive the wall thickness from the internal span. However, particularly in the post reformation era, it cannot be stated with certainty that the few cases occurring were not purely coincidental. Although comprising a discernible group within that period, they are considerably fewer in proportion to the period total than those of earlier times.

There are several points concerning slenderness ratio which are worth recording. Firstly, it never significantly exceeded the 1:20 recommended by Alberti and the Stielitz Treatise for towers, and then only in structures (Tantallon and Crichton accommodation towers) with thicker adjacent walls. Secondly, (and apart from the two exceptional examples just mentioned) it was only from the Transitional period that the ratio fell into the range 1:8 - 1:12 found by Rondelet in his research on free-standing walls. Coincidentally it was in this period that the 1535 Barmkin Act was passed setting a standard of 1:6 for free-standing Barmkin walls. The ensuing very diverse spread of slenderness ratios might be argued to indicate a total disregard of this as a structural design tool. However, there may be another way of looking at this situation. As was concluded earlier, there was an obviously *conscious* choice of a slenderness ratio in the Act, and this coincided with that of the Edinburgh Flodden Wall. The concept seems now to have become embedded in the structural understanding of the building trades. From that time onwards the slenderness ratios for most structures actually fell in a higher range: around 1:8 - 1:12. Granted, there are others of lower ratio, but those do so, not because of profligacy or incompetence, but because they were relatively low buildings, not exceeding around 5.5 metres, and builders were obviously in the habit of conforming to a generally accepted minimum thickness of $2\frac{3}{4}$ feet. Rarely do walls appear less than this dimension, no matter how low. This was probably quite justifiable in view of the relatively unstructured rubble walls that were then the norm. Walls of perfectly squared and coursed ashlar blocks might well have told a different story. This minimum was found only in one example to have been disregarded: the Tolquhon entrance range.

So, again, while both slenderness and span may have had some part to play in building design, a minimum basic dimension became increasingly standardized. The two exceptions to this trend are firstly service walls which would obviously be sized according to the services they were required to accommodate; secondly fortified walls where a relatively consistent standard of about 6 feet thickness was adopted from early, right through to the mid sixteenth century; the incidence of those walls over 2 metres thick becoming progressively less common.

12 SMALL VAULTED CHURCHES

12.1 INTRODUCTION

This group comprises almost exclusively structures of the late medieval period - the fifteenth century through to the early years of the sixteenth, mainly churches or church units that were collegiate, and represents a tradition of barrel vaulting that, whilst by no means restricted to this period alone, is only commonly found in ecclesiastical building at that time. The few examples dating thereafter, and particularly post-Reformation, are aisles that are relatively insignificant, with one exception, the grandly classical Archerfield Aisle at Dirleton Church, more a transept in scale, with its accurately semi-circular vault.

As regards canons of overall structural proportionality, it will be recalled that unvaulted churches tended to conform to certain generalized conventions which governed the proportions of overall structural height to span: the Norman twelfth century was characterized by church units that were slightly taller than their width. Thereafter the opposite was the case, excepting transepts. Now with these later barrel vaulted churches when the height is taken to mean the point at which the vault springs, an identical situation to the unvaulted churches is found (figure 12.1): choir/chancels are wider than their height, and the ratio of 1: 0.8 is noticeably popular, particularly for choir/chancels; the opposite, vertical emphasis was again more popular for transepts. Thus, examples up to '0.9' are wider internally than their height to vault springing; those over '1' are higher than their width.

Figure 12.1 VAULTED CHURCHES: SPAN : HEIGHT RATIO
(i.e. span : height of vault springing)

Ratio 1:	12th/13th Cent.	Early Scottish	Transitional	Post-Reformation
0.4		S		
0.45				
0.5				
0.55				A
0.6		T		A
0.65			Q	
0.7		Q Q		
0.75				
0.8		A Q Q Q N		A
0.85	1	Q		
0.9			A	
0.95		P		
1		Q T T		
1.05		Q T T		
1.1		1 T T T		
1.15				
1.2				
1.25				
1.3		P S		
1.35		S		

N	nave
Q	choir/chancel
1	combined nave/choir/chancel in one unit
A	aisle
T	transept (these are invariably higher than their width, since their height is dictated by the rest of the church but their function does not require the same width as the nave or choir)
P	porch
S	sacristy

12.2 WALL THICKNESS DETERMINANT - HEIGHT OR SPAN?

It will be recalled that the wall-thickness of unvaulted churches was found to be largely dependent on span in the Norman period through the use of quadrature, but thereafter the situation was far from clear. From the generalized statistical analyses there was little to choose. In the end, the possibility of some design method using a diagonal as described by Rondelet had to be considered most likely, particularly in view of the height / span conventions prevailing at that time. But all that was for unvaulted structure. The writings of both Lechler and Rodrigo Gil on *vaulted* structures, it will be recalled, emphasized the relationship of wall thickness to *span*. The situation is complicated again by the fact that there was an obviously conventional proportional relationship between the height to eaves or springing and span. An understanding of the unvaulted churches was achieved at one level by comparison of pairs of examples. A similar approach is now made with the vaulted variety (Figure 12.2 & 12.3). Again, the principle of this operation is to compare one church unit against another, each pair sharing at least one similar dimension: either span or height or wall-thickness. The choice of pairs follows no pre-ordained agenda. They are of course only a sample. There is not the space to compare every unit against every other. Most of those not shown simply reveal similar proportional differences in all three dimensions. Those included show some variation in two of the dimensions, which may indicate which of height or span is most influential over wall thickness. For instance, in the first comparison the span of Ladykirk and Crichton choirs are almost the same, but there is a height difference which may logically be the reason for the thicker wall. Where buttresses are present the wall thickness should be read as the figure in the right hand column: 'WITH ½ BUTTRESS'

Figure 12.2 COMPARISONS OF *DIFFERENT* CHURCHES WHERE *HEIGHT* APPEARS TO DETERMINE WALL THICKNESS

SITE	SPAN	HEIGHT	WALL THICKNESS	WITH ½ BUTTRESS
Similar span but greater height and wall thickness:				
Ladykirk Q/N	7.1	4.75	0.93	1.63
Crichton Q	7.2	6	1.33	2.05
Seton Q	6.65	4.65	1.07	1.7
Bothwell Q	6.63	6.9	1.23	1.93
Borthwick A/T	5.8	3.35	1.04	1.6
Dunglass N	6	4.72	1.35	1.8
Dunglass T	4.2	4.34	.99	-
Crichton T	4.8	5.5	1.3	-
Aberdour A	3.51	2.06	0.75	-
Corstorphine S	3.5	4.75	1.15	-
Dirleton A/T	4.7	3.7	0.97	-
Crichton nT	4.75	5.4	1.3	-
Seton Q	6.65	4.65	1.07	1.7
Dunglass N	6	4.72	1.35	1.8

N	nave
Q	choir/chancel
1	combined nave/choir/chancel in one unit
A	aisle
T	transept
P	porch
S	sacristy

Figure 12.3 COMPARISONS OF *DIFFERENT* CHURCHES WHERE *SPAN* APPEARS TO DETERMINE WALL THICKNESS

	SPAN	HEIGHT	WALL THICKNESS	WITH ½ BUTTRESS
Similar height but greater span and wall thickness:				
Dunglass T	4.2	4.34	0.99	-
Carnwath A/T	5.25	4.3	0.83	1.42
Crichton nT	4.75	5.4	1.3	-
Seton nT	5.46	5.41	1.08	1.73
Corstorphine S	3.5	4.75	1.15	-
Ladykirk Q/N	7.1	4.75	0.93	1.63
Corstorphine S	3.5	4.75	1.15	-
Dunglass N	6	4.72	1.35	1.8
Greater height but similar span and wall thickness:				
Dunglass S	4.03	1.67	0.96	-
Seton S	3.86	5.08	1	-
Greater span and wall thickness but less height:				
Crichton nT	4.75	5.4	1.3	-
Carnwath A/T	5.25	4.3	0.83	1.42

N	nave
Q	choir/chancel
1	combined nave/choir/chancel in one unit
A	aisle
T	transept
P	porch
S	sacristy

A rather different picture begins to appear: where there are differentials that are defined with sufficient clarity to be worth recording, they now reveal a very mixed situation. Only about half show that height was a more significant factor than span in the determination of wall-thickness, when comparing parts of various churches with those of other churches. The situation is clearly more complex than that of unvaulted churches. However, these are all comparisons between different parts of *different* churches. What happens when different parts of the *same* churches are compared? In most cases these are all roughly contemporary (Figure 12.4).

Figure 12.4 COMPARISONS WITHIN *SAME* CHURCH WHERE *SPAN* APPEARS TO DETERMINE WALL THICKNESS

SITE		SPAN	HEIGHT	WALL THICKNESS	WITH ½ BUTTRESS
Similar height but greater span and wall thickness:					
Corstorphine	T	4.65	5.23	1.15	2.4
	Q	6.5	5.15	1.45	2.9
Crichton	T	4.8	5.5	1.3	-
	Q	7.2	6	1.33	2.05
Dunglass	T	4.2	4.34	0.99	-
	Q	5.33	4.5	1.25	-
Corstorphine	S	3.5	4.75	1.15	-
	Q	6.5	5.15	1.45	2.9
Dunglass	Q	5.33	4.5	1.25	-
	N	6	4.72	1.35	1.8
Dunglass	T	4.2	4.34	.99	-
	N	6	4.72	1.35	1.8
Seton	S	3.86	5.08	1	-
	Q	6.65	4.65	1.07	1.7
Corstorphine	S	3.5	4.75	1.15	-
	T	4.65	5.23	1.15	2.4
Greater height, but similar span and wall thickness:					
Dunglass	T	4.2	4.34	0.99	-
	S	4.03	1.67	0.96	-

N	nave
Q	choir/chancel
1	combined nave/choir/chancel in one unit
A	aisle
T	transept
S	sacristy

In every case it begins to appear that *span* has been the determinant factor of wall-thickness. In no cases at all has height been found to be an influence. This and the previous set of comparisons produces a somewhat confusing picture of late medieval practice in structural design: sometimes height but more often span seems to be most influential. Of course it is almost impossible to know without documentary evidence whether each church in the sample was designed by a different mason or architect, or if one was responsible for several. The figures do suggest, however, that the architect of each whole church (and the possibility must be recognised of more than one architect in each case) at least practised a roughly consistent formula for vault abutment in the different parts of that building. One final comparison at a general level is called for. Figure 12.5 shows juxtaposed the slenderness and span ratios for all the vaulted church units surveyed. Again, as in the case of unvaulted churches the ranges are similar but there is a tighter clustering of span ratios implying that this was the dominant influence at a general level.

Figure 12.5 VAULTED CHURCHES: Span and Slenderness ratios compared
(where buttressed, the ratios shown include half the buttress projection)

	Span ratio 1:				**Slenderness ratio 1:**			
1.7								S
1.8								
1.9			T					
2								
2.1							A/T	
2.2							T	
2.3								
2.4								
2.5								
2.6					N N			
2.7						Q Q		
2.8							A	
2.9						Q Q/N		
3				S			A/T	
3.1							T	
3.2			T					
3.3	N N							
3.4		Q						
3.5		Q						
3.6			A/T			Q Q		
3.7			T T A/T					
3.8							A/T	
3.9		Q Q		S				
4								
4.1								S
4.2			T	S			T	
4.3		Q						
4.4		Q/N					T	
4.5								
4.6								
4.7			A					
4.8			A/T					
4.9								
5								
5.1								S

N	nave
Q	choir/chancel
1	combined nave/choir/chancel in one unit
A	aisle
T	transept
S	sacristy

12.3 BUTTRESSES

As with unvaulted churches the question has to be asked, in what circumstances do buttresses appear on vaulted church buildings and is there any consistency in, firstly, their appearance at all, and secondly their projection. Figure 12.6 shows all the church units, listed in order of height to the vault springing. That the use of buttresses decreases progressively amongst the lower structures is perhaps predictable, but seems of little significance compared with the situation when the same buildings are listed in descending order of span (Figure 12.7).

Figure 12.6 VAULTED CHURCHES in order of HEIGHT

SITE		SPAN	HEIGHT	W/T	W/T + Buttress	W/T + Half Buttress
S.SALVATOR'S	s1	8.65	9.5	1.33	3.03	2.18
S.SALVATOR'S	n1	8.65	9.5	1.7		
DALKEITH	Q	8	8.25	0.91	2.51	1.71
BOTHWELL	Q	6.63	6.9	1.23	2.63	1.93
CRICHTON	Q	7.2	6	1.33	2.78	2.05
SETON	sT	5.43	5.97	1.08	2.38	1.73
CRICHTON	sT	4.8	5.5	1.3		
SETON	nT	5.46	5.41	1.08	2.38	1.73
CRICHTON	nT	4.75	5.4	1.3		
CORSTORPHINE	T	4.65	5.23	1.15	2.65	2.03 (C/A)
CORSTORPHINE	Q	6.5	5.15	1.45	3.05	1.98
WHITEKIRK	Q	6.27	5.13	1.38	2.78	1.9
SETON	S	3.86	5.08	1		
LADYKIRK	Q/N	7.1	4.75	0.93	2.33	1.63
CORSTORPHINE	S	3.5	4.75	1.15		
DUNGLASS	N	6	4.72	1.35	2.25	1.8
S.QUEENSFERRY	Q	6.8	4.72	1.43		
SETON	Q	6.65	4.65	1.07	2.32	1.7
DUNGLASS	Q	5.33	4.5	1.25		
DUNGLASS	bothT	4.2	4.34	0.99		
CARNWATH	A/T	5.25	4.3	0.83	2.01	1.42
HADD. ST.MARTIN		5	4.3	1.32		
WHITEKIRK	P	3.07	4	1.06	2.16	1.4 (C/A)
HADD. ST. MARY	A	4.3	3.9	0.95		
DIRLETON	A/T	4.7	3.7	0.97		
BORTHWICK	A/T	5.8	3.35	1.04	2.14	1.59
CORSTORPHINE	P	2.44	2.31	0.76		
ABERDOUR	A	3.51	2.06	0.75		
UPHALL	A	4.25	1.85	0.97		
DUNGLASS	S	4.03	1.67	0.96		
DALGETY	A	2.9	1.6	0.7		
STOBO	P	2.43	1.6	0.83		
N. BERWICK	P	3.73	1.26	0.86	2.06	1.46

(C/A)	Angled buttresses at corners only
N	nave
Q	choir/chancel
I	combined nave/choir/chancel in one unit
A	aisle
T	transept
S	sacristy

Figure 12.7 SMALL VAULTED CHURCHES in order of SPAN

SITE		SPAN	HEIGHT	W/T	W/T + Buttress	W/T + half Buttress
S.SALVATOR'S	s	8.65	9.5	1.33	3.03	2.18
S.SALVATOR'S	n	8.65	9.5	1.7		
DALKEITH	Q	8	8.25	0.91	2.51	1.71
CRICHTON	Q	7.2	6	1.33	2.78	2.05
LADYKIRK	Q/N	7.1	4.75	0.93	2.33	1.63
S.QUEENSFERRY	Q	6.8	4.72	1.43		
SETON	Q	6.65	4.65	1.07	2.32	1.7
BOTHWELL	Q	6.63	6.9	1.23	2.63	1.93
CORSTORPHINE	Q	6.5	5.15	1.45	3.05	1.98
WHITEKIRK	Q	6.27	5.13	1.38	2.78	1.9
DUNGLASS	N	6	4.72	1.35	2.25	1.8
BORTHWICK	A/T	5.8	3.35	1.04	2.14	1.59
SETON	nT	5.46	5.41	1.08	2.38	1.73
SETON	sT	5.43	5.97	1.08	2.38	1.73
DUNGLASS	Q	5.33	4.5	1.25		
CARNWATH	A/T	5.25	4.3	0.83	2.01	1.42
HADD. ST.MARTIN		5	4.3	1.32		
CRICHTON	sT	4.8	5.5	1.3		
CRICHTON	nT	4.75	5.4	1.3		
DIRLETON	A/T	4.7	3.7	0.97		
CORSTORPHINE	T	4.65	5.23	1.15	2.65	2.03 (C/A)
HADD. ST. MARY	A	4.3	3.9	0.95		
UPHALL	A	4.25	1.85	0.97		
DUNGLASS	bothT	4.2	4.34	0.99		
DUNGLASS	S	4.03	1.67	0.96		
SETON	S	3.86	5.08	1		
N. BERWICK	P	3.73	1.26	0.86	2.06	1.46
ABERDOUR	A	3.51	2.06	0.75		
CORSTORPHINE	S	3.5	4.75	1.15		
WHITEKIRK	P	3.07	4	1.06	2.16	1.4 (C/A)
DALGETY	A	2.9	1.6	0.7		
CORSTORPHINE	P	2.44	2.31	0.76		
STOBO	P	2.43	1.6	0.83		

(C/A)	Angled buttresses at corners only
N	nave
Q	choir/chancel
1	combined nave/choir/chancel in one unit
A	aisle
T	transept
S	sacristy

Here is an apparently more consistent picture and, although there are some exceptions to the obvious trend of buttressing structures of over 5 metres span, these are mostly explicable as aberrations and will be discussed later. On the face of it, this arrangement of these figures does lend weight to the probability that span was the principal influence on wall-thickness of vaulted structures.

Next we require to ascertain at what point there is any discernible equivalence between buttressed and unbuttressed churches. If it is assumed that span was the principal influence over wall thickness, then our first enquiry must be into span ratio. Figure 12.8 shows a summary of figures for the various individual church parts, of all periods together.

Figure 12.8 VAULTED CHURCHES: SUMMARY OF SPAN RATIOS

Ratio 1:	Chancel/ choir	Nave	Transept/ Aisle	Sacristy	Small Aisle	Porch
1.4						B
1.5						
1.6			B			
1.7	B					
1.8	B					
1.9						b
2	B B		B			B
2.1		B	B			3
2.2	B					
2.3			B			
2.4						
2.5			B			
2.6	B					
2.7						
2.8			b 3			b
2.9	b					X 1
3	b			1		
3.1		B				3
3.2			b b			1
3.3	B 3	b				
3.4	b 3					
3.5	b					
3.6		3	1 1 b 3 3			
3.7			b			
3.8						
3.9	b 3			1		
4	3	b	X			
4.1			3		1	
4.2			1 1	1		
4.3	1 b		3			X
4.4	3	X			1	
4.5	X X	3			1	
4.6						
4.7	b				1	
4.8	1		1			
4.9						
5	3		X X			
5.1		1				
5.2						
5.3						
5.4	X					
5.5	X 3					
5.6			X			
5.7						
5.8						
5.9						
6						
6.1						
6.2	X					
6.3			X			
6.4						
6.5		X				
↕						
7.6	X					
↕						
8.8	X					

1	Unbuttressed structure
X	Buttressed structure, based on walls only, excluding buttresses
b	Buttressed structure, based on walls together with half buttress projection
3	Buttressed structure, based on walls together with one third buttress projection
B	Buttressed structure, based on walls together with total buttress projection

There is an obvious concentration of unbuttressed structures from 1: 5.1 down to 1: 3.6 and less for some smaller units. These are shown as "1" on the chart. The buttressed structures are, as before, shown variously with ratio taken on wall-thickness alone, "X"; wall-thickness plus full buttress projection "B"; with half projection "b" and, in addition, with one-third projection "3". Brackets have been drawn in to delineate the approximate 'zones' where the majority of each group, excepting outliers, are found, together with some colouring to assist identification of trends. Evidently there is some equivalence between the unbuttressed wall, and the buttressed wall with between a half and one-third of the projection of the buttress. What is also striking about these statistics is the extent of the spread relating to buttressed structure based on walls only (X). These range from 1: 2.9 to 1: 8.8, a spread of 5.9. Compare this with the spread of ratios of the same structures including their full buttress projection (B): 1: 1.4 to 1: 3.3 (a spread of 1.9, most of which are actually concentrated in a spread of only 1.2) and an impression is gained of the immense equalizing effect of the buttressing. Such a trend reveals some commonality of approach to the problem of abutment calculation amongst medieval architects.

Some averages from these span ratios are worthy of comment. Firstly, taking all the unbuttressed structures, the average span ratio over the seventeen examples is 1: 4.05. This compares with the general recommendation of Rodrigo Gil and various others of 1: 4 as a span ratio for the *entire* abutment of a round vault (Appendix I, Section 4).

Averages for buttressed structures, however, tell a very different story: the average of fifteen examples, based on wall-thickness plus entire buttress projection is only 1: 2.45. Taking the wall-thickness alone, the average is 1: 5.43. This is an appropriate point at which to digress for a moment to make a comparison with continental work as evidenced by the instructions of Lorenz Lechler, the two surviving editions of which differ in their recommendations (Appendix 1 Section 5). The accepted interpretation for the vaulted choir of a hall church in the early sixteenth century stipulates a wall-thickness one tenth of the choir width, and buttress projection of slightly more than double the wall-thickness. The total abutment to span ratio would be 1: 3.3. The other edition suggests a ratio of nearer 1: 4 where it was the buttresses that were slightly shorter. The details are ambiguous but are not of as much consequence to us as the general principle of walls being around half as thick as the buttresses were long and the overall span ratio, taking into account the full buttress projection, being between 1: 3.3 and 1: 4. The ratios of Lechler's exemplars with half the buttress projection are 1: 4.9 and 1: 5.45 respectively. Of course this relates to vaults which are ribbed and therefore probably much lighter than Scottish pointed barrel vaults. The German subjects were probably much more scientifically and economically designed generally. The use of buttresses with true ribbed groin vaults is of course entirely logical, the weight and thrusts of the vault webs being channelled down the ribs directly to the buttresses and thence to the ground - 'thrust management'. With barrel vaults, however, the situation is entirely different. The vault exerts an even load along the entire length of supporting wall, along which any buttresses merely have a stiffening effect. They only begin to assume the more active role of 'thrust management' if the wall in between is opened up to large windows, the arches of which deflect the vault thrusts sideways to the buttresses in a crudely similar way to that of a groin vault. The only cases where this can be claimed are St. Salvator's, Dalkeith chancel, (both of whose vaults were lost long ago) Seton transepts, Bothwell chancel and, to a lesser extent, Ladykirk. All the others are characterised by smaller windows being punched through the wall at sometimes irregular intervals. In the light of this fundamental difference alone, it is perhaps not surprising that the more commonly used span ratio of around 1: 4 in medieval Scotland for wall thickness alone was considerably less than Lechler's recommendations approximating to 1: 10 for the same dimension. This marks out structures such as Dalkeith choir, at 1: 8.8 (wall thickness alone), as being exceptional to Scottish work, and in an altogether different, possibly continental league.

From all these figures it should be possible to work out an equivalence with the unbuttressed wall. The average wall-thickness plus half the buttress projection comes to 1: 3.37. Wall-thickness plus one third of buttress projection gives 1: 3.86; one-quarter projection gives 1: 4.15. The equivalence is theoretically somewhere between one quarter and one third of the buttress projection, and it would seem from these figures that Scottish architect/masons used this as a rough rule-of-thumb guide when designing buttressed walls. And yet that was rarely the case. In fact this just confirms the danger of excessive generalization and, particularly, over-reliance on average figures. Closer examination of individual buildings shows just how diverse the real situation often is. There is something of a shortage of usable examples where different parts of a church, buttressed and unbuttressed, were roughly contemporary, but Crichton and Dunglass serve our purposes quite adequately. Here are their span ratios:

	wall only	wall plus full buttress	wall plus half buttress	wall plus one-third buttress	wall plus one-quarter buttress
Crichton choir	1:5.5	2.6	3.5	4	4.2
transepts	1:3.6				
Dunglass choir	1:4.26				
sacristy	1:4.2				
transepts	1:4.2				
nave	1:4.4	2.67	3.3	3.6	3.8

At Crichton clearly there is an equivalence between the span ratio of the choir's wall plus half the buttress projection and that of the unbuttressed transepts. At Dunglass there seems to be an entirely different situation. While the actual spans and wall thicknesses differ widely, they do so in very similar proportions, so all the span ratios are almost identical. The buttresses on the nave would appear to be superfluous at first sight: there is no sense of equivalence of total abutment between buttressed and unbuttressed structure as at Crichton. We will return to Dunglass later, but for the moment these two examples confirm the dangers of working only from averages.

Before moving on, one further example is worth citing in this matter. The buttressed south wall of St. Salvator's in St. Andrews seems over-buttressed when compared with the plain north wall:

	wall only	wall plus full buttress	wall plus half buttress	wall plus one-third buttress	wall plus one-quarter buttress
St. Salvator's south	1:6.5	2.85	3.97	4.5	4.9
north	1:5.1				

Less than one quarter of the buttress seems to be doing any work. However, it is not so simple as that. The buttressed south wall has large and regular fenestration; the north is entirely solid. The south wall is 1.33 metres thick with buttresses projecting a further 1.7 metres; the north is just 1.7 metres thick (and some careful estimation is needed to reach this figure since on the cloister side it has been refaced) - it is the only example we have which gives an indication of the equivalence between a buttressed windowed wall and an unbuttressed solid one, in a single vaulted structure in Scotland. Unfortunately in this case the vault was dismantled in 1773, so further enquiry into this example is almost impossible.

12.4 QUADRATURE AND ROTATION

If span was then the principal determinant of wall thickness and abutment, in the light of this, and perhaps also of the findings in connection with wall/buttress sizing in unvaulted churches, the possibility must be explored of a decisive role being played by quadrature, by the rotation of the diagonal of the core square. It will be recalled that in some unvaulted churches this dimension overlapped about one third of the buttress projection.

Now it comes as little surprise to find that the walls of vaulted structures are thicker, often much thicker than unvaulted. Predictably therefore the line created by rotation falls within the wall-thickness more often than not, and therefore cannot actually define its thickness. Of thirty-three examples, this is the case in eighteen. In a further seven cases the rotation line overlaps the wall-thickness; in only eight, possibly nine, does it appear to actually define the wall-thickness. Five of those overlapping or underlapping come within 10 centimetres of the wall-thickness. In these circumstances it is tempting to question, where rotation appears to define wall-thickness, whether it really does so, or are we only seeing a number of lucky coincidences. At best, it certainly does not appear that rotation was a universal or even common method of defining wall-thickness, though it is worth noting, before moving on, that it may sometimes have been used. For the record, the buildings where this may have been the case are as follows:

Seton: Sacristy, Transepts
Dunglass: Choir, Nave, Transepts
South Queensferry: Choir
Dirleton: Archerfield Aisle
Aberdour: Phin Aisle

The principles of quadrature were sought in terms of the buildings' plan. However, if we now turn to the section of this building type, another possibility immediately presents itself.

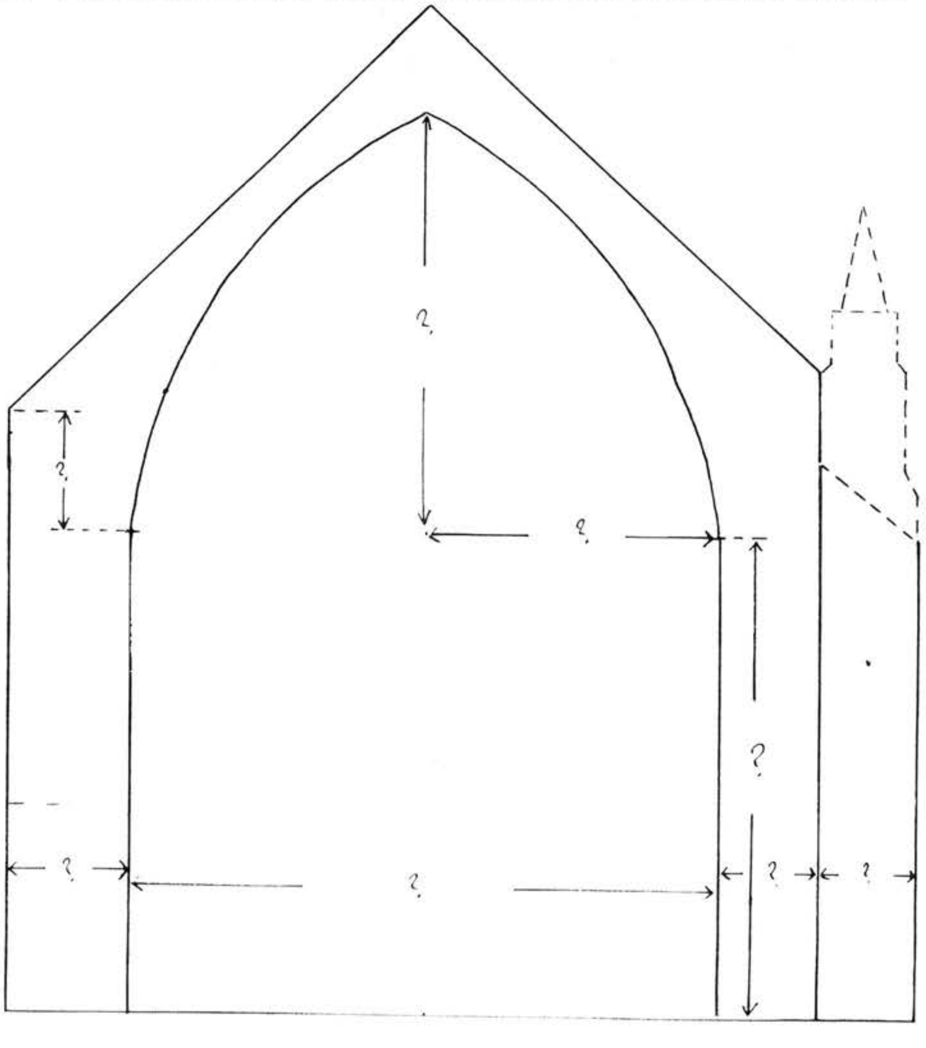
12.5 TRIANGULATURE

It should be remembered that this research is restricted to an enquiry into the sizing of *structural* elements rather than the general design of space and volume as defined by the structure. Of course there is much of interest to be discovered in that field which is prompted not least by the well-known controversy over the design of Milan Cathedral, and it will be necessary to explore the spatial aspect to a limited extent in order to ascertain whether or not it has a bearing on the sizing of structural elements, but little more.

A hypothetical cross-section mixing the typical elements of churches of this period with pointed barrel vaults has been constructed in figure 12.9 and it shows a number of variables and relationships within and between structural elements which require investigation. These are:

i) the relationship of wall-thickness, with and without buttresses, to span.
ii) the effect, if any, of extraordinary height.
iii) the relationship of wall-thickness to buttress projection.
iv) the relationship of abutment to the shape of the vault, in particular its span to height ratio between springing and apex. For instance, a lower, less steeply inclined vault should theoretically require greater abutment than a more steeply inclined example.
v) the size of the vault 'shoulder' or 'haunch' i.e. the difference between the height of the internal springing and the external eaves. This is a highly significant element in vault construction providing a counter-weight to divert the lateral thrusts of the vault to a more vertical direction. It is equivalent to the purpose of the pinnacle on the buttresses of high quality churches, and indeed may sometimes be used in conjunction with that device. Theoretically, its size might materially affect that of the abutment.
vi) the effect of sloping the buttress head in contrast to building it up above the eaves, with or without a pinnacle.

Figure 12.9 Possible proportional relationships in the structure of vaulted churches



So, how can a study of triangulature help with all this?

Examination of the cross-section of the survey samples shows that quite commonly the pointed barrel vault is formed on the basis of an equilateral triangle. However, this figure is not always used in the same way. A summary of the different formats is to be found in figure 12.10 over the following pages, together with lists of the structures which conform to them.

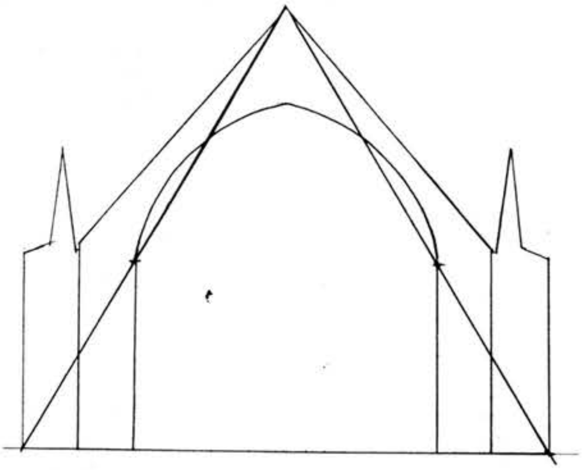
Figure 12.10 METHODS OF DESGN BY TRIANGULATURE IN AISLELESS VAULTED CHURCHES

NB Diagrams are schematic only, do not represent actual features of the churches concerned, and are not to scale

CATEGORY A

Apex of outside roof ridge - inside vault springing - outside base of buttress:

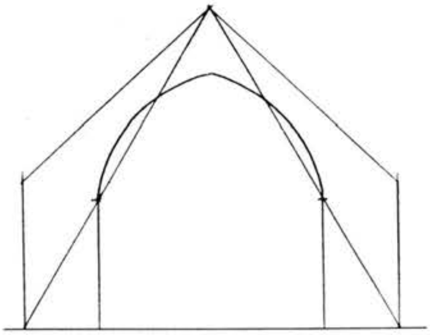
Crichton	choir *
Corstorphine	choir *
Whitekirk	choir *
Seton	choir *
Borthwick	aisle / transept
Carnwath	aisle / transept



CATEGORY B

Apex of outside roof ridge - inside vault springing - outside base of wall

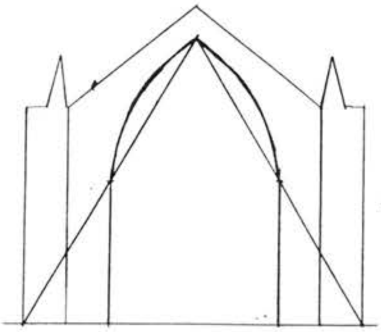
Dunglass	sacristy



CATEGORY C

Apex of inside vault - inside vault springing - outside base of buttress

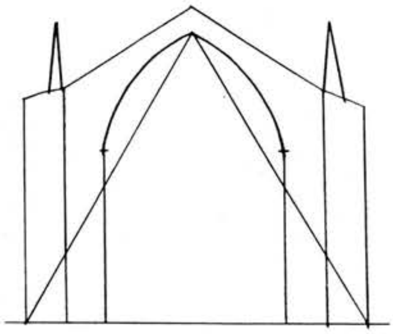
Ladykirk	choir *



CATEGORY D

Apex of inside vault - outside base of buttress

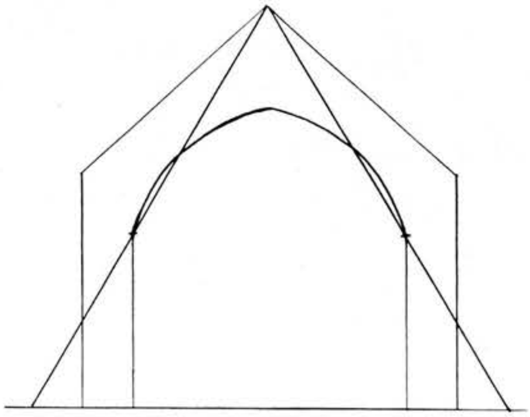
Whitekirk	porch
St. Salvator's	nave/choir
Dalkeith	choir
Dirleton	aisle/transept



CATEGORY E

Apex of outside roof ridge - inside vault springing

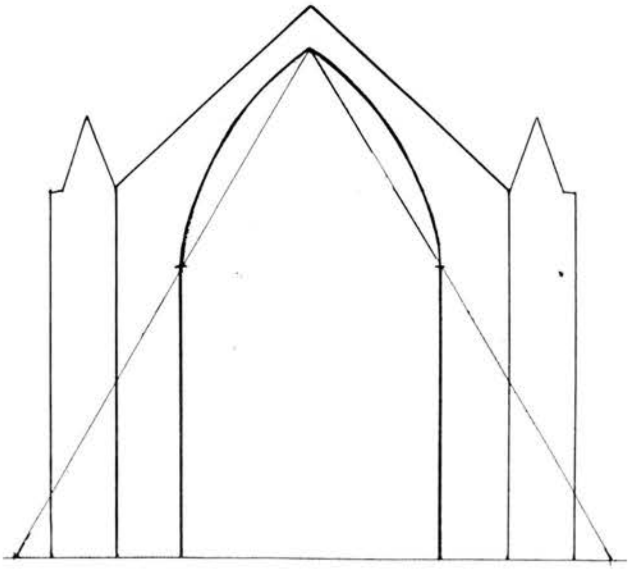
Crichton	transepts
Corstorphine	porch
Corstorphine	sacristy
Aberdour	aisle
Haddington	aisle



CATEGORY F

Apex of inside vault - inside springing

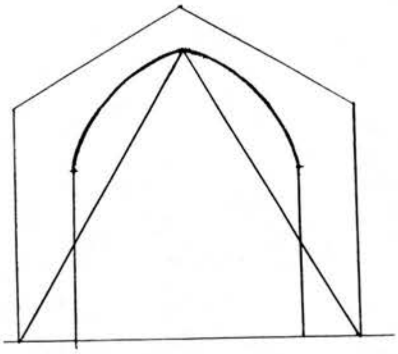
Seton	north transept



CATEGORY G

Apex of inside vault - outside base of wall

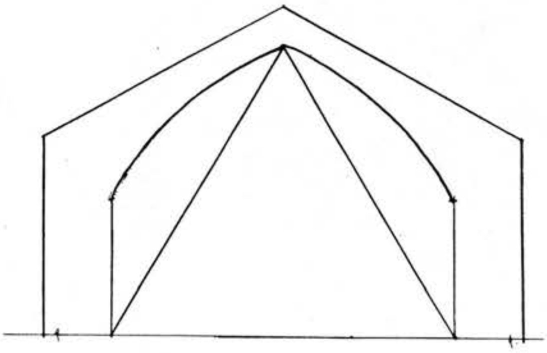
Dalgety	aisle
S. Queensferry	choir



CATEGORY H

Apex of inside vault - inside base of wall

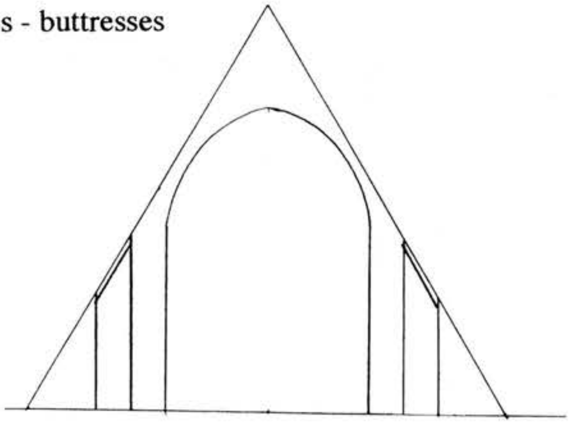
N. Berwick	porch
Uphall	aisle



CATEGORY I

Apex of outside roof ridge - eaves - buttresses

Bothwell	choir



CATEGORY J

No recognizable Triangulature

Seton	sacristy, south transept
Dunglass	choir, transepts, nave
Stobo	porch

CATEGORY K

Hybrids using Egyptian Triangles

Corstorphine	south transept

Admittedly this exercise might run into the old problem of trying to read or even construe certain geometric forms into the structures under examination, and so open the discussion to the sometimes justifiable ridicule of the cynics. The figures however do speak for themselves. They derive directly from the measurements taken on site. In any event there is no reason why the medieval architect himself would have used such geometric forms quite loosely, not necessarily conforming to any preordained programme for triangulature. In the hands of the many different levels of skill, experience and fastidiousness, through the considerable timespan of five centuries, and over a whole continent, there surely must have been more than one method of interpretation of the concept of triangulature. The evidence of Rodrigo Gil's conversations with other masons on the subject of vault abutment alone, proves that diversity and experimentation were universal. Such geometric figures, whilst undoubtedly creating slaves of some designers, would have merely served as "help-diagrams" (II Roosval, 1944) to many others, for application in a variety of different ways according to the requirements of the design process, and the building's function.

Perhaps it is appropriate here to restate some fundamentals of this research. In very few places in this whole thesis are any absolutes or certainties claimed. The evidence is merely weighed and the possibilities or probabilities discussed. If certain key dimensions of a building make up such geometric forms as squares, diagons or equilateral triangles, it is reasonable to assume that such forms were *probably* intended, particularly given the famous maxim by Villard de Honnecourt, "Science lives only by the science of geometry. There is no other artifice nor handicraft that is wrought by man's hand but it is wrought by geometry...wherefore I may say that men live all by geometry" (quoted in II Shelby 1972: 396). Of course written documentary evidence in the case of each building is the ultimately desirable proof, but in studies of this nature, such is almost never available: in effect, the buildings are the only documents we have.

Various general observations on the diagrams are appropriate and these will first be dealt with alongside the basic principles of where triangulature is to be found. Experience having often shown that individual cases reveal much more than statistical generalization, some individual church units will then be explained in an attempt to analyse how the architects arrived at each structural design solution.

It quickly becomes obvious from the diagrams that, whilst triangulature might have commonly been used to set out the overall form of a structure, it did not necessarily dictate the sizing of walls, especially if buttresses were also to be employed. The only instances where this was certainly so is where the triangle defined the apex of the vault, either internal or external, the springing of the vault, and the outside surface of the walls, as in category (B). It will be noted that there is only one example found in this category from the buildings surveyed, and it has to be accepted that it may be unique, or alternatively representative of others yet undiscovered. In the cases (category A) where buttresses are involved, it is only the total of wall-thickness and buttress that is defined, leaving the architect to work out how thick each of these should be individually. To all this a further qualification must be added: where the base of the equilateral triangle coincides with the outermost surface of wall or buttress at the base, this is not always tantamount to the wall-thickness, for in some cases a water table may protrude boldly at this level, and this may or may not be incorporated in the overall triangular design. Where the triangle does extend beyond the outer surface of wall or buttress and incorporates the water table the church part listed bears an asterisk. What is remarkable is that these instances are all choir structures and that most of them share another characteristic of canonical proportion: the 1: 0.8 height to span ratio. Although such coincidences are of intrinsic interest, of greater significance for the purposes of this research is the fact that triangulature in these and doubtless some other cases was simply the geometric basis of an overall design form. It obviously does not play a more definitive role in the structural design, particularly in deciding the wall thickness.

From all this it might be concluded that whilst there is at least one instance (mentioned above regarding category B) where triangulature performs a guide to structural design, there are more where it is a loosely ideological basis for the complete building form, and nothing more. The quest for a comprehensive methodology for structural design continues.

12.6 THE VAULT HAUNCH

Quite apart from wall and buttress size, also sought is some system for deciding the size of the vault haunch - the area of wall-head at the base of the vault created by the difference in height between the internal vault springing and the external roof eaves, which was generally higher. The considerable variation in this element provokes further enquiry. Logically a greater haunch should generally provide a heavier counterweight to the lateral thrust of the vault. In effect it served the same purpose as the pinnacle on the buttress head. But how was its size determined?

In many cases an answer can be worked out which seems to be very straightforward, although the presence of buttresses presents an additional complication. The line of the internal wall surface is projected upwards, beyond the vault springing (figure 12.11). From the springing also, a line is projected to the vault apex, or the roof apex. The angle at which this line is subtended (significantly, often 30°) is then repeated for a line projected outwards from the springing, (henceforth referred to as the 'haunch angle') and it is along this line that the roof eaves are defined. Now of course we have in many cases the beginnings of a further equilateral triangle, inverted. But how is the point at which the roof eaves is set finally determined? This will of course also be the point which defines the outer wall surface, and therefore the wall-thickness.

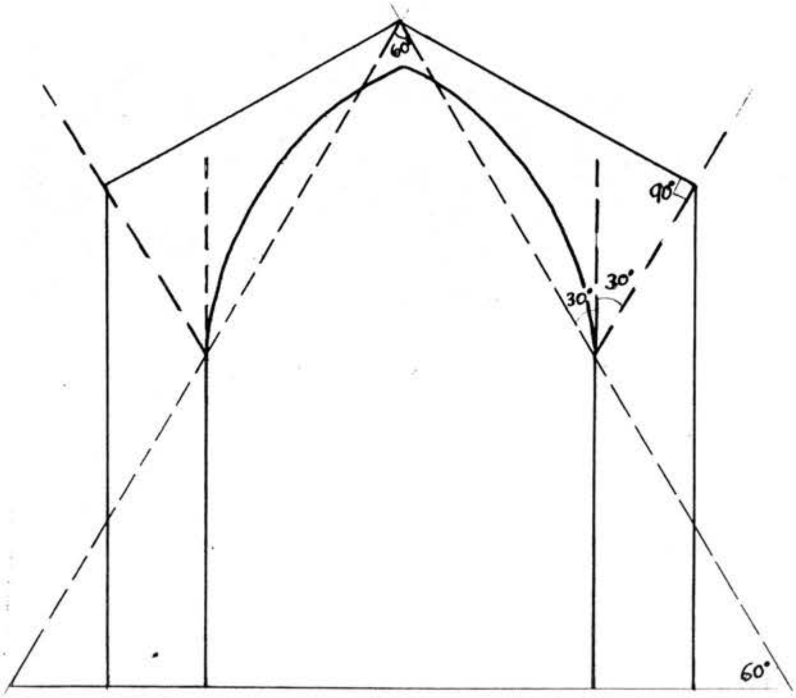


Figure 12.11 Method of designing vault haunch by triangulature

Whilst again the situation is often complicated by buttresses, a majority of examples are characterized by the line of the roof apex to eaves being set at right angles to the line which has just been drawn to the eaves from the vault springing. If this angle is not exactly 90° it is then commonly within three degrees of it and this is not necessarily an inaccuracy on the part of the builder: there is an obvious difficulty in measuring precisely where the roof apex is in relation to the eaves, when the gable is obscured by coping stones or the ridge is inaccessible due to the presence of a polygonal apse. In spite of these slight discrepancies from the norm, it seems obvious that a right angle has in most cases been intended at the eaves, and it is this that has defined the wall-thickness. This will henceforth be referred to as the 'eaves angle'. Of course this process required careful measurement and drawing out; it cannot have been easily 'designed' on site in the airspace where it was to be realized in quite the same way as pegs and string might have been used to 'design' the ground plan in situ. However, in the event that must actually be just how the design was drawn up. The formwork for the vault would, after all, have been made up on the ground, lying on its side. The voussoirs for the vault would have been roughly cut or at least planned and ordered from the quarry, so the external apex of the vault would have been known. The rest could have been done with pegs and string.

Obviously there are exceptions to, and variations on all of this, particularly the haunch angles, and to quantify all of this more specifically, figure 12.12 shows a breakdown of the various permutations that occur in this area of the surveyed sample of vaulted structures. The left-hand column lists buildings where both the angle from the springing to the apex and from the springing to the eaves is 30°; the next column where these two angles are not 30°, but they are nevertheless identical to each other. The third column lists buildings where there has obviously been no attempt to make the two angles similar, and finally are shown those buildings with negligible or no haunch at all.

Figure 12.12 HAUNCH ANGLES

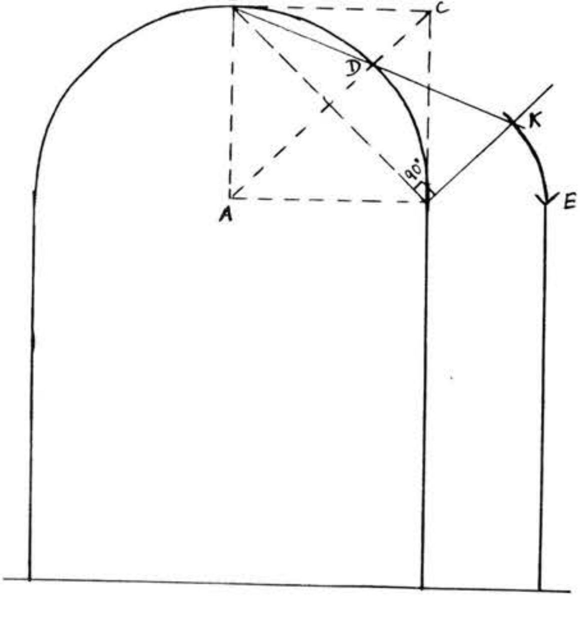
(WITH EAVES ANGLES OF 90° OR WITHIN 3° OF THAT)			(OTHER CASES)	
30°/30°	ANGLES OTHER THAN 30°		DISPARATE ANGLES	NO HAUNCH
Crichton T's	N. Berwick P	45°	Seton sT	Corstorphine Q
Corstorphine T	Whitekirk Q	38°	Dunglass T	“ S
Seton Q	S. Queensferry Q	33°	“ N	“ T
“ nT	Aberdour A	48°	“ C	“ P
Borthwick A/T	Dalgety A	32°	“ S	Whitekirk P
Ladykirk Q/N	Haddington S	38°	Dirleton A/T	Seton S
? Dalkeith Q			Stobo P	Bothwell Q
Crichton Q				Carnwath A/T

A most interesting coincidence becomes noticeable when comparing this table with the triangulature categories in figure 12.10 . Where there are entirely disparate angles in the haunch (third column) we find a very similar list appearing in category J where no recognisable triangulature is to be found. Furthermore, both lists have many subjects in common with the group of buildings mentioned earlier, whose wall thickness may have been defined by quadrature, by the rotation of the internal core square. This suggests that both the form and structure of some churches was indeed derived from quadrature alone, as a conscious alternative to triangulature. In others, where equal angles are found at the haunch, triangulature has been used throughout, both as a system of design not only of overall form, but also of individual structural members. The importance of this cannot be overemphasized, but it is obviously not universally applicable.

12.7 VAULT ABUTMENT

So far we are still reliant on mere geometry and a vague notion of appropriate span ratio to discover how abutment was decided and nothing has so far been suggested for those cases which do not 'fit' such methods. Nothing as yet has been found which takes account of both the span and height of the vault. This is perhaps an appropriate point to engage the theories worked out by Rodrigo Gil and later analysts on how best to derive vault abutment. Unfortunately many of these relate only to perfectly round vaults and not to pointed variations. They have already been explained in Appendix I and will henceforth simply be referred to by the name of the inventor, and the number of the solution as it appears in the Appendix. The methods which offer the greatest potential assistance are as follows:

Figure 12.13 Rodrigo Gil's Method (Appendix I Section 4.3.4)



Whilst it has been shown that this can be adapted for the characteristic Scottish segmental vault, no such adaptation can be so readily envisaged for the pointed vault. However, on closer inspection, the method can actually be used unadapted just as well for a this type (setting the point "B" at the inside apex of the pointed vault), producing a proportionately thinner wall (figure 12.14).

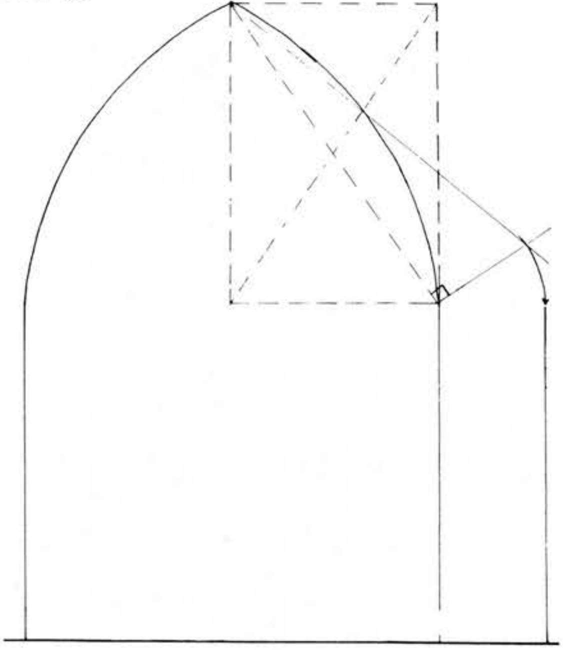


Figure 12.14 Rodrigo Gil's Method (as in Fig 12.13) adapted to a pointed vault

This of course is logical, since part of the purpose of pointed arches and vaults was to obviate the need for some level of abutment. The problem with this method applied to Scottish stone building is that it suggests wall-thicknesses which are thinner than the actual built works by between around two thirds to seven eighths in unbuttressed buildings. The drawing in figure 12.14 gives a span ratio of 1: 4.6 which is around the upper limit for an unbuttressed structure, the only buildings exceeding this figure being the choir of South Queensferry, and the much later Archerfield Aisle at Dirleton, both of which will be discussed later. Where there are buttresses, Gil's method encroaches anything up to half way through the buttress projection at most. There are of course exceptions: for instance where the solution is very close to the actual wall-thickness such as the sacristy at Seton and the transepts at Crichton. But these appear to be mere coincidences - there does not seem to be any consistent correlation with Scottish practice. The method applied in its basic form to round vaults does not even produce a result similar to the one round-vaulted structure in our sample: Dirleton's Archerfield aisle, mentioned already above. Here the span ratio is 1: 4.8, Gil's would be 1: 3.4.

Rodrigo Gil's theory shown in Section 4.3.5 of Appendix I is simply unworkable for a pointed arch and is therefore ignored for this building type.

Gil's method number (6) is again for round vaults, and the voussoir depth dimension is theoretically required. Once the vault is built and roofed this is of course impossible to find out. For this reason the method as it stands is useless for this research. However, that does not preclude the adaptation of the method to a finished pointed vault. Figure 12.15 shows this as well as use of the method based on the apex of a hypothetical round vault of the same span.

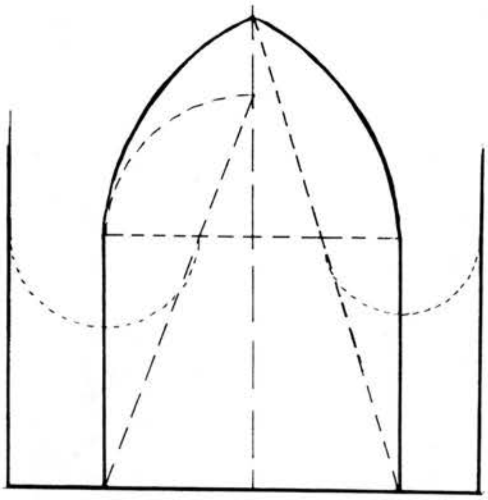


Figure 12.15 Rodrigo Gil's method (Appendix I Section 4.3.6) adapted to pointed vaults

This is a very practical solution, taking account of both height and span, and in the case of a pointed vault, the pitch of the intrados. Despite these obvious merits the method unfortunately produces results in our survey sample widely divergent of what was actually built, variously under- and overlapping the outside wall surface with some 'near misses' and just one lucky 'hit'.

Jean Rondelet's method (Appendix I Section 4.6) is dependent on a knowledge of the voussoir depth and is problematic to apply to a pointed vault where this is not known.

A more promising prospect is found in Gauthier's method of 1727 (Section 4.5) which is usable for any shape of vault (figure 12.16). However, when compared with medieval Scottish structures Gauthier's solutions always have thicker walls in cases where no buttresses are involved. Where there are buttresses, these are overlapped between one half and two thirds by Gauthier's solution.

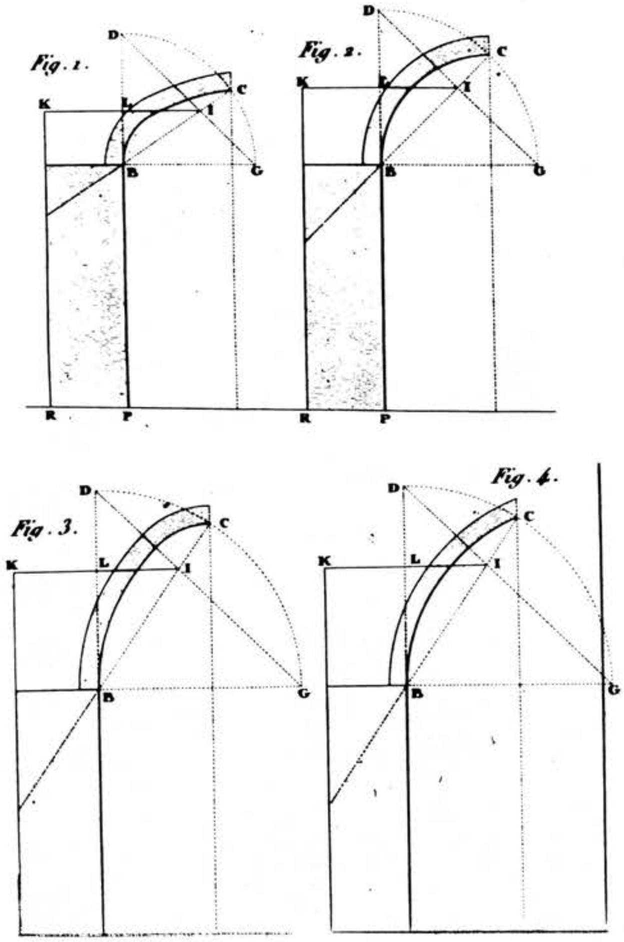


Figure 12.16 Gauthier's method of abutment design (Appendix I Section 4.5)

Leaving all these methodologies aside, we are really only left with that of François Dérand, often wrongly attributed to Jacques-François Blondel who published it in his *Cours d'Architecture* (1678). Needless to say, it is the simplest, and perhaps therefore the most attractive, if it is assumed that the architects of medieval Scotland were concerned with simplicity, with finding a methodology that involved least 'calculation', arithmetical or geometrical. The principle is illustrated in figure 12.17 where the haunch and eaves angles are also shown for reference.

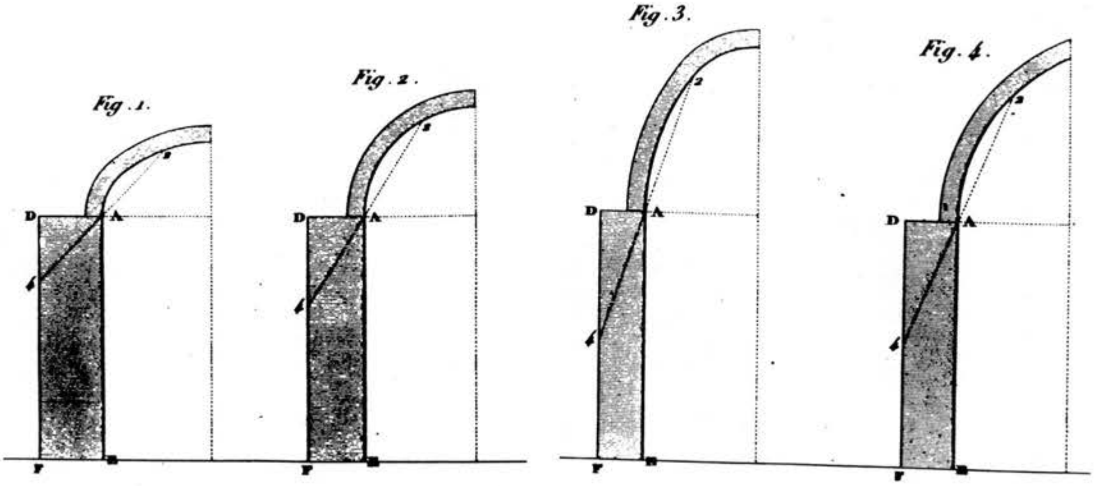


Figure 12.17 Dérand's method of abutment design (Appendix I section 4.4)

The intrados of the arch or vault is divided by three equal chords. The inclines of the side chords are then extended at the same angle down from the springing for a distance equal to their length above the springing. Where they then terminate (the point "4" on Dérand's diagram) should mark the outer surface of the supporting wall and thus gives a safe minimum wall thickness. The method takes account of both the span and the pitch of the vault and is therefore in an elementary way crudely rational, for in effect it is attempting to take account of both the direction and magnitude of the forces, even if these are being 'calculated' by constructive geometry, rather than in accordance with modern statical theory. Because of this, there is some justification for referring to it as Dérand's 'vector' and this term will be used henceforth, although it is recognized that it does not constitute a vector as understood in modern engineering terms. Incidentally, it is also a method which could quite possibly have been developed from the constructional shape of the timber formwork over which the vault was built.

More significant than any of this is the fact that in the vast majority of our survey sample, the end point, "4" in Dérand's diagram, is to be found just inside the outer wall surface. In buttressed structures, it encroaches the buttress projection by up to one third in most cases. It hardly needs to be pointed out that this is roughly the extent in which was found the buttressed equivalent of an unbuttressed wall as far as span ratio was concerned.

In order to test this out on a comparative basis let us create a hypothetical span ratio using Dérand's vector: the distance from the inside wall surface to the point where the vector terminates within the actual wall-thickness, or in the buttress projection, is deemed for this purpose to represent *the* wall-thickness, or perhaps an *ideal* wall-thickness. The span is then divided by this dimension to give what we will call 'Dérand's ratio'.

The results become clear in figure 12.18 which superimposes the new ratio on to figure 12.8 shown earlier. The range into which Dérand's ratio falls is smaller than any other, basically 1: 3.7 to 1: 4.6. This constitutes a spread of only 0.9 excepting outliers where exceptional or unusual circumstances prevail, otherwise a spread of 1.8 all inclusive. The principal outliers are, firstly at the lower end of the scale, the south transept of Corstorphine (1: 3.4) whose eccentricities are inexplicable, though a fuller discussion follows shortly; also at the upper end, the choir of Ladykirk at 1: 5.2 which can be more logically explained, again later. Nearly all the others fall into the same ordinary span ratio category based on wall-thickness plus one third of the buttress projection. They also fall in the middle area of the spread for unbuttressed structures. Finally, they make an interesting comparison to Lorenz Lechler's recommendations of 1: 3.3 - 1: 4, and to Rodrigo Gil's general preference for a 1 : 4 span ratio, which of course include *total* abutment.

Figure 12.18 VAULTED CHURCHES SPAN RATIOS WITH DÉRAND'S RATIO SUPERIMPOSED

Ratio 1:	Chancel/ choir	Nave	Transept/ Aisle	Sacristy	Small Aisle	Porch
1.4						B
1.5						
1.6			B			
1.7	B					
1.8	B					
1.9						b
2	BB		B			B
2.1		B	B			3
2.2	B					
2.3			B			
2.4						
2.5			B			
2.6	B					
2.7						
2.8			b3			b
2.9	b					X 1
3	b			1		
3.1		B				
3.2			bb			3
3.3	B3	b				1
3.4	b3		●			
3.5	b					
3.6		3	11b33			
3.7	●	●	b	●	●	
3.8		●				●
3.9	b3●		●●	1●		
4	3●	b	X		●	●●
4.1	●●		3		1	●
4.2	●		11●	1		
4.3	1b		3●		●	X
4.4	3●	X●		●	1	
4.5	XX●	3			1	
4.6			●●			
4.7	b				1	
4.8	1		1●		●	
4.9						
5	3		XX			
5.1		1				
5.2	●					
5.3						
5.4	X					
5.5	X3					
5.6			X			
5.7						
5.8						
5.9						
6						
6.1						
6.2	X					
6.3			X			
6.4						
6.5		X				
↕						
7.6	X					
↕						
8.8	X					

1	Unbuttressed structure
X	Buttressed structure, based on walls only, excluding buttresses
b	Buttressed structure, based on walls together with half buttress projection
3	Buttressed structure, based on walls together with one third buttress projection
B	Buttressed structure, based on walls together with total buttress projection
●	Any structure, Dérand's Ratio

What is implicit in all this at a general level is that Dérand's ratio does reflect a possible 'ideal' but that in actual built work this ideal was only loosely adhered to. The ranges of ratios which other solutions fall into are, after all, larger. However, the difference really is only marginal in many cases. Perhaps it was treated not so much as an ideal for perfectly rational structural design, but more as a guide for referral when concentrating on the business of creating a design based on triangulature or quadrature. That, however, is too broad a generalization, and in order to test out Dérand's method properly, and indeed the other benchmarks of span ratio and triangulature, each case must be examined individually, and this will follow shortly. Before that, there are some other matters to tackle at a general level.

12.8 THE RELATIONSHIP OF WALL-THICKNESS TO BUTTRESS PROJECTION TAKING INTO ACCOUNT FENESTRATION

A complicated issue to untangle in cases of buttressed structures is how the medieval architect decided what proportion of total abutment should consist of wall structure and how much buttress. Lechler's thoughts on this have already been mentioned but rarely can any equivalent be found in Scottish building.

It was mentioned earlier, when comparing Scottish barrel vaults with true ribbed groin vaults, that buttresses in Scottish work really only performed a stiffening function to a vault-bearing wall unless that wall was pierced by windows which filled most of the space between the buttresses. In those cases, the window arch formed the crude equivalent of a ribbed groin, deflecting the weight and thrust of the vault to the buttressed wall section in between each pair of windows. Now it is only logical that, if a window is to take up most or all of the wall length between buttresses, then the wall should be relatively thin, and the greater volume and strength of masonry given to the buttress. Where there were to be only small windows or none at all, it is structurally more logical to build a thicker wall with smaller stiffening buttresses. Is this what happened in practice?

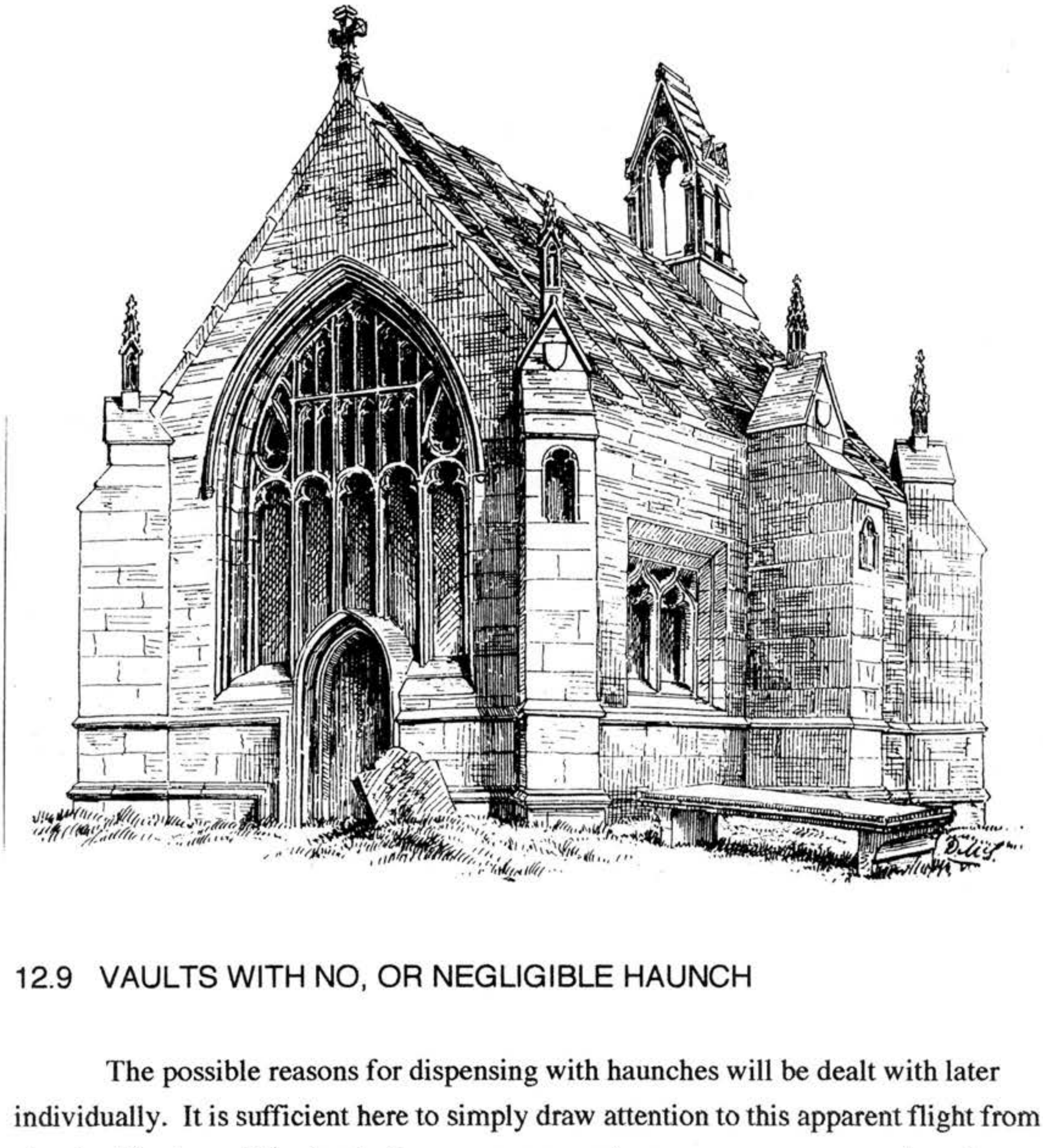
Dividing the buttressed structures of our survey sample into three groups, those with major buttress-to-buttress fenestration, those without, and an intermediate group provides a most instructive result.

Large Windows	Medium	Smaller Windows
Bothwell choir	Crichton choir	Corstorphine choir
Seton choir		Whitekirk choir
Seton transepts		Dunglass nave
Dalkeith choir		Borthwick aisle/transept
St. Salvator's		
Ladykirk choir/nave		

The group with more and larger windows are characterized by either buttresses which are considerably longer than the wall-thickness, or which have additional counterweight, that is they continue upwards above the eaves line, or both. Those with smaller windows have buttresses which are either roughly equal to the wall-thickness or are in some cases even less. Crichton falls roughly midway between the extremes in all respects, having some good-sized arched windows, slightly deeper buttresses capped with elegant pinnacles. In all these examples, therefore, we find some structural logic in this particular respect.

Not so logical is the structure of Carnwath (figure 12.19) whose walls are only 0.83 metres thick compared with buttresses projecting a fulsome 1.18 metres and boasting chunky saddle-back counterweights above eaves level, and all this when there are only two windows of diminutive size and rectangular form. How can all this be accounted for? On balance the design is hard to justify, but two factors help: Carnwath's walls are thinner in absolute terms than any of the other of the vaulted churches, and based on wall thickness alone has one the highest span ratios. Secondly it is one of those few churches which lacks a haunch at the base of its vault for reasons that will be considered later, and therefore lacking counterweight at this vital point, requires compensatory abutment. Here another problem has been encountered which requires some initial examination at a general level.

Figure 12.19 Carnwath Church aisle (MacGibbon & Ross 1896 vol III, p.350)



12.9 VAULTS WITH NO, OR NEGLIGIBLE HAUNCH

The possible reasons for dispensing with haunches will be dealt with later individually. It is sufficient here to simply draw attention to this apparent flight from structural logic and to ask whether any compensatory measures were employed.

At Carnwath we have already noted a solution. A similar measure of deep buttressing, but without counterweights, is to be found at Bothwell. But these are really more to cope with the grand fenestration noted earlier. The most likely source of compensation at Bothwell is simply the unusually steep pitch of the vault on the outside - an equilateral triangle of 60°, which the architect must have believed would ensure adequate vertical thrust to counterbalance lateral stresses from the voussoirs. (It is understood that Bothwell's triangular roof is not solid masonry right up to the apex on the outside, as are most other barrel-vaulted examples.)

At Seton's sacristy and at Corstorphine all four vaults - choir, sacristy, transept and porch - all lack haunches and at each of these as well as the porch at Whitekirk, the architect has compensated by slightly thicker walls in relation to span; that is a slightly lower span ratio compared to other comparable structures, much lower in the case of Whitekirk's porch.

12.10 CASE STUDIES

At a general level then, most of the apparent oddities and inconsistencies of structural design can be given at least some explanation or justification. However, there is great danger in excessive generalization and some more specific coverage of individual examples is required to try and get into the mind of the medieval architect and find out how the various tools of the trade - span ratio, Dérand's vector, triangulature and quadrature were variously combined.

Rather than looking at the individual church parts in isolation under the triangulature categories formulated earlier, all the parts of each church will be taken together, even in cases where some parts have been the subject of entirely separate building campaigns. Where that is the case, it will be made clear. The churches will be dealt with in no particular order other than that those consisting of several individual parts will be discussed first.

12.10.1 *Crichton Collegiate Church*

Founded on the site of an existing church, whose form may have had some influence over this later building, the choir was built from c. 1449 followed by the transepts and tower (VII Fawcett, 1994: 170). The roofs were originally of similar height but were lowered, those of the transepts considerably more so, in a 'restoration' of 1898. As far as possible, the analysis is based on the original roof heights evidenced by the surviving weather tables on the sides of the tower. With the exception of one peculiar feature, the choir at Crichton is typical and representative of a type, and therefore makes a good starting point.

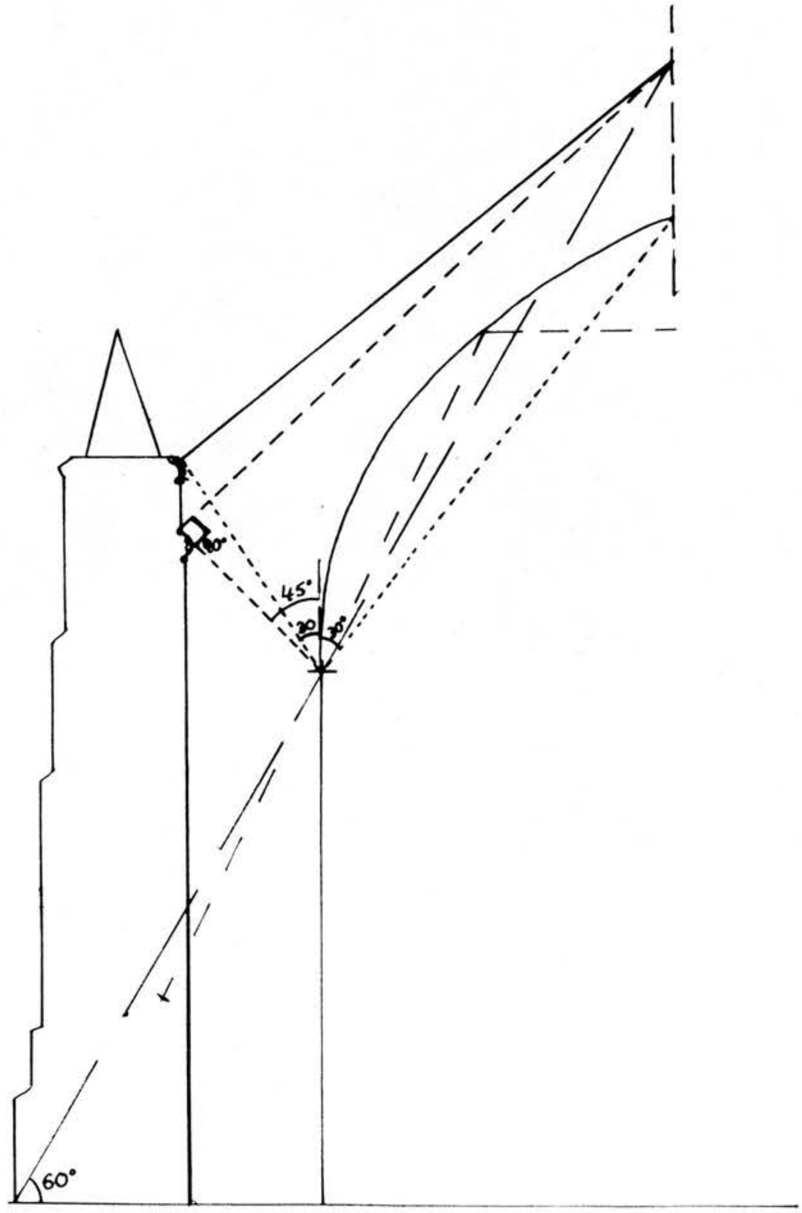
The plan of the choir is a double diagon, but there is no evidence for quadrature having been used elsewhere in the building. The span to height ratio (to the springing of the vault) is 1: 0.8, characteristic of so many other choirs of this period. The span ratio (wall-thickness to span) is 1: 5.5 for wall alone, 1: 2.6 with entire buttress, 1: 3.5

with half the buttress. The windows in the side walls do not by any means fill the space between the buttresses. The choir section is loosely an equilateral triangle incorporating the original external roof apex, vault springings and the water table on the outer extremity of the buttresses. The haunch angle is 30°. The eaves angle, however, reveals an anomaly which is peculiar to Crichton and possibly problematic to explain away. It measures about 97 degrees which of course destroys any nice geometric harmony in an otherwise perfect design. Why is this? One possible reason lies in the unusual feature of a second slightly canted decorative frieze just below the wall-head, similar to the one sited at eaves level, and more typically found in that position in Scottish work generally. Alternatively friezes such as this are occasionally to be found 'supporting' a parapet at the wall-head. Because at Crichton the wall above this frieze protrudes slightly outside the plane of the rest of the wall, it would seem that some sort of dummy parapet wall is indeed intended. It may have been more obvious before the 1898 roof alterations. Anyway, if an alternative haunch angle is created by extending a line from the vault springing to the top of this lower frieze, and then a line is drawn from there to the original roof apex, a right angle results at the eaves. If this seems a mere convenient coincidence, then it is at the cost of geometric perfection in the haunch angle which, now at 45 degrees, bears no relationship to the 30 degrees of the line extending from there to the apex.

According to Dérand's theory the wall-thickness would have been inadequate to withstand the overturning forces of the vault: his 'vector' overlaps the wall-thickness and encroaches about twenty centimetres of the buttress projection. The very fact of this suggests tentatively that the builder may have been aware of the possible 'overflow' of the thrust outside the wall thickness and, because some windows albeit not particularly large ones were required in the side walls, consciously decided not to build thicker walls, but to settle for the present dimension and add buttresses.

The transepts make a most useful comparison with this choir in many ways. As noted in connection with unvaulted churches, the structural and spatial design of transepts in general is more often forced to conform to that of the choir/nave of the 'parent' church for aesthetic or other considerations, rather than to canons more appropriate to their individual structural requirements. Crichton is no exception, and despite much narrower span, the transepts share the same height of wall-head and roof apex (at least before the 1898 lowering) as the choir. In contrast to the choir they have no side wall windows and no buttresses. The span ratio is 1: 3.6 - almost identical to that of the choir if half the buttress projection there is included (1: 3.5).

Figure 12.20 Crichton Collegiate Church - section



Analysis of the use of triangulature requires an element of speculation and assumption: the vault from springing to the present (post-1898) outside roof apex forms an equilateral triangle, just as in the choir. Because the whole structure is so much narrower, the base of this triangle falls well outside the walls. The problem which is most concerning though is the apex of the triangle. In all other cases where triangulature has been found this has been at the apex of either the interior vault, or the external roof ridge. Now the present roof ridge which coincides with the triangle apex was created in 1898 and we can therefore hardly be justified in finding triangulature in this structure. However, there may be a case for this. The present roof ridge actually represents the true *structural* external apex of this vault; it is only about half a metre above the internal vault apex and is probably therefore formed from the top of or just above the vault keystones. The rest of the pre-1898 roof was built up to make it visibly and artificially conform in height with the choir roof. But the original structural 'design' might well have been much nearer to the basic voussoir arch and present roof height. Certainly if that was so, and if the present roof apex or a point near it formed the apex of the triangular design then we also have a haunch angle of a convenient 30°, and an eaves angle of 90°, just as in the choir.

The wall-thickness of the transepts is only fractionally less than the 1.35 metres of the buttressed choir, yet the steeper pitch of its vault ensures that Dérand's vector falls comfortably within that thickness. Comparison of the windowed and buttressed choir with the blank and unbuttressed transept walls is perhaps made most instructive by the application of this latter test. Again, it is almost as if the builder was aware of the line of force and its extent, consciously choosing a wall thickness adequate to contain it, in preference to using a thinner wall with buttresses, as in the choir. Windows were after all not required in the sidewalls of the transepts. At this point a comparison of Dérand's ratio (that is the relationship of the internal span to the dimension from the internal wall surface to the point where Dérand's vector terminates in the wall thickness) also becomes potentially instructive. It is 1: 4.5 for the choir, and an almost identical 1: 4.57 for the transepts. This similarity, if not coincidental, suggests strongly that Dérand had actually lighted on a method that medieval masons might really have used. That the same ratio should have been used in two such disparate buildings could be of no little significance. We may never know whether the Scottish architects were consciously aware of or used anything like Dérand's vector, but the disparate parts of Crichton church certainly suggest that they possessed some system or logic which at least had the same end result. Can it be found elsewhere with apparently similar purpose and effect?

12.10.2 *Whitekirk Parish Church*

The vaulted and buttressed choir was built, together with the rest of the church (which is unvaulted), in the first half of the fifteenth century to very similar proportions as Crichton. Again in plan the choir is a double diagon. The internal span to height ratio to the springing is 1: 0.8 also. The span ratio is 1: 4.5 for wall alone; 1: 2.25 with full buttress; 1: 3 with half buttress; 1: 3.4 with one-third buttress. The equilateral triangle on which it is based defines the roof ridge apex, the vault springing and the outer extremity of the buttresses. The haunch angles agree at about 38°, the eaves angle 90° - all similar to Crichton, apart from the span ratio because Crichton is about a metre wider, despite which Dérand's vector still overlaps the wall to encroach the buttress by about ten centimetres, again very comparable with Crichton.

The only other vaulted part of Whitekirk is the little porch with a decorative, ribbed, round barrel vault. The walls here are 1.05 metres thick and they are augmented by a pair of angled corner buttresses, ignoring which the span ratio is 1:2.9. Now suspicion is aroused when it is realised that this span ratio is very similar to the combined wall *and* buttress ensemble in the choirs here, at Crichton and elsewhere. Furthermore Dérand's vector falls well within the wall thickness, and does not encroach on to the buttress at all. There are two points of significance here: firstly Dérand's ratio at 1: 4.1 is almost identical to that of the choir (1: 4.2). Secondly, because Dérand's vector does not encroach on the buttress at all, where usually on buttressed structures an overlap is universal, the buttresses appear to be entirely superfluous to the structural requirements of the porch. What logic can there be in this? The entrance elevation reveals all (figure 12.21). The buttresses have niches for figural sculpture, long since lost, perhaps St. Mary and St. Baldred, who would have thus welcomed the visitor. The evidence suggests that it is for this rather than any structural purpose that the buttresses exist.

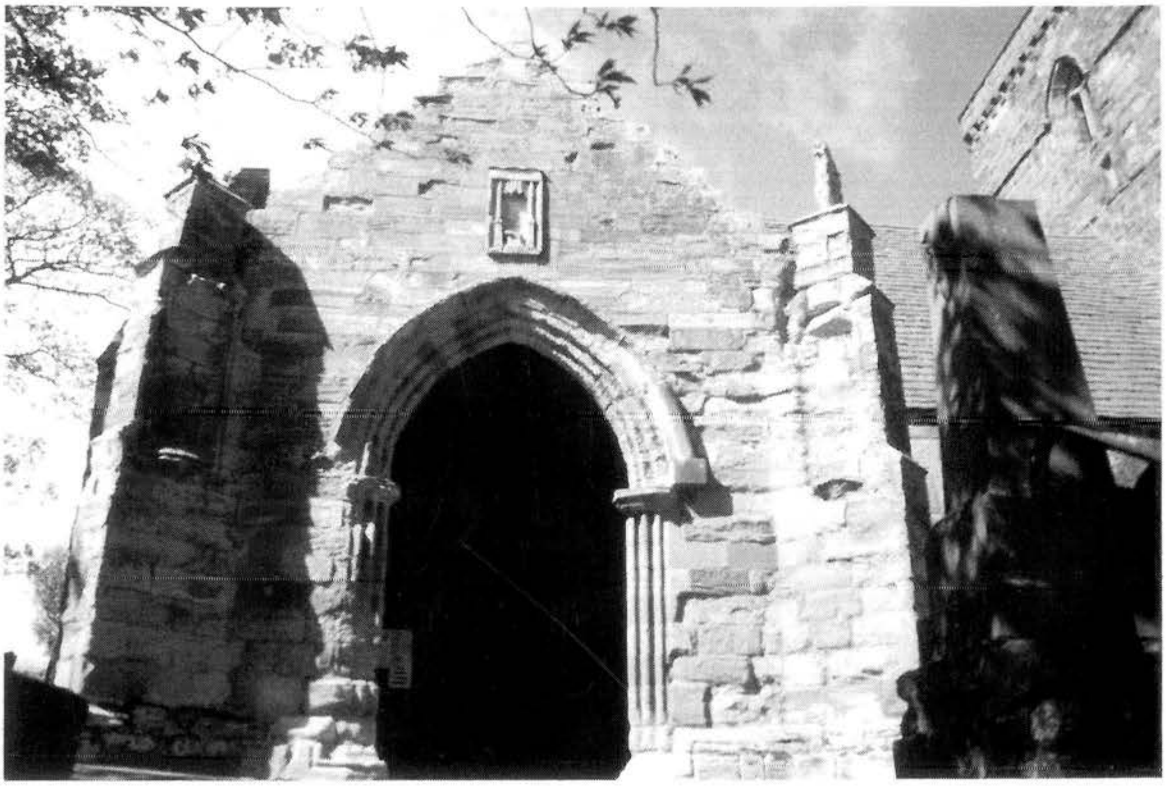


Figure 12.21 Whitekirk Parish Church - porch

12.10.3 *Seton Collegiate Church*

The choir again conforms to all the same canons of triangulature, including haunch and eaves angles, as the previous examples, but here there is a complication: the buttresses continue upwards above the line of the roof eaves and it is significant that the haunch and eaves angles both take this into account. In order to achieve the usual 30°/90° relationship, the eaves angle does not occur at the roof eaves itself but at the top of the buttress. This is really very logical because the extra buttress structure is in effect performing the function of additional vault haunch. This is probably required because Dérand's vector overlaps the wall-thickness of this structure to a much greater extent than the previous examples - about forty centimetres, being about one third of the buttress projection.

The sacristy is slightly later, c. 1500, and its unbuttressed design is founded on an entirely different basis. The plan is a near-square of 1: 1.15. This is of course the approximate ratio of the perpendicular height to the side of an equilateral triangle, which may just be coincidental. Rotation of the core square is not sufficient to define the wall

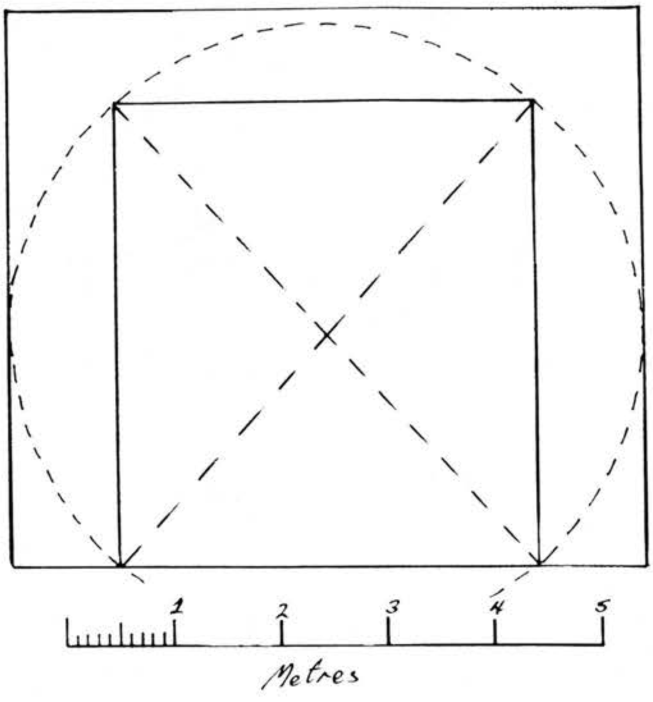


Figure 12.22 Seton Collegiate Church - sacristy

thickness but, strangely perhaps, rotation of the *entire* rectangle does achieve this (figure 12.22). This is a significant departure from what has so far been found to be conventional practice, and is worthy of noting. Relationships based in quadrature also dominate the internal dimensions in section which, from floor to springing is a vertical diagon, from springing to apex is a horizontal diagon - each to within about ten centimetres accuracy. In effect, the entire interior is based on three identical horizontal diagons piled one on top of the other. Interestingly, the span ratio achieved by the particular brand of quadrature employed on the unbuttressed sacristy, 1: 3.86, is comparable with the 1: 3.9 of the choir walls with *half* the buttress projection. Whether this was intentionally 'calculated' can only be speculated, but the similarity is quite characteristic of some mixed buttressed and unbuttressed structures within one building as noted at Crichton. What is intriguing is how the architect of the sacristy, if consciously influenced by the span ratio of the choir which is based in triangulature, managed to create a design using quadrature where Dérand's vector falls much more comfortably within the wall-thickness by about fourteen centimetres. There do not appear to be any relationships based on equilateral triangles apart from the plan and, unlike any examples looked at so far, there is no haunch at all, the interior springing and external eaves levels being about the same.

Seton's transepts present something of an analyst's nightmare: dating is difficult but from available evidence the north one was started sometime before 1540, the south, sometime after 1544. This is a considerable time after the construction of the choir and even the sacristy. It was probably, therefore, designed by a different architect. How did he do it, and to what extent was he influenced by the methods employed in the earlier work?

Given that transepts were, by convention, narrower than choirs but of similar height (at least externally) we might expect to find at least those characteristics. They are indeed narrower by about 1.2 metres, but they break with convention by being higher by around one metre in most internal dimensions, also at eaves level outside.

The wall-thickness is 1.05 metres. Now this must have been decided in one of two ways: either it was simply copied from that of the choir which is very similar, or it was based on quadrature: rotation of the core square, or possibly a solution was consciously sought which incorporated both. We may never know, but it is possibly significant that in section, the span and height to springing of the north transept is an exact square. Above that the vault is based almost exactly on an equilateral triangle: it is actually about 58°-58°-64° - forgivable perhaps. It is within the limits of these discrepancies that the haunch and eaves angles (incorporating the buttress head) conform to the pattern set by the choir. Furthermore, Dérand's vector just overlaps the wall-thickness to encroach the buttress a mere twelve centimetres or so.

The later south transept appears on the face of it to have been designed by yet another architect, or the same one having a rethink, or either copying the north transept very badly. Rotation has again been used to derive wall-thickness but the springing is higher by about half a metre destroying any regularity of geometrical composition: there are no squares or equilateral triangles in section, and haunch and eaves angles are similarly corrupted. The architect has returned to the same buttress design as that of the choir (the north transept buttresses are different), but his attention to geometric perfection is lacking. Perhaps he had little interest in geometry for its own sake, his priority being rather a combination of superficial visible homogeneity, together with structural stability which, if judged by Dérand's vector, is identical to that of the earlier north transept, overlapping on to the buttress by about the same twelve centimetres. Perhaps this is confirmed by reference to Dérand's ratio: as in previous examples, we again find an extraordinary homogeneity amongst all the disparate parts of Seton in this measurement tool: the choir and sacristy are both 1: 4.4; the transepts both 1: 4.6.

12.10.4 *Dunglass Collegiate Church*

The choir, sacristy and nave of Dunglass are all thought to date from sometime between the 1420s and '40s and shortly thereafter the transepts and tower were added (VII Fawcett, 1994:168). Both the nave and choir share the usual span to springing height proportion of around 1: 0.8. Typically, those of the transepts are taller in relation to span. The section of the sacristy is tightly controlled by an equilateral triangle incorporating roof apex, vault springing and external base of side walls, thus defining wall-thickness. There the system seems to end: haunch and eaves angles reveal no consistent triangulation, although the latter at 84° may have been aimed loosely at a right angle. Perhaps of greater significance is Dérand's vector, which only overlaps the wall-thickness at ground level and then burrowing harmlessly for about twenty centimetres more.

Back to the main church units. Side wall fenestration is restricted to a few small segmental arched openings punched through, and only the nave has buttresses. The one characteristic which seems to unite all five parts of Dunglass is span ratio. Choir, nave, transepts and sacristy are all of widely differing widths and wall-thicknesses but their span ratio is remarkably consistent:

choir	1:4.26
sacristy	1:4.2
transepts	1:4.2
nave	1:4.4 wall only.

Perhaps what is surprising is the relative conformity of the nave to this pattern, when it also has buttresses. In earlier examples it was found that the span ratio of buttressed structures had to incorporate around one third to one half of buttress projection in order to equate with that of unbuttressed parts. For Dunglass nave, that would result in a span ratio of between 1:3.3 and 3.6. Clearly at Dunglass the use of buttresses on the nave is not carried out with any attempt at economic or 'scientific' wall design. As mentioned, there are few windows and they are small, hardly weakening the wall structure. The buttresses on Dunglass nave are clearly just a precautionary measure to stiffen, added with no thought of benefiting from any economies they might enable in the basic wall structure. This seems an entirely appropriate explanation given the generally rather unsophisticated design of the overall structure. However, perhaps it is flawed. Perhaps the nave is designed scientifically using buttresses to enable thinner walls and it is the walls of the choir and transepts that are actually dangerously thin. A comparison of the span ratios with those of Crichton emphasizes the point:

Crichton	choir	1:5.5 wall only	1:3.5 wall plus half buttress
	transepts	1:3.6	
Dunglass	nave	1:4.4 wall only	1:3.6 wall plus one third buttress
	transepts & choir	1:4.2	

In what terms did the architect of Dunglass regard wall structure and buttresses? Apart from the sacristy mentioned earlier, no use of triangulature is to be found at Dunglass: there are no equilateral triangles anywhere, nothing is to be found in the haunch angles and only the eaves angle of the nave is anything like a right angle at 88°. In the absence of any such characteristics some indications of quadrature might be expected. It was noted earlier that the wall thickness of Dunglass was possibly designed by quadrature but there was only an approximate match which looked as though it may only have been coincidental. The main parts of Dunglass seem to defy all attempts at analysis. What is to be done?

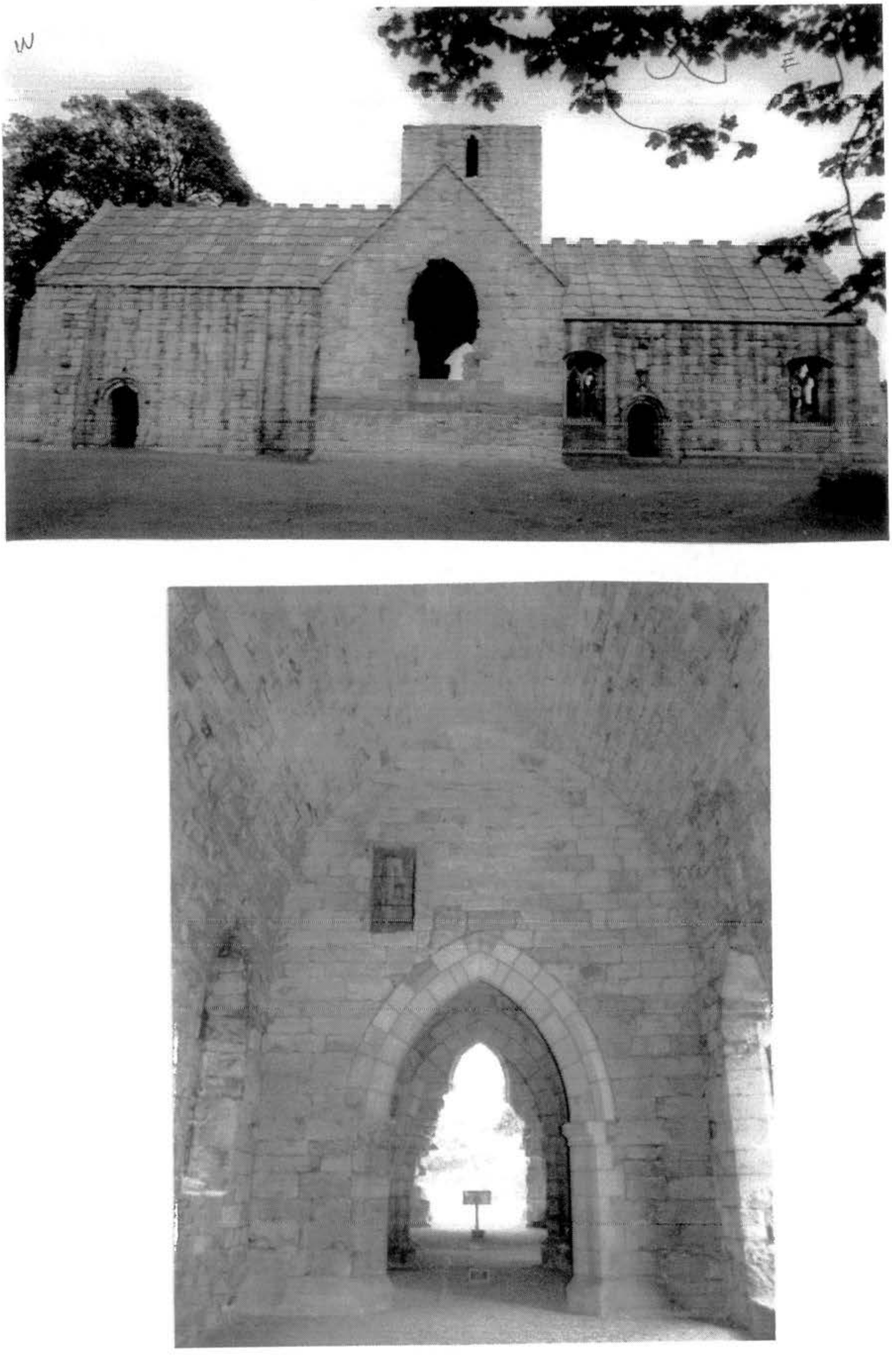
Returning to the drawing board for re-examination of some of the basic methodologies, we look again at quadrature. Why does it not work? Rotation of the core square falls short of the outer wall surface by about seventeen centimetres in the choir, thirteen centimetres in the transepts and sixteen centimetres in the nave. These are sufficient discrepancies to rule out design of the wall-thickness by this method, until that is, the proportional relationship of these figures as against the span of the structures under consideration is noticed:

choir $\frac{0.17}{5.33} = \frac{1}{31}$

transepts $\frac{0.13}{4.2} = \frac{1}{32}$

nave $\frac{0.16}{6} = \frac{1}{37}$

Figure 12.23 Dunglass Church - elevation, and looking through the nave, crossing and choir



The amount by which the walls are thicker than the results of rotation are almost identically proportional, surely indicating that they were indeed designed by this method, but with some proportional adjustment to thicken them sufficiently to conform to some other canon of structural design.

Back at the drawing board it quickly becomes obvious on what basis that canon of structural design might have been founded: Dérand's vector. It has already been noticed how in the sacristy, even alongside the use of triangulature, the position and extent of this most versatile tool had been worked out to coincide with ground level as it passed out beyond the outer wall surface. In the nave, choir and transepts, it is obvious how the vector terminates almost exactly on the outer wall surface. Here, in contrast to the trend for vaulted structures to conform to a geometric model, we have a case of most parts of a whole church designed solely and more precisely according to a more scientific and, for its day, rational methodology. Dérand's ratio in the case of each part is almost identical to the span ratios, which in turn are all very similar. This again suggests that there was some conscious awareness of the vector as a design tool.

One question still remains, however. If the nave structure is so dependent solely on the precise application of Dérand's vector, and the span ratio is virtually the same here as in the other parts, why then are buttresses needed on this structure alone? The most obvious answer to this is staggeringly simple, and was first hinted at earlier in this chapter: there seems to have been a convention that *all* structures of greater internal span than about five metres were buttressed, presumably as an additional 'belt and braces' safeguard for large structures, and almost none below that span required buttresses. For the latter scenario, we have already noted how those on the little porch at Whitekirk were merely vehicles for statuary.

We have dealt so far with a fairly standard structural design type, all the examples of which are characterized by a substantial haunch, sometimes augmented by a section of buttress which actually oversails the roof eaves. Whether the architect was concentrating more on geometry or his understanding of statics, as evidenced by the accuracy with which wall-thickness was defined by Dérand's vector, seems to have had little or no bearing on the existence of the haunch. Now we come to a number of structures, which are in a minority in our survey sample and probably therefore in the country as a whole, which have relatively insubstantial haunch or even none at all. In one case, the roof eaves line is even slightly below that of the vault springing inside. How can such apparent aberrations be accounted for? The haunch should theoretically constitute a vital part of the management of the vault's lateral stresses, and yet the architects of these few buildings seem to have been either oblivious to that concept, or have perhaps experimented and found the haunch structurally unnecessary. This phenomenon occurs in two widely divergent forms: where the entire external roof constitutes part of an equilateral triangle, as at Bothwell collegiate church; in a more conventional structure where triangulature governs apex and internal vault springing, principally at Corstorphine church, which will receive our attention first.

12.10.5 *Corstorphine Collegiate Church*

The choir and south transept are thought to have been added around 1425-9 to an earlier nave, and the little western porch is reputed to date from around 1646 (VII Fawcett, 1994:150-1). There are elements in the design of Corstorphine that are utterly extraordinary: the choir that was added is much wider than the nave: was it intended one day to rebuild the nave to the same width? Probably not since that would have encroached on the new south transept, unless there was a change of mind somewhere in the process. It is impossible to know what was in the minds of the architect and client. The choir is a near-square in plan, about 1: 1.18. The transept is similar at 1: 1.16. Without wishing to be seen trying to 'fit' these spaces to any particular geometric forms, it does so happen that they are not very far off the proportions of an equilateral triangle. If this was intended, than it is indeed a very unusual phenomenon to find this figure utilized in a *plan* situation.

In overall section, the choir is clearly based on such a triangle which, in common with many choirs, defines roof apex, vault springing and buttress base. The span to springing height ratio is the usual 1: 0.8, and the wall-thickness to span ratio is 1: 4.5 (walls only), 1: 2.9 (wall plus half the buttress). Dérand's vector falls just outside the walls, about 20 centimetres onto the buttress. But then we come to the haunch or lack of it. How can this be explained? It has no structural logic and, perhaps more worrying, there does not seem to be much in the way of compensating factor in other aspects of the design. It has already been noted that Corstorphine's span ratios are slightly lower than average which might offset their absence: the difference is marked when comparing against some of the more daring structures which do benefit from this feature:

	Wall alone	Wall plus half buttress
Corstorphine choir	1: 4.5	1: 2.9
Ladykirk choir	1: 7.6	1: 4.35
Borthwick aisle	1: 5.57	1: 3.65

But it is only marginal when compared with some others:

	Wall alone	Wall plus half buttress
Whitekirk choir	1:4.5	1:3
Dunglass nave	1:4.4	1:3.3

As mentioned Dérand's vector follows the trend of just overlapping the wall onto the buttress. There is no indication of compensation for loss of haunch in the pitch of the vault.

By process of elimination, we must look for more positive reasons why the haunch has been omitted. Having noted the possibility of the peculiar use of triangulature in the *plan* of this structure, perhaps there exists some obscure origins of the roof structure in this method. Measurement of the angles, internal vault springing to apex and external eaves to roof ridge reveals an interesting coincidence, both being about 51°. At first sight perhaps this is an insignificant number, but it is actually very important: isosceles triangles with base angles of this amount are referred to by Viollet-le-Duc as "Egyptian Triangles" (X 1863-72: 391 ff) being made up of two 3-4-5 triangles set vertically back-to-back. Most medieval builders would almost certainly have known the significance of such triangles from their use, amongst other things, of creating a right angle. The section of Corstorphine is thus a consciously developed hybrid combining both equilateral and "Egyptian" triangles. Fortunately its abutment is able to withstand the overturning stresses from the vault. Unfortunately for us, one possible mitigating factor has been lost. The buttresses were altered in the eighteenth century to sport a fine set of both dummy and real sundials in place of whatever pinnacles or other counterweight may have been there.

The sacristy at Corstorphine similarly has no haunch. Its vault is relatively horizontal but its walls are thick enough to absorb Dérand's vector and an equilateral triangle links its roof ridge with vault springing. "Egyptian" triangles are absent but both the roof and the vault are based instead on right-angled isosceles triangles (45°-45°-90°). This is a third triangle that was known and very useful to medieval builders: it was one quarter of a square; the relationship of its short to long sides is 1: $\sqrt{2}$; a perpendicular erected to its apex is half the length of its base. It was thus very easily constructed.

The south transept of Corstorphine is perhaps even more puzzling than the choir. In plan following the proportions of an equilateral triangle; in section the roof at

48° does not quite form an "Egyptian" triangle, the vault even less so. The eaves outside are actually lower than the vault springing inside - a sort of 'negative haunch' of 0.5 metres. The barrel vault was once ribbed, but the ribs have long since disappeared. It is a widely held view that ribs were more frequently used in late medieval Scotland in a purely decorative role and this may well be so in many instances. In this case, however, suspicion is aroused because, in addition to the 'negative haunch', the relatively shallow incline of the vault (height : span 1: 2.5) causes Dérand's vector to fall outside the wall surface by about 20 centimetres, and Dérand's ratio at 1: 3.4 is the lowest in the whole survey sample.

There are *no* side wall buttresses to absorb the thrust, only angled corner buttresses which would be effective if the ribs were load-bearing, and more especially if they sprang from the corners. But they don't; they rise from about half way along the side walls where there is no additional abutment. Corstorphine's transept remains something of a mystery, conforming to absolutely no recognisable canons of structural design. One thought, it can hardly be called an explanation: given the interest in triangulature in both plan and section at Corstorphine, there is a distinct impression that the architect is trying to display some sort of virtuosity in this basis of his art. Standing back from both the choir and transept in particular, the broad low sweep of the roofs, ending in the bold stepped but relatively unemployed corner angle buttresses, seem to boast the triangular quality of the building which would not be achieved so effectively with higher haunches (figure 12.24).

If all this seems improbable or inexplicable, perhaps the final mystery lies in the little vaulted porch supposedly built on to the western face of the tower around 1646, some two centuries after the initial building. It is to the great credit of the architect, that after all that time, unless by pure coincidence, he has consciously studied the design basis of the choir and transept and reverted to the same approach to vault construction using no haunch at all. This is particularly curious in view of the totally disjointed nature of the church as a whole, appearing as so many disparate parts haphazardly thrown together. It might be most rewarding, if sufficient material has survived, to re-examine the dating of this little structure. The design is otherwise wholly conventional with the vault springing defined by an equilateral triangle from the roof ridge.

Figure 12.24 Corstorphine Church - South Transept

12.10.6 *Bothwell Collegiate Church*

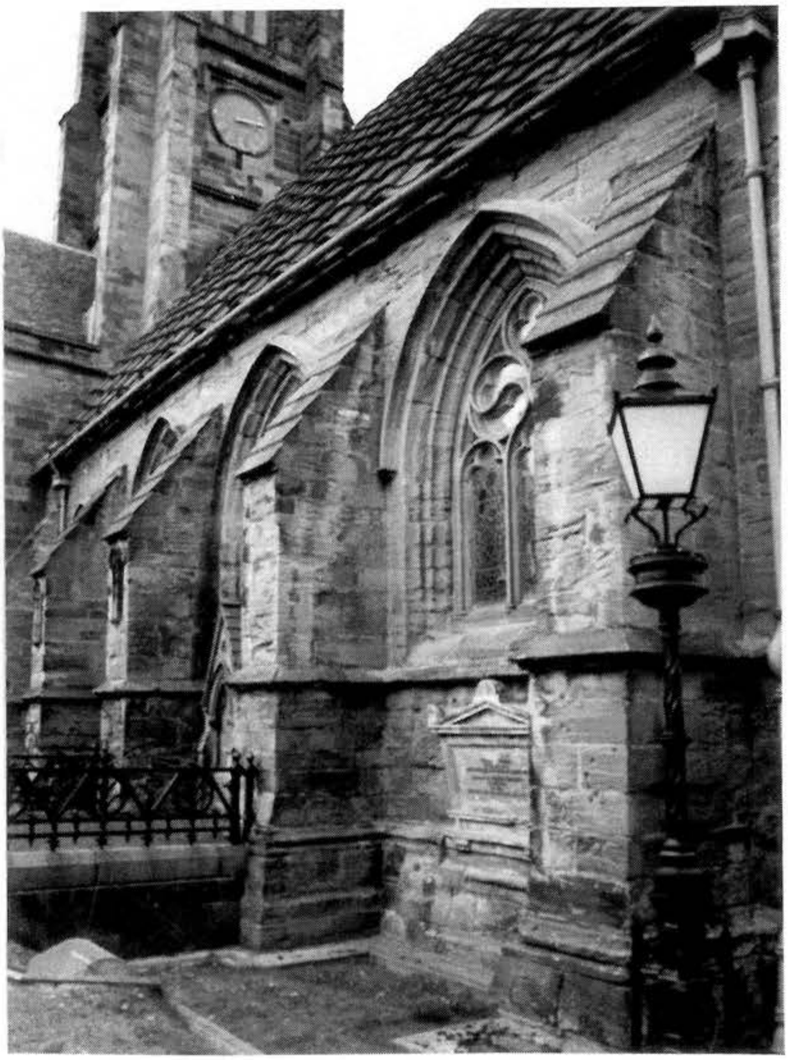
Bothwell (c.1400) deserves mention on several counts, not least since it breaks with convention in choir design: the ratio of span to springing height is reversed to become the almost canonical 1: 0.8 rectangle placed *vertically*. In some other ways it is very conventional. For instance the span ratio compares almost identically with that of Crichton:

	Wall only	Wall + ½ buttress
Crichton	1: 5.5	1: 3.5
Bothwell	1: 5.4	1: 3.4

However, Dérand's vector overlaps the buttress about 40 centimetres, roughly twice as much as at Crichton.

The sectional design of Bothwell represents a very different approach to triangulature, the profile of entire external roof pitch providing the equilateral triangle. The pitch of the buttress heads are set at the same angle giving a very visible effect of triangulature. Again, as at Corstorphine this visual effect is boldly accentuated by the total absence of a haunch. Otherwise the only difference between the two is that Bothwell is a monument to the perfection of the equilateral figure, Corstorphine is to the particular qualities of the "Egyptian". The essential difference between the two is that while Corstorphine's profile is structural, being of solid masonry, that of Bothwell is only partly structural: the upper part of the roof being far too massive a volume to be of solid masonry, endangering all below. The relatively steep profile here is understood to be of timber-framed construction at least in the upper section, while the lower section is more likely to be solid since, as mentioned previously, there is a pressing need for some amount of haunch to counterweight the vault thrust down the relatively slender abutment between the windows. Despite all this the aforementioned extent of encroachment by Dérand's vector leaves some cause for concern.

Figure 12.24 Bothwell Collegiate Church



12.10.7 *Ladykirk*

Dating from 1500, Ladykirk is a truly exceptional church in many ways, and yet with many not so obvious features that are more common. In section its most noticeable departure from convention is an apparently higher than usual vault. Actually the entire internal proportions, span to total height are similar to most other examples: about 1: 1.5. At Ladykirk the difference is that the vault springs from a level that is lower than usual. This of course results in an untypical span to springing height proportion of 1: 0.67, lower than the conventional 1: 0.8. The external roof pitch and position of the eaves, however is much more conventional. Because of this the haunch angle is still able to conform to the usual 30° and thus be in line with the equilateral triangularity of the entire church section, if the internal rather than the external apex is used (figure 12.26).

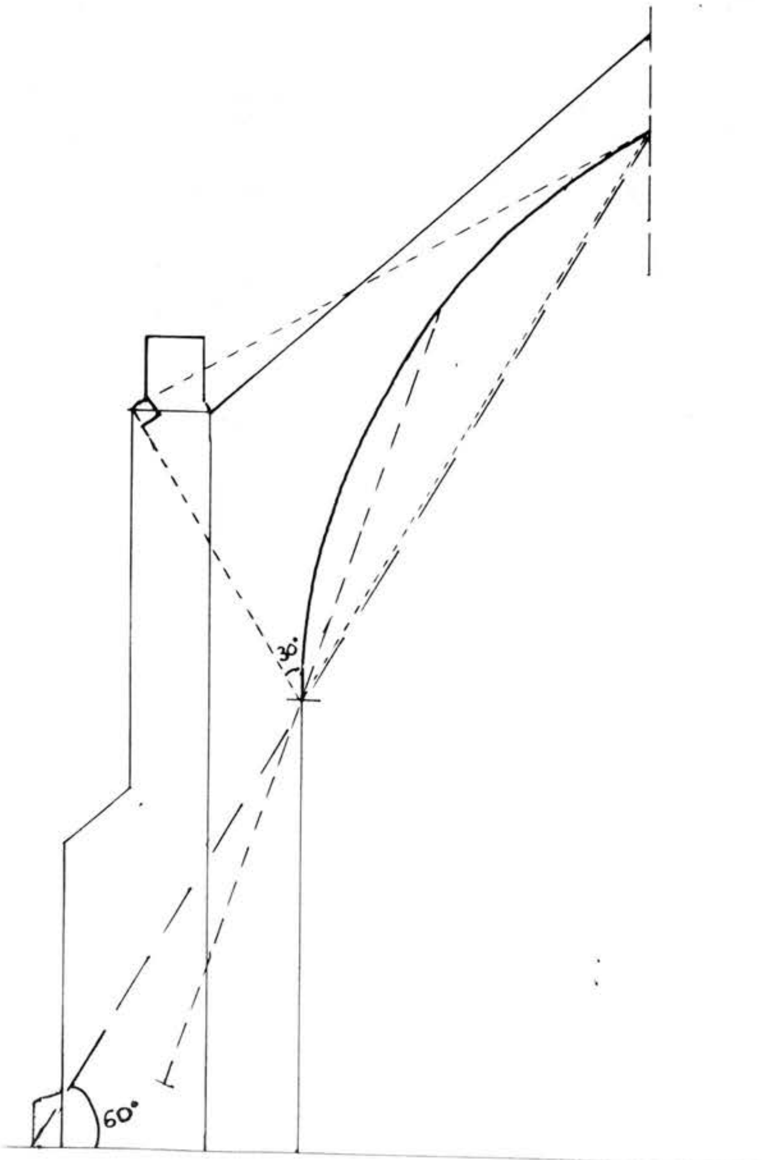


Figure 12.26 Ladykirk Church: section of nave/choir

As mentioned earlier, the walls of Ladykirk are unusually thin, the span ratios for both wall thickness alone (1: 7.6), and with half buttress projection (1: 4.35) being the highest apart from Dalkeith. The span ratio based on total wall thickness and buttress (1: 3) even begins to approach the ideal sought by Lechler, Rodrigo Gil and later Rondelet.

Even more exceptional than these figures is the 1 : 5.2 of Dérand's ratio which is the highest of *any* of the buildings recorded. The vector encroaches some 40 centimetres over the buttress, much more than most other examples, and terminates in the considerably deeper lower section. If the buttress was only as deep as the upper section for its full height, the vector would terminate perilously close to the outside edge. Now the fenestration at Ladykirk is regular and wide, but not high, and it is noteworthy that the pronounced intake part way up the buttresses coincides with the springing of the window arches on the side elevations at least (figure 12.27). It is likely that the buttresses have been thoughtfully designed with both fenestration and Dérand's vector in mind. Nevertheless, the considerably greater overlap of the vector at Ladykirk compared with many other churches is noted with concern.

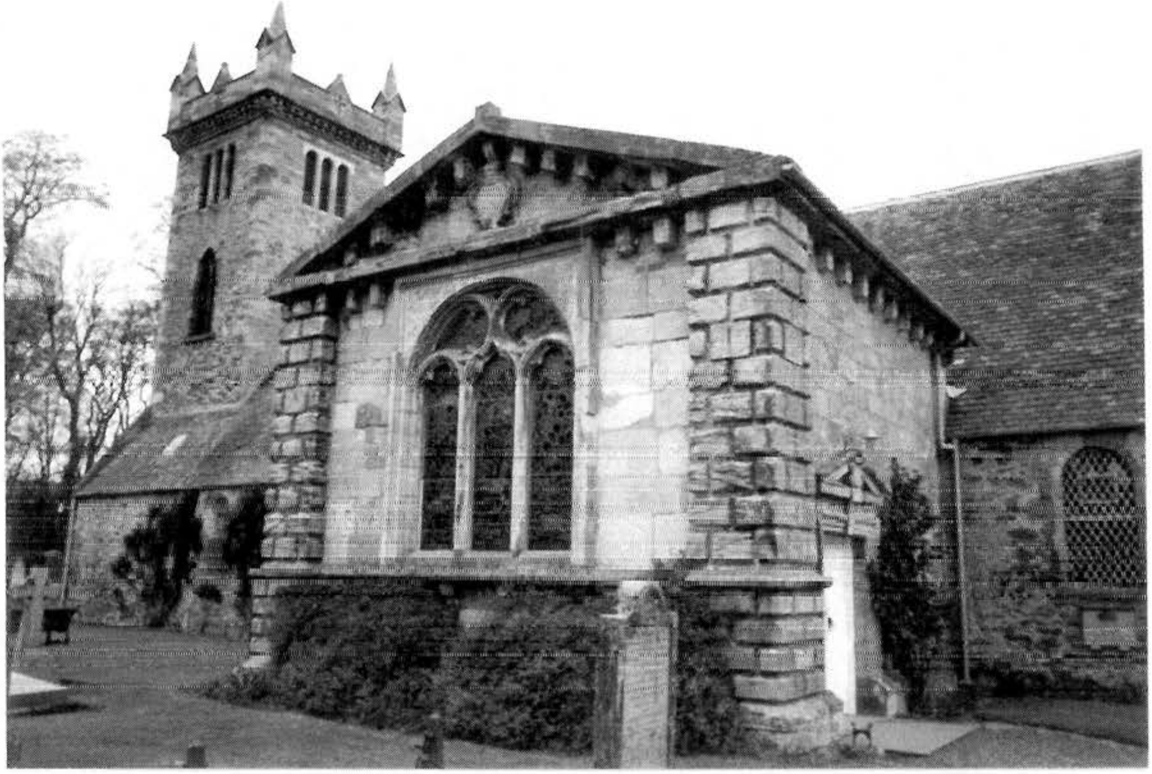
Figure 12.27 Ladykirk Church

12.10.8 *Dirleton Church: Archerfield Aisle*

What happened after the reformation? Dating from 1664 and therefore not strictly within the scope of this research, this aisle which is one of the icons of early classical design in Scotland provides an instructive insight into the problems of reconciling earlier structural solutions with later geometric methods (figure 12.28). The vault is virtually a perfect half circle above a space whose sectional dimensions follow medieval conventions for choirs: 1: 0.76. Predictably perhaps for an essentially classical structure there are a profusion of relationships based on quadrature, most of which are 1: 1.25 or 1:√2. Included in the latter is the wall-thickness, defined by rotation of the internal core square.

However, triangulature is not dispensed with: from the internal vault apex, an equilateral triangle can be found based, not at the outside surface of the walls, but at the foot of the clasping corner 'buttresses'. Of course these are not presented as buttresses but as rusticated corner piers. As such they serve as little more than decoration, giving no direct abutment to the round barrel vault. This is all the more remarkable when we find Dérand's vector terminating on their outside surface with a precision that it would be hard to claim as coincidental. In effect, Dirleton appears to be a hybrid or perhaps transitional, apparently favouring an archaic geometric rather than rational design basis: the walls are very thin in relation to the span 1: 4.8 - in fact the *highest* ratio in an unbuttressed building, and this for a vault that is round rather than pointed, therefore exerting overturning stresses in a more horizontal direction. That only lip-service is paid to Dérand's vector in an age when the use of this device had actually been published (1643) demonstrates either total ignorance or daring beyond the call of masonic duty. On the face of it, the disregarding of Dérand's vector and the preoccupation with style and geometric relationships, not least the rotation which defines the side wall thickness, suggests another possibility: that by now experience had shown that walls could be thinner, particularly if carefully constructed, and that the old rules-of-thumb or canons of structural stability such as Dérand's vector could be reduced to the status of eccentricities of design.

Figure 12.28 Dirleton Church - Archerfield Aisle



It is worth mentioning in this connection another less important structure of the early seventeenth century: the architect of the Phin Aisle of Aberdour Church has also disregarded Dérand's vector, which falls about 20 centimetres outside the wall surface. Perhaps economic or other constraints in the building boom from the mid sixteenth century had engendered a disregard of earlier practice. Had this ever been the case previously? Let us look at a similar example from much earlier.

12.10.9 *South Queensferry Carmelite Church*

Coincidentally, almost every aspect of the building in both plan *and section* is based on quadrature, the wall-thickness itself being determined by rotation. This has resulted in an almost identical span ratio of 1: 4.76 to Dirleton's 1: 4.8. Again, these two are just about the highest span ratios for unbuttressed walls in the survey sample.

In what seems like a genuine attempt to compensate for this, the church is given a substantial haunch the angle of which, 34°, is the same as that extending from the springing to the apex. The eaves angle is 90°. Here then are elements of triangulature. However, the architect was either ignorant of, or chose to disregard Dérand's vector which falls about 25 centimetres outside the wall surface. The choir does not appear to have suffered as a result. The same cannot be said however for the tower, where Dérand's vector similarly hangs in the air about 20 centimetres beyond the outside wall surface. This will be discussed further in a later section.

12.10.10 *Carnwath: St. Mary's Aisle*

This is essentially a transept added from 1425 to an earlier structure when it achieved collegiate status. Its internal plan to the original junction arch is an exact square and its internal span to springing height ratio is a very conventional 1 : 0.82. Then begin the differences. The walls are very thin for the span (1 : 6.3 span ratio on walls alone) but this is easily compensated by the deep buttresses (1 : 3.67 span ratio and including half buttress) which is a similar figure to Crichton (1 : 3.5) and Borthwick (1 : 3.65) and even Bothwell (1 : 3.4). Dérand's vector overlaps almost half the buttress. As previously mentioned, Carnwath's buttress is deeper than the wall-thickness, despite the lack of fenestration. It is also a structure with no haunch and it is supposed that perhaps the buttress may compensate for this. The fact remains however that Carnwath is one of a few structures where Dérand's vector encroaches over the buttress by more than 40 centimetres, about 50 centimetres in this case.

12.11 DÉRAND'S VECTOR AND AN INTERESTING COINCIDENCE

We have seen many instances where this design tool appears to be crucial to structural design and stability, and it is noteworthy also how consistent its use seems to have been, terminating just within the wall-thickness of unbuttressed churches, just overlapping where there are buttresses. The consistency with which Dérand's ratio has been found to be the same or very similar in various different parts of the same church, even when built at different times, is compelling. There is much evidence to suggest that Dérand had found the method by which medieval masons 'calculated' their vault abutment. And yet there seem to be some questions left unanswered. In particular the inconsistency of the overlap of the vector on to buttresses: while many examples show this dimension only between around 12-22 centimetres, there are others where it is around 40-50 centimetres and an exceptional handful of possibly up to double that number. – –

Does such inconsistency after all relegate Dérand's vector to the scrapheap of non-applicable or inappropriate design theories listed earlier? Or can there be an explanation in terms of structural design? Let us look at the amounts by which encroachment occurs and see if any patterns emerge.

0-5 cms	10-25 cms	40-50 cms	90+ cm
Dunglass nave	Crichton choir	Seton choir	? St. Salvator's
	Corstorphine choir	Ladykirk choir/nave	? Dalkeith
	Whitekirk choir	Bothwell choir	(vaults lost in both)
	Borthwick aisle/transept	Carnwath aisle/transept	
	Seton transepts	Corstorphine transept	

Corstorphine south transept (bracketed) is not strictly classifiable since the vector overlaps the wall-thickness by about 15 centimetres but there are only corner buttresses set at approximately 45 degrees. The figures for St. Salvator's and Dalkeith are actually unknown since the vaults do not survive and the above estimate is based on a very approximate conjectural restoration.

Taking the categories from left to right, Dunglass has already been discussed. The vector coincides almost exactly with the wall thickness. The 10-25 centimetre group is unremarkable and consists of those good solid average structures of the Lothians which conform to so many trends. But what about Seton? Why do the later transepts fall into this category, and the earlier choir into the 40-50 centimetre group? Furthermore what has caused the other structures to fall into this category? Some of them have already received comment concerning structural oddities such as lack of haunch (Bothwell, Carnwath, Corstorphine). Ladykirk has also already been noted as exceptional. Seton has so far appeared quite conventional in most respects. On the face of it there is very little to be found linking these structures. And yet there is one feature that they do all share, albeit in diverse forms, which is glaringly obvious : ribs.

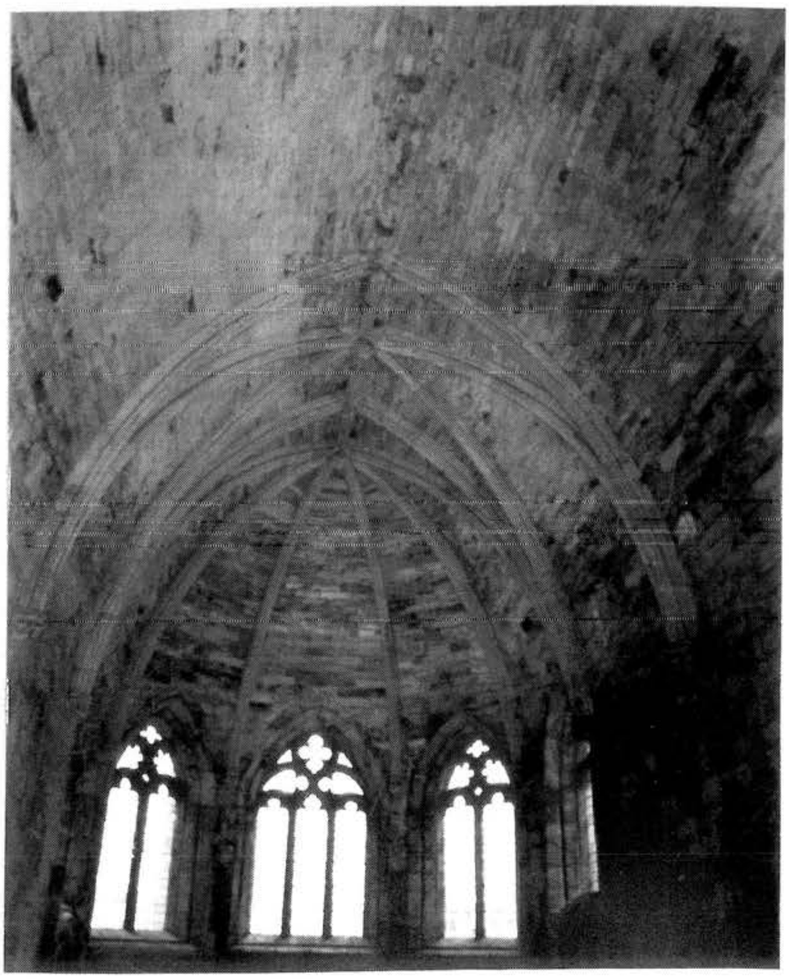
Ribs are a hitherto unmentioned subject. In Scottish barrel vaults they have been repeatedly relegated to the status of, for instance, a "decorative veneer" (VII Fawcett, 1994: 7) though sometimes a stiffening or strengthening role has been attributed in a very non-specific way to the wider transverse ribs. On the face of it that is not difficult to imagine for that particular vault type as found at Bothwell, Ladykirk and Carnwarth. What might be harder to justify is a structural function for the ribs of Corstorphine's south transept and Seton's choir. At the former we have already noted the otherwise inexplicable overlapping of Dérand's vector of the wall-thickness because of the very shallow profile of the vault and the relatively high span ratio of 1:4.

Now the ribs have long ago been lost but 'ghosts' of their original positions remain and it is possible to roughly judge their effect: if Dérand's vector is drawn from the underside of the ribs, supposing them to be about a typical 20 centimetres thick, instead of from the vault intrados, then it terminates safely just *inside* the wall-thickness. At last some sense can be made of this otherwise puzzling structure.

Applying the same principle to Seton makes similar sense: it will be recalled that earlier a possible connection was made between the excessive overlap of Dérand's vector and the 'compensation' of extra high buttresses. If the thickness of the ribs are taken into account, Dérand's vector now overlaps the buttress by only about 20 centimetres, a similar amount to other unribbed structures, amongst which of course are the later transepts.

Whilst looking at the vaulting of this church it is worth dwelling for a moment on the unfinished appearance of the choir (figure 12.29). The ribs at Seton have traditionally been thought of as aesthetic rather than structural (Fawcett, 1994:178)

Figure 12.29 Seton Collegiate Church Choir



and, in a sense, this view seems entirely logical since they do decorate the presbytery area, over the altar. This is also of course the section which was built first, and was built with large pointed windows - all by the first Lord Seton. The vaulting of the rest of the choir was done by the second Lord Seton after obtaining collegiate status in 1492. It is really very perplexing that this should not be ribbed. Where else can such a 'fizzling out' of rib work be found? There seems no sense of purpose or 'design' in the way this rib pattern simply terminates without any form of aesthetic punctuation. It so obviously should be part of a continuous scheme the full length of the choir, rather than terminating where it does. If indeed that was the original intention, then the notion that its sole purpose was to 'decorate' just the presbytery seems flawed. It perhaps had a structural function after all. But if it did, why then did the builder of the rest of the vault not continue the work with the use of ribs? We will probably never know. Is it perhaps that the will to continue such an expensive scheme ran out: a different architect was used to finish the job who possibly failed to take into account the effect on abutment of the rib work, or who considered that it would not be structurally unsafe. The ribs at Seton, if judged by Dérand's vector, are just as structural as those of Bothwell, Ladykirk and elsewhere, and if they are structural at Seton, then they may well be also at other similar sites: St. Giles, Edinburgh choir aisles, the presbytery at Melrose, the upper hall at Dundonald Castle for instance.

What seems so instantly plausible about the notion that these and other ribs do have a structural function is that in most cases they are very roughly around 20 centimetres deep, and this is roughly the amount by which the position of Dérand's vector differs from those in unribbed structures. If this design tool, or anything like it, was actually used by the architects of these buildings, it provides convincing evidence that the rib was a structural as opposed to merely an aesthetic device as employed in these Scottish barrel vaults.

12.12 SUMMARY AND CONCLUSIONS

The study of these few churches has revealed much about masonry building design during this period. Several conventions appear to have been very common , indeed possibly almost universal within Scotland:

1) There ~~does~~ seem to have been a general convention of overall structural proportions, particularly for choir structures, that is reminiscent of the comments expressed about similar concepts in the rebuilding of Siena Cathedral.

2) It was common practice for the church section to be based on the equilateral triangle for overall form, but probably not for structural elements specifically. No doubt there may have been some religious significance in the incorporation of a perfect three sided figure for the most sacred part of the building.

3) In these cases a hybrid form of triangulature was then also used in an inverted configuration to define both the wall thickness and haunch size. By this method the vault haunch size was effectively a subject of the pitch of the vault. Where there is no haunch, there is generally some other compensatory device.

4) Where triangulature was not used in design of the church section, the plan including wall thickness was possibly based in quadrature.

5) The fact that one example (Corstorphine) was found not to be based on the equilateral but the "Egyptian" triangle suggests that there may be other examples of this as yet undiscovered.

6) In all these cases, both triangulature and quadrature was used flexibly as "help-constructions" to provide a framework from which individual solutions could be worked out.

7) The final determinant of wall thickness had to be a device such as Dérand's vector which took account of vault pitch. It is noteworthy that, in the case of unvaulted churches, it was also concluded that some diagonal design method might also have been commonly used.

8) To churches of over 5 metres internal span, buttresses were nearly always added, whichever of the two geometric design methods had been used.

9) The relationship of wall thickness to buttress projection was generally determined by the size and number of windows. Further research would be needed on a larger number of examples to work out if there was any particular principle, formula or rule of thumb by which this was done. As a very general rule an unbuttressed wall was equivalent to a buttressed wall plus between around one third to one half the buttress projection. Buttresses were thus found to be of structural rather than aesthetic function in every case except that of the porch of Whitekirk.

10) Ribs of all sorts appear to have a structural rather than, or as well as, decorative function, and these are incorporated in the 'calculation' of wall thickness by Dérand's vector, or whatever other means.

11) Although, as stated in (6) above, triangulature was commonly only employed for the main structural section in a generalized capacity enabling formation of an overall framework, the cases of Corstorphine and Bothwell suggest that it was sometimes the architect's intention to make a visual statement or virtue of the geometric figure.

In conclusion, it does appear that Scottish architects in the fifteenth century employed carefully and logically worked principles, variously combining geometry and primitive statical methods to 'calculate' with no small degree of precision the thickness of walls and the size and shape of buttresses in support of stone vaulting, always compensating one apparent potentially weak area by strengthening another. Considerable flexibility seems to have been the norm in the use of geometric forms which appear to have been utilized in many different ways in order to either assist or to justify particular design arrangements. Such flexibility was of course commensurate with the characteristic range of span ratios which can appear so daunting to the modern mind when trying to interpret the medieval architect's methods.

13 VAULTED, UNFORTIFIED DOMESTIC STRUCTURE

13.1 INTRODUCTION

This group of structures are mostly from courtyard ranges, and numbers are greatest from the mid-sixteenth century onwards. There are three quite distinct categories of vaulted domestic structure:

Multiple Transverse Barrel Vaults (often with side passage)

These have already been examined under "Unvaulted Domestic" for reasons given more fully in that section, principally because transverse vaults do not abut the long side walls which tend therefore to be the same thickness on the vaulted ground floor as at higher levels.

Multiple Pillared Ribbed Groin Vaulted Undercrofts

The complexities of these structures, which are nearly all of the period from the twelfth to the fifteenth centuries, really put them beyond the scope of this research. Limited coverage will, however, be given at the end of this chapter in order to set out what has come to light, and secondly, to draw comparisons with what has been found in the more comprehensive description and analysis of longitudinal barrel-vaulted structures.

Longitudinal Barrel Vaults

These are the principal subject of interest in this section. Most examples incorporate in a single structure at least two, sometimes three, different structural problems:

i) because the lateral thrusts of the vault require abutment in the long side walls, these must be of appropriate thickness to fulfil that role, at least at ground floor level. The level of abutment is relatively straightforward to assess, most dimensions being simple to access, having no extra buttressing, and rarely having more than narrow slit windows.

ii) because the walls of subsequent storeys have no vault to abut, theoretically they can be built to an entirely different specification: that of support for a timber trussed roof structure alone.

iii) supposing a courtyard range situation (which indeed applies to most examples chosen), walls facing the outside world are likely to be thicker for security purposes than those facing the courtyard. This aspect has been dealt with separately in chapter 8. For the purposes of this particular section where an external wall structure is thicker for security purposes, the overall width used in analysis has been adjusted to exclude such extra thickness in order that structural considerations alone can be examined. The sample and their basic dimensions are listed below.

Figure 13.1 Vaulted Domestic structures surveyed

Period	Site	Span (m)	Wall Thickness (m)
12C	Dryburgh Chapter House	6.8	1.4 + 0.2
14/15C	Dirleton Hall Range	6.2	3.4
15C	Crossraguel Calefactory	5.35	1.1
L15C	Balgonie Hall Range	6.05	1.5
L15C	Linlithgow Pal. W. Range	5.75	1.5
M16C	Craigmillar E Range	4.2	1.04
M16C	Aberdour Kitchen Range	5.2	0.8 - 0.9
M16C	Provost Skene's House	4.47	1.3
L16C	Crichton Stables	6.8	0.95
L16C	Auldhame	5.4	1.4 - 1.5
L16C	Dunnottar Kitchen	5.7	1.05
L16C	Dunnottar Brewery	4.72	0.9
L16C	Balmbreich SE Range	5.2	1.6
L16C	Barnes vaults 1 & 10	3.9	0.8
L16C	Barnes vaults 2 & 9	5.54	1.14
L16C	Garleton	5.15	0.96
L16C	Culross Kitchen block	4.2	0.95
E17C	Houston courtyard building	4.4	0.85
E17C	Caerlaverock Nithsdale Aptmts.	5.3	1.1
E17C	Balgonie accom. block	5.4	1
E17C	Culross strong room block	3.75	0.95

In the examples surveyed there is considerable variety of size and form of the vaults themselves, if only because the ground floor has been designed for very different purposes in different buildings - some for prestigious habitation, some for cooking, some for mere storage. These are manifest in variations not just in both span and height, but also in curvature of the vault. It has already been ascertained that there were some fairly standard wall thicknesses for unvaulted domestic structures, both fortified and unfortified, to some extent regardless of variations in span and height. It follows that in some cases, where the vault span and height are more than those standard wall thicknesses will support, some additional abutment will have been needed in the vaulted ground floor. How was this calculated?

It has been noted how in vaulted church design there were various different approaches to the problem: most designs in cross-section were based on triangulature, in particular the equilateral triangle; a few ground-plans were based on quadrature by rotation of the square formed by the internal span, but in the final analysis most were subject to the limitations imposed by Dérand's vector or some such device with similar effect. Can similar trends be found in these structures which are much less architecturally sophisticated but which, nevertheless, still require to be structurally stable?

13.2 TRIANGULATURE

Did triangulature have any part to play in the design of these domestic vaults? It was noticed that in vaulted churches equilateral triangles could be found connecting either the internal or external apex with various points on the ground, as well as the vault springing in many cases. If it was difficult measuring the exact position of the external apex on churches, it was even more so in buildings with enclosed room spaces above the ground floor vault, but nevertheless sufficient data has been gathered to draw up a schedule of the possible instances where triangulature may have been used. It will be recalled that the possibilities for the useful application of triangulature in church architecture were many, and there were many variations just on the application of the equilateral triangle alone. There were also incidences of isosceles triangles (the "Egyptian" with base angles of 51 degrees, identified by Viollet-le-Duc, which was basically two '3-4-5' triangles set back-to-back on their sides of 4 units., and the right-angled with base angles of 45 degrees). All these triangles have been highlighted, both because they have been identified in measured surveys, and because they could easily have been constructed on the ground by the medieval mason using no more than pegs and string. A further triangle has been 'invented' for the purposes of this research which might conceivably have been used by medieval builders. It is a variation on the Egyptian triangle. If the medieval architect found reason to create such a triangle, he might equally have set two '3-4-5' triangles back-to-back on their shortest sides of 3 units. This creates a more horizontal figure with base angles of 39 degrees each (figure 13.2). Again, it could have been constructed easily using pegs and string.

Now, armed with this array of four possible (what shall be called 'elemental') triangles, how might they be applied to these simple domestic structures in ways which will enable their use to determine the sizing of certain structural members? Figure 13.3 shows in a single schematic diagram just one side of each of the six possible modes of application for triangles in domestic vaults. These have been designated *a, b* and *c* where connecting to the internal vault apex, and *d, e* and *f* to the external apex. Applying these six different formats to each of the surveyed examples produced the angles shown in figure 13.4. Where one or more of these is found to be one of those angles indicative of triangulature (39, 45, 51 or 60 degrees) this has been highlighted in colour. Now given the inaccuracy which might result from settlement, changing floor levels, weathering and other imponderables, it was decided to highlight also any angle which was within *one* degree of those indicative of triangulature.

Figure 13.2 The Egyptian Variant Triangle

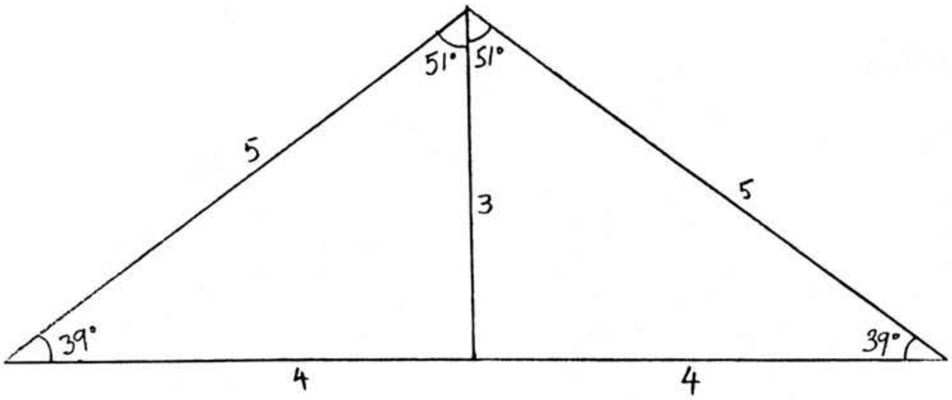


Figure 13.3 The possibilities for application of triangulature to barrel-vaulted domestic structure

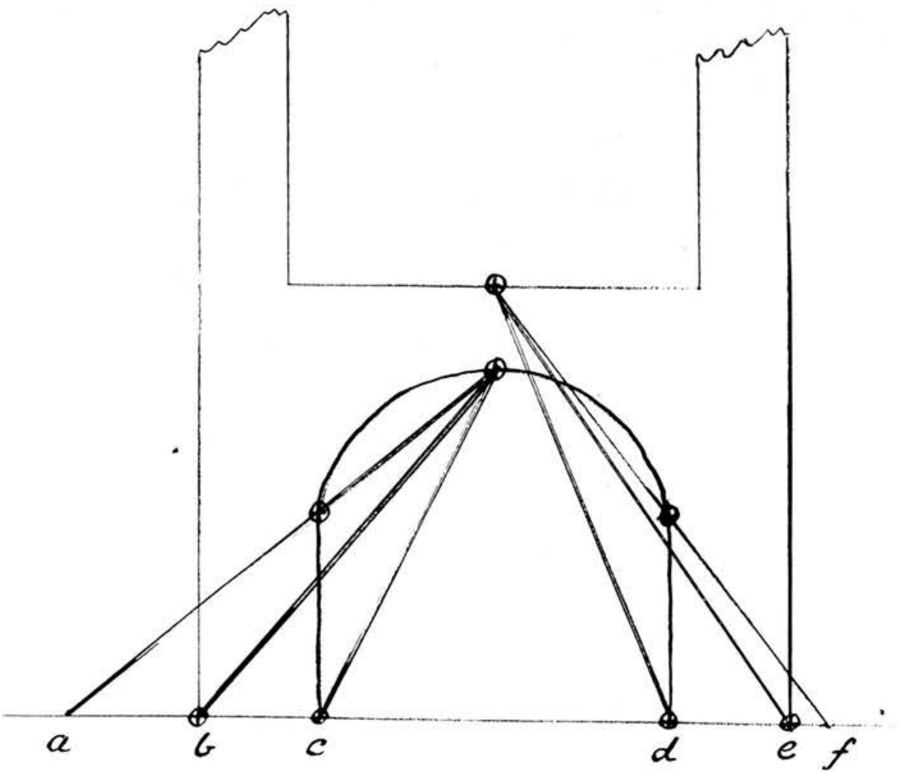


Figure 13.4 VAULTED DOMESTIC: TRIANGULATURE SUMMARY

		Angles to INTERNAL apex			Angles to EXTERNAL apex			
Date	Site	*a*	*b*	*c*	*d*	*e*	*f*	
12C	Dryburgh Chpt House	45	51	62	64.5	55	49.5	
14/15C	Dirleton Hall Range	38	38	58	61	41	45	
15C	Crossraguel Calefactory	29	46	56	60	50.5	37	
L15C	Balgonie Hall Range	38	39.5	51	55	43.5	44	
L15C	Linlithgow Pal. W. Range	35	45	57	61	50	45	
M16C	Craigmillar E Range	37	44	55	61	51	51	
M16C	Aberdour Kitchen Range	43	48.5	56	58	50	45.5	
M16C	Provost Skene's House	37	36	49	52	39	42	
L16C	Crichton Stables	43	50	56	59	52	46.5	
L16C	Auldhame	38	38	51	54	43	45.5	
L16C	Dunnottar Kitchen	39	42	51	55	45	45	
L16C	Dunnottar Brewery	35	37	45	52	43	45	
L16C	Balmbreich SE Range	40.5	33	47	50	36	44	
L16C	Barnes vaults 1 & 10	42	50	59.5	62	53	48	
L16C	Barnes vaults 2 & 9	38	40	50	54	45	44	
L16C	Garleton	33	37	46	50	41.5	39	
L16C	Culross Kitchen block	35	39	50	55	44	43	
E17C	Houston courtyard building	29	38	47.5	50	40.5	33	
E17C	Caerlaverock Nithsdale Aptmts.	36	38	48	55	45	45.5	
E17C	Balgonie accom. block	41	36	45	50.5	42	48	
E17C	Culross strong room block GF	33	34	46	51	39.5	40	
E17C	Culross strong room block 1F	33	44	55	59	48	40	Totals
Totals of possible triangles:								
Equilateral (60 degrees)		-	-	1	6	-	-	7
Egyptian (51 degrees)		-	3	5	7	5	1	21
Right Angled (45 degrees)		1	4	4	-	4	10	23
Egyptian Variant (39 degrees)		5	7	-	-	2	3	17
Totals		6	14	10	13	11	14	Grand Total **68**

Inspection of the results looks at first sight very exciting. There seem to be plenty of 'hits', though these must be analysed in context. For instance, the appearance of equilateral triangles and indeed of angles exceeding 60 degrees seems predominantly characteristic of the earlier periods, but that is because most of the early vaults are more commonly for habitation of some sort and are thus higher in contrast to the lower, more utilitarian or storage structures of the later period. What is also particularly noticeable is that for most examples more than one triangle type could have been used, and it is difficult to determine whether or not this was intentional, or one, or indeed both triangles are merely coincidences.

The appearance of more than one significant angle in any one building is a remarkably common occurrence, and is worth investigating, for in some cases, if two different triangles have been used to connect different parts of the vault, they may actually define the thickness of walls or apex. For instance, the incorporation of angles *c* and *f* into two different triangle types in one structure would actually determine *all* those dimensions. Indeed, that combination itself is not uncommon. If only the pairs of angles *a* and *b*, *b* and *c*, *d* and *e*, *d* and *f* indicated one or more of the afore-mentioned triangles, then the wall thickness at least would be defined, and indeed these coincidences are also quite common.

On a general level though, how safe is all this? Granted, lots of possible cases of triangulature have been identified, but are there too many to be credible? The number of 'hits' and coincidences on the triangulature schedule is very high, but then they may be nothing more than chance coincidences. After all, taking one figure either side of 39, 45, 51 and 60 does not actually leave much in between! In church design incidences of triangulature were much more limited in scope, being dependent on a less broad range of options per structure. Granted, this is mainly because the churches were mostly of similar size and proportion to each other, especially the choir/chancels. As far as could be seen, each church vault was only based on *one* type of triangle. Furthermore this was only used to roughly define the overall proportions of the cross-section, not often the sizing of individual structural elements.

For mere humble storage cellars would an architect have bothered with the accurate delineation of a certain triangle at all? Furthermore, would he really have engaged two or even three different triangle types just in order to determine the wall thickness? Of course the possibility of this cannot be entirely ruled out. What makes this scenario even less likely though, is that even if one triangle formed the basis of the internal height and span (*c*) there still does not appear to be a system which tells the architect which other triangle to use in order to define the wall thickness. There is no clear pattern that has obviously been followed. The results are all very random.

The only conclusion that can safely be drawn from all this, especially given the difficulties of measurement, is that the overall form of these domestic vaults probably conforms in most if not all cases to at least one or other of the three or four commonly used triangles, and it seems reasonable to suppose that these may have been employed, as with some churches, simply as "help-diagrams" around which to create the overall shape of the structure in section. For definition of the actual wall thickness and vault abutment we must look elsewhere.

13.3 SPAN RATIO

Figure 13.5 shows the span ratios of all the surveyed examples and, excepting a few outliers and oddities which will be dealt with later, reveals a most interesting pattern, the majority clustering unmistakably round several specific ratios. What is happening? The middle cluster (1: 4.8) represents the use of quadrature: the inside span in relation to the outside is 1: √2. Rotation of the diagonal of the internal core square has obviously been used to determine the wall thickness in these cases. What about the group around 1: 3.7 - 1: 4? Again comparing the internal to external spans, we arrive at the ratio 1: 1.5, which is the same as 2: 3. Both this and the 'root-2' relationship are of course easily constructed on the ground using nothing more than pegs and string. A further easily identifiable 'pegs and string' relationship is to be found in the sixteenth century range of Balmbreich which is based on the 'golden section' ratio of 1 : 1.618.

One point about these ratios that is immediately obvious is how similar they are to those of some vaulted churches. The domestic structures range from 1: 3.7 - 5.4 excluding outliers, which corresponds remarkably with both unbuttressed churches, and also buttressed churches if taken with one third of there buttress projection (figure 12.8). Perhaps this should only be expected, but it is perhaps a little illogical given that the churches have pointed vaults, the domestic ranges round or segmental which exert more lateral thrust.

Figure 13.5 VAULTED DOMESTIC: SPAN RATIO SUMMARY

Ratio 1:

1.8	Dirleton				
1.9					
2					
2.1					
2.2					
2.3					
2.4					
2.5					
2.6					
2.7					
2.8					
2.9					
3					
3.1					
3.2	Balmbreich				
3.3					
3.4	Skene's House				
3.5					
3.6					
3.7	Auldhame				
3.8	Linlithgow				
3.9	Balgonie Hall	Culross Strong Rm			
4	Craigmillar				
4.1					
4.2					
4.3					
4.4	Culross Kitch.				
4.5					
4.6					
4.7					
4.8	Dryburgh	Crossraguel	Caerlaverock	Barnes 1	Barnes 2
4.9					
5					
5.1					
5.2	Dunnottar Brew'y	Houston			
5.3	Garleton				
5.4	Balgonie Accom.	Dunnottar Kitch.			
5.5					
5.6					
5.7					
5.8	Aberdour Kitch.				
5.9					
6					
6.1					
6.2					
6.3					
6.4					
6.5					
6.6					
6.7					
6.8					
6.9					
7					
7.1	Crichton Stables				

Those are all very straightforward, but perhaps more of a problem for analysis is the group around 1: 5.2 - 1: 5.4. This in internal : external span terms is around 1: 1.38. Now that of course is not far off the 'root-2' relationship of 1: 1.4142. In fact, to fit that ratio, the internal spans would only have to be adjusted by the following amounts:

Dunnottar brewery range	9 cms
Dunnottar kitchen range	14 cms
Garleton free-standing lodging	15 cms
Balgonie 17th C range	13 cms
Houston courtyard range	10 cms

Again, those are the adjustments necessary to the internal span. Translated to terms of wall thickness, half these amounts should be added to each of the two side walls. So the walls of Balgonie's seventeenth century accommodation range, for instance, which are now almost exactly one metre, would be 1.065 metres. In the light of this, should these not just be included in the group whose wall thickness has certainly been defined by rotation? Possibly so. And yet they form such a distinct and (slightly) separate group. In fact they diverge from the 1: √2 group by a marginally greater amount than the 2: 3 group. Even if they are tested against the schedule of triangles in figure 13.4, they do not form a distinctive group in that respect. They share no sectional characteristics in common. They must remain, for the moment, something of a mystery.

The only outlier at the high end of the schedule is Dirleton with its massively walled fifteenth century hall range. Heavily fortified on the outside, the courtyard side wall thickness is inexplicably oversized, particularly since it is built, partly underground, into solid rock. At the other extreme are the kitchen range at Aberdour and the free-standing stables at Crichton. These will receive attention later. For the moment it can be concluded with reasonable safety that the dimensions of walls supporting most domestic ground floor vaults were derived by geometric means from the span of the structure, in the light of which it was not considered worthwhile testing the slenderness ratio. However, in the face of some variety of these geometric means, if only two principal variations, the question still remains how did the architect choose between them?

13.4 DÉRAND'S VECTOR

If previous investigations into church structure are anything to go by, the answer probably lies in Dérand's vector. How does this tool look when applied to this group of buildings? Rather than trying to cover each one in detail, let us examine a handful of examples which are either typical and representative of a larger number, or are exceptional in some way, starting with the earliest.

13.4.1 *Dryburgh Abbey Chapter House*

Dating to the mid-twelfth century, the east end of this structure protrudes beyond the line of the dormitory range above and is therefore a rare case of a surviving free-standing barrel vault of such early date. The ground floor wall thickness is 1.4 metres, that of the floor above only marginally less, about 1.3 metres.

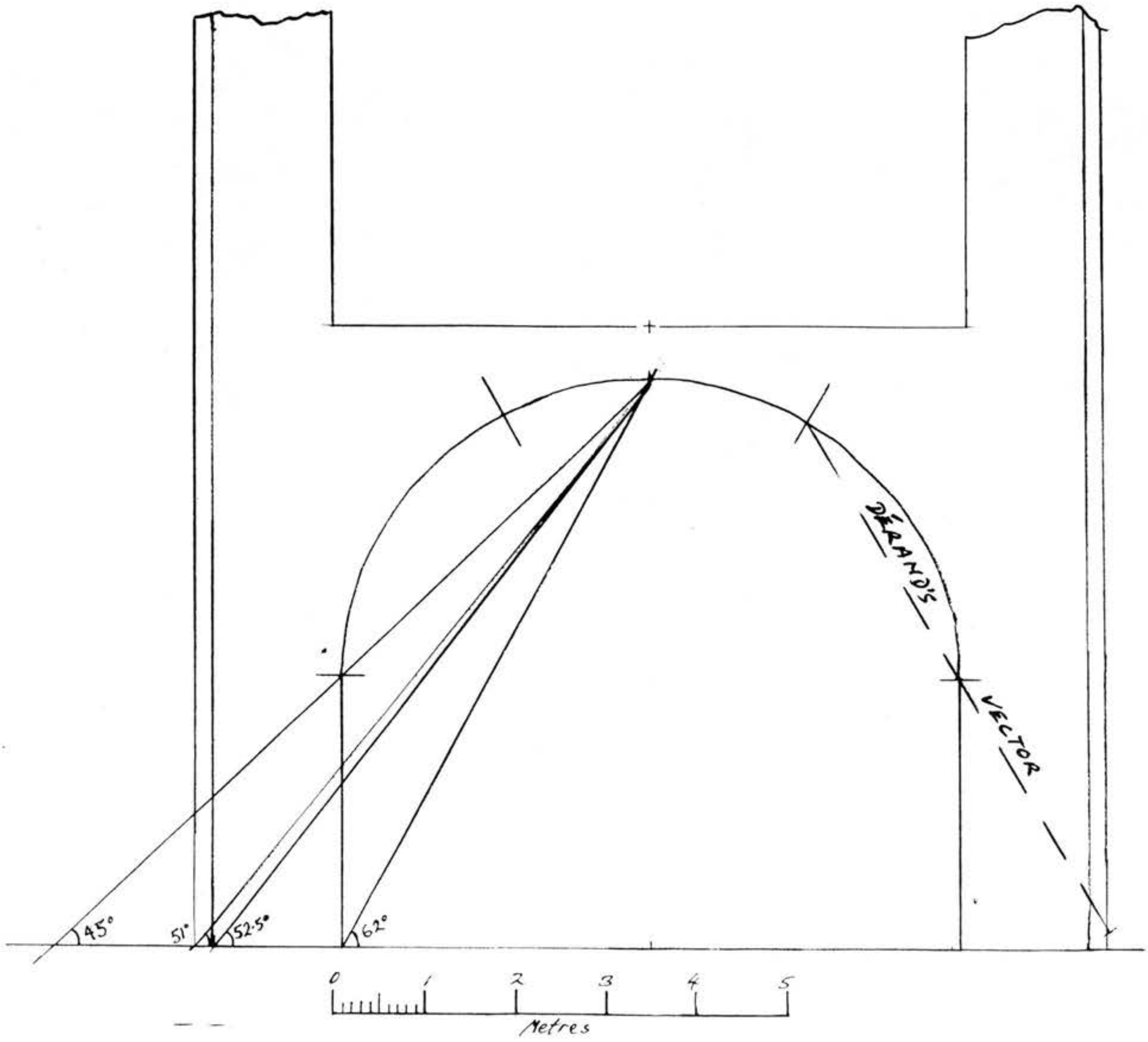
A chapter house is generally reckoned to be the second most prestigious space in a monastic complex and the vault at Dryburgh, although a plain barrel, is no exception to this. It is more nearly a perfect hemicycle than most throughout the country in its overall proportions, if slightly distorted in curvature. Of geometric origins it seems to have been constructed from both triangulature and quadrature. Whilst up to three elemental triangles are suggested in its section (figure 13.6) the wall thickness could also have been 'calculated' by rotation of the core square. To this has then been added the pilaster buttresses that are typically found in Norman and early Gothic building. What distinguishes this structure from others with pilaster buttresses (Duddingston and Cockpen churches) is that in the latter rotation defined the *total* wall thickness including buttress, whereas here at Dryburgh the buttress is additional. Can there be any explanation for this? Possibly a variation on usual practice has been employed because this building is barrel-vaulted, and what follows may support this idea.

If judged by Dérand's vector, the wall thickness alone is insufficient for abutment of the vault by a fraction over 20 centimetres. Coincidentally the pilaster buttresses happen to be 20 centimetres thick. The 'discovery' of abutment 'calculation' by Dérand's vector at this early date is regarded with much caution. Pure coincidence cannot be ruled out until or unless some other examples can be found.

Neither, however, can its incidence be ruled out - there is mounting evidence that it was a method used by medieval architects, and if this was so it had to have been invented or developed sometime.

Finally, on reflection, it would perhaps be best to keep an open mind on whether triangulature has been used also at Dryburgh. It is, as mentioned, a highly prestigious structure and here, if in none of the other examples, more than one layer of design rationale might have been deemed appropriate for whatever reason.

Figure 13.6 Dryburgh Abbey Chapter House (12th Century)



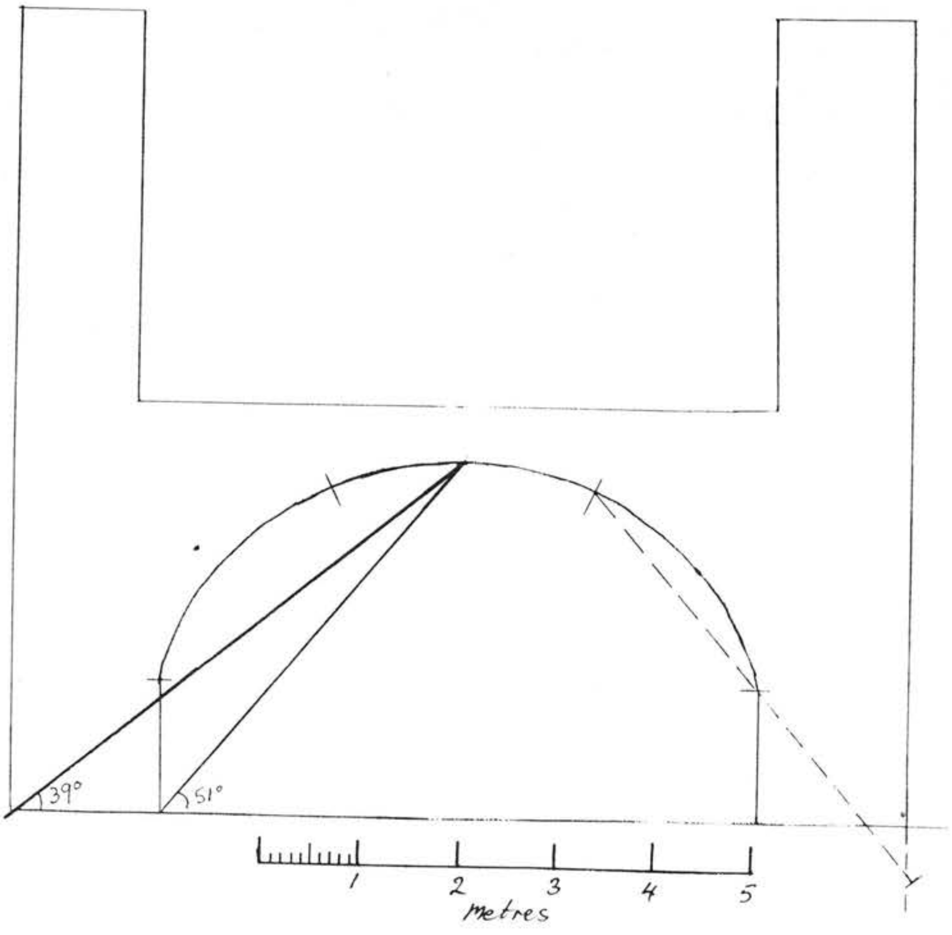
13.4.2 *Balgonie Hall Range 1496*

This is a more characteristic 'storage' vault under a great hall (figure 13.7). Whatever its actual function (it is now used as a chapel for weddings) it is typical of many whose vault springs from relatively low down (1.4 metres) and whose curvature is a relatively shallow segmental form. Possibly of significance in its design are the presence of two elemental triangles in its section. Because of the shallow pitch of the vault, the lateral thrust will of course project out at a commensurably shallow angle and the incline of Dérand's vector will reflect that. Because the springing is so low, that line burrows safely underground and, in view of this, it might have been logical to economize on masonry with thinner walls. However, any such potential saving has been totally disregarded and the wall thickness has been 'calculated' so that Dérand's vector extends roughly to the line of the outer wall surface, but about 60 centimetres underground. It is as if the ability of the ground to absorb the lateral thrust of the vault has been ignored. Similar situations occur at Provost Skene's House, Auldhame and the south east range at Balmbreich. All these structures share a common internal/external span ratio of about 2: 3.

In contrast to this model are several other structures which all share otherwise similar superficial characteristics: the storage or service vaults of Dunnottar kitchen and brewery, the 17th century accommodation range at Balgonie, the Culross palace kitchen block, one of the partly free-standing vaults at Barnes, the lodging at Garleton and finally the Nithsdale apartments at Caerlaverock Castle. In all these are relatively shallow segmental vaults which spring from quite low down, and hence Dérand's vector descends into the ground whilst still within the wall thickness. However, unlike the Balgonie Hall Range model described above, the walls are relatively thinner, and the vector extends out beyond the line of their outer surface into the ground. There were either two completely separate schools of thought on subterranean thrust management or, alternatively, these two different groups of buildings were built on completely different soil or foundation types. Interestingly, the internal/external span ratio of this group all fall between 1: 1.37 and 1: 1.45. In other words they all hover around the 1: 1.4142 relationship achieved by rotation of the diagonal of the core square.

If these two groups were segregated by geographical location, or by date, or by some standard of build quality, it would be all too easy to attribute these two different approaches to vault abutment to one or other of those factors. But they follow no such patterns. If it were possible to ascertain the quality of the subsoil, this might indicate whether that was influential, but unfortunately this could not be done. The fact that two different ranges at Balgonie are treated in entirely different ways (let it be noted however that they are separated by at least a century) may indicate that the nature of subsoil was not an issue. What remains undiscovered is the depth of the foundations of these various buildings. Could it be that thinner walls coincide with deeper footings? Here is an interesting point of departure for further research. Either way, the extent of Dérand's vector was safely accommodated by some sort of abutment, be it wall structure or the ground. There are, however, a few exceptions to these models which now demand explanation.

Figure 13.7 Balgonie Hall Range (1496)

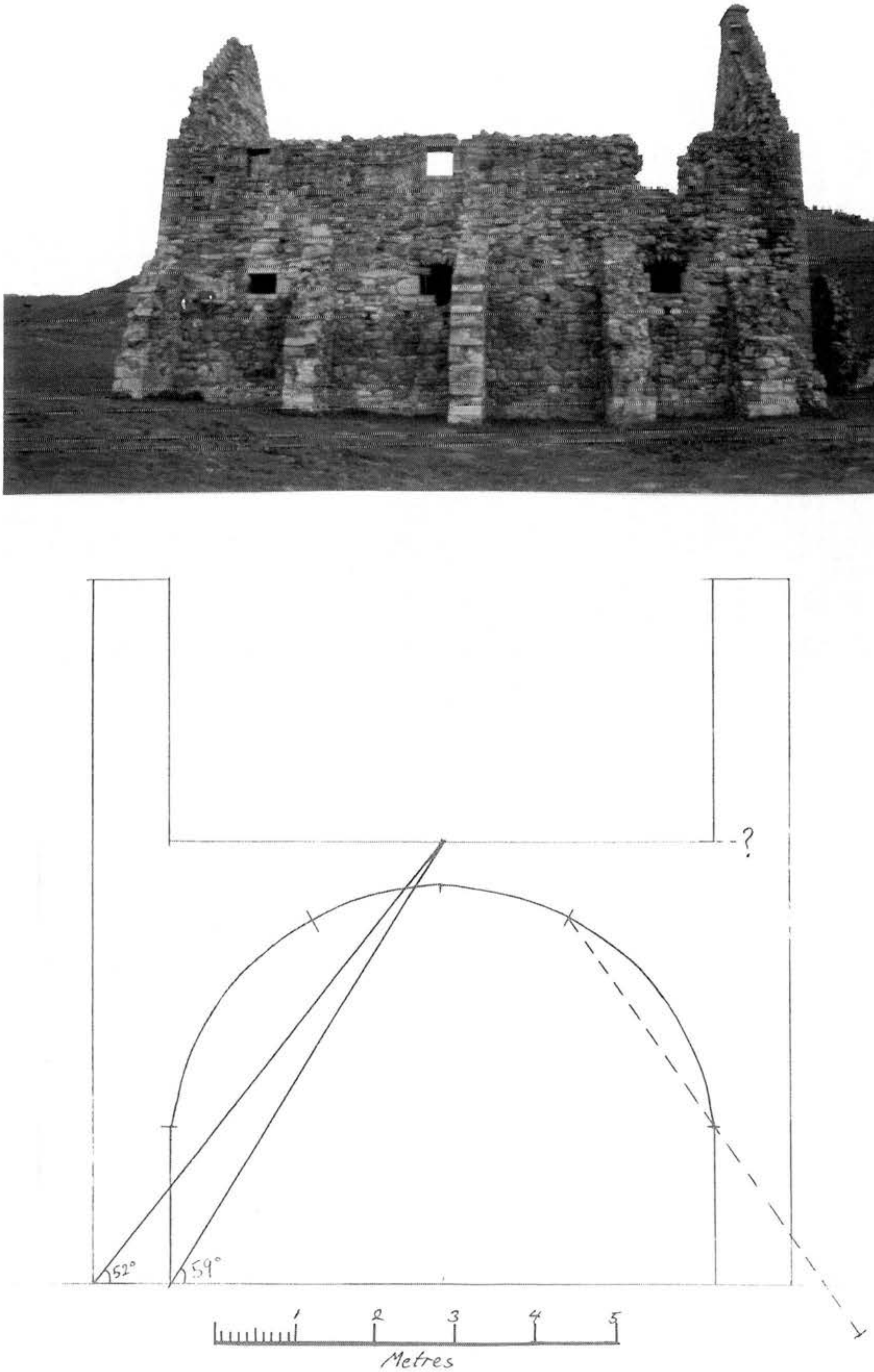


13.4.3 *Crichton Stables*

Part of Earl Bothwell's improvements of the 1580s, the stables at Crichton are a long, free-standing block. Above the vault is accommodation for ostlers on the first floor which, unfortunately, could not be accessed for measurement. Survey of the ground floor vault, however, revealed a fatal flaw in the design (figure 13.8). The span of the vault at 6.8 metres is the widest found anywhere (except for some churches, where vaults were invariably pointed rather than segmental). It is supported on walls only 0.95 metres thick, the thinnest of all those surveyed except one. Quite what was the basis for their 'calculation' to such inadequate standard is difficult to know. Perhaps what is most significant though, is that Dérand's vector terminates well outside the wall surface. It comes as little surprise to learn that, some time following completion, the vault began to fail and buttresses were then added along both sides of the structure.

The questions beggared by Crichton stables are many: was the architect incompetent or the contractors fraudulent? Was a vault not intended originally when setting out the foundations? Were buttresses intended from the outset but not built until later? It has to be observed that buttresses were almost unheard of in Scottish secular building. Whilst the exact position of the external apex is not known, an estimate based on other measurable examples suggests that possibly this is a case where a combination of Egyptian and equilateral triangles was cobbled together for the job and some sort of blind faith applied to a solution grounded in geometry alone. The answers to these may never be known but what is clear again in this situation is the apparent validity of Dérand's vector as an indicator of the adequacy or otherwise of the abutment.

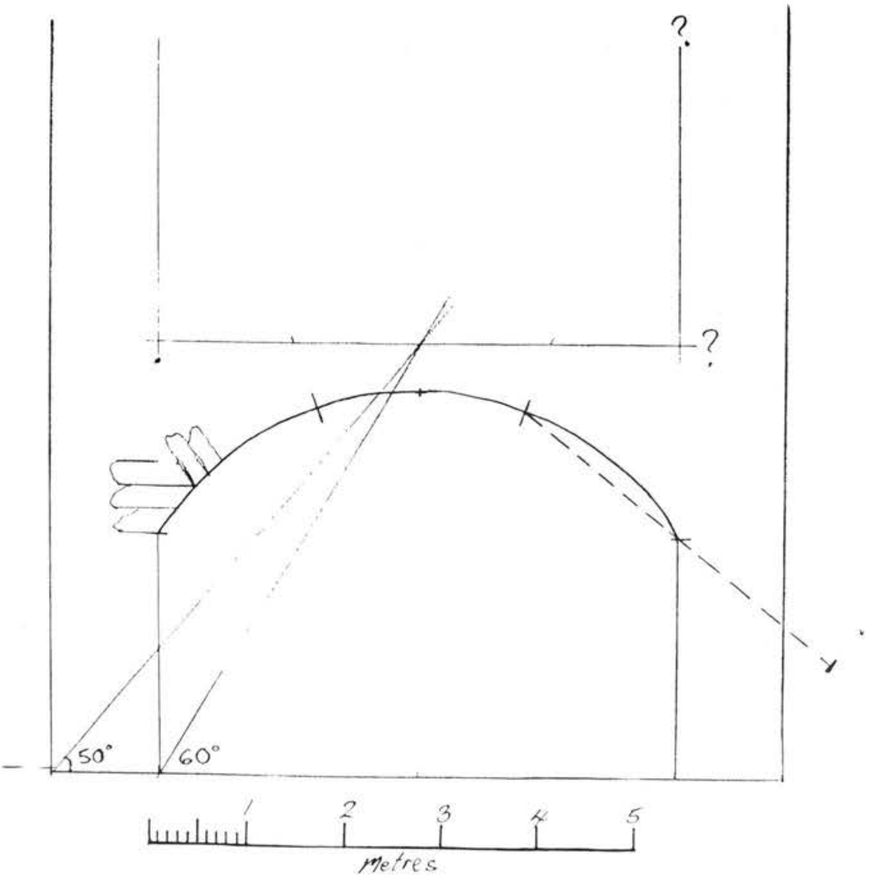
Figure 13.8 Crichton Castle Stables (Late 16th century)



13.4.4 *Crossraguel Calefactory Block*

Part of the fifteenth century rebuilding program after the destruction of the Wars of Independence, the shallow vault of this structure sits on what appear to be perilously thin walls. The angle at which Dérand's vector extends (Figure 13.9) results in its termination about 0.5 metres outside wall surface. Not surprisingly perhaps, the vault has fallen. But that is all that has happened - the vault has simply fallen in; it was, after all, a relatively shallow vault, and taking into account the crudeness of much Scottish vault construction with few voussoirs actually cut to wedge shapes, perhaps this is not surprising. What is possibly more surprising is that the side-walls have not been over-turned or buckled. Theoretically that is what should have happened if they were insufficiently thick for the vault's lateral thrust, if Dérand's vector was a meaningful device for vault thrust measurement. Perhaps the fact that they show no such failure is an indication that, after all, Dérand's vector is invalid. This case might indeed call that whole theory into question. But there is something subtly different about the construction of this, and indeed some other vaults at Crossraguel, as well as a few other sites which have been identified elsewhere.

Figure 13.9 Crossraguel Calefactory (14th/15th century)



13.5 THE *TAS-DE-CHARGE*

It was quite common for the lowest voussoir on each side of an arch, the springers, to be laid flat rather than at an angle, and for their intrados to be shaped with the curvature of the arch. At Crossraguel it is the first *three* voussoirs on each side that are so laid creating a crude *tas-de-charge*. Figure 13.10 shows the feature in the tower house at Crossraguel of similar date, where it is similar and more easily photographed due to the way the wall has fallen away. The reasons for this device, possibly first appearing at Chartres Cathedral, have never been satisfactorily explained. Whilst Viollet's diagram (figure 13.11) and description are well known, he never really worked out a reason for its appearance. The most useful attempt so far has been made by Shelby and Mark (1979:128-30) who, in their interpretation of Lorenz Lechler's instructions of 1516, propose that the highest voussoir to be laid horizontally transferred the lateral thrust of the vault directly through a course of masonry in the wall out to the buttress where it would be deflected downwards by the weight of the upper part of the buttress, including the pinnacle if there was one (figure 13.12).

Figure 13.10 Crossraguel Tower: *tas-de-charge* feature in the ruined vault

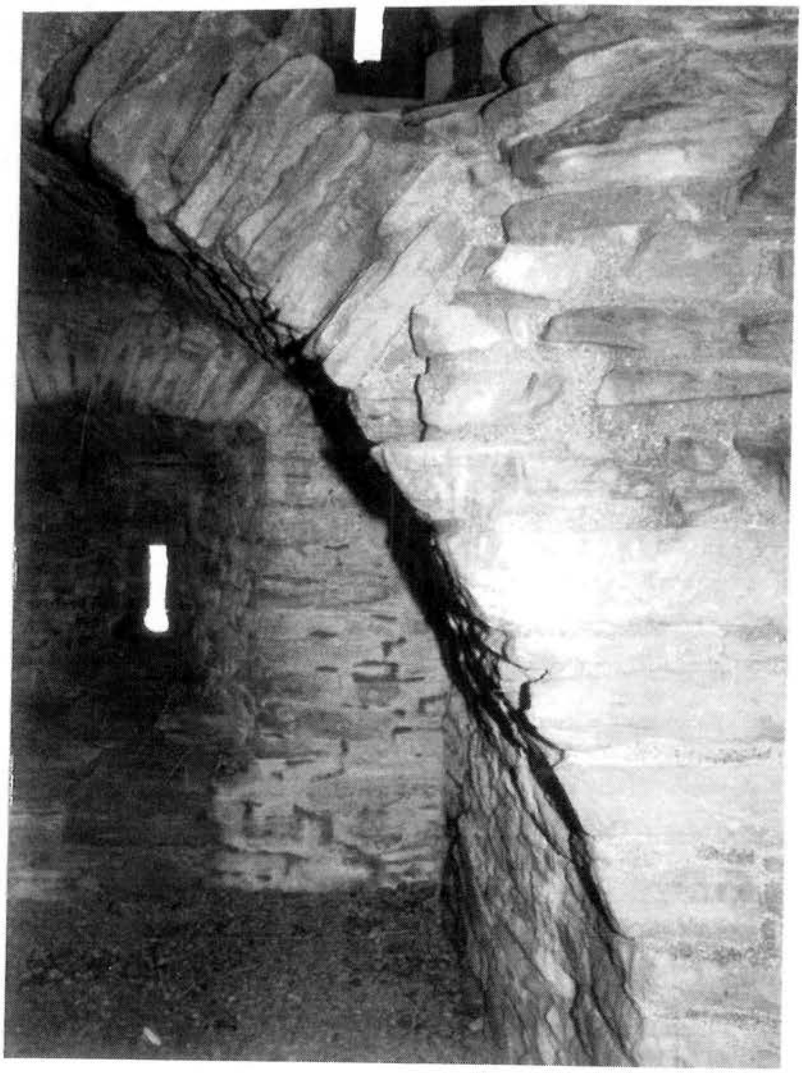


Figure 13.11 Viollet-le-Duc's drawing of a *tas-de-charge*

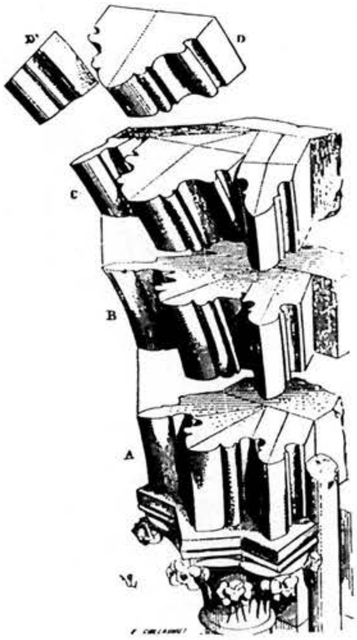
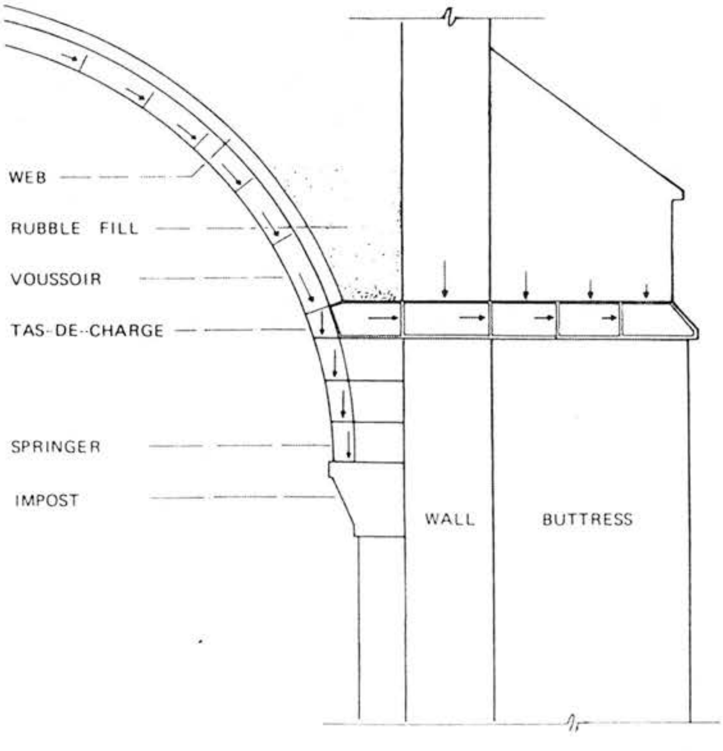


Figure 13.12 Interpretation of Lorenz Lechler's *tas-de-charge* by Shelby and Mark (1979: 128)



Plausible though this may be, it clearly does not operate in the same way at Crossraguel where there is no buttress and no continuous course of masonry taking the sideways thrust of the vault anywhere!

There is, however, the germ of an idea in Shelby and Mark's explanation which may have some relevance to Scottish building practice. Let us suppose that the construction of a vault is carried out in two building seasons: in the first the side and end walls are constructed, in the second, once these have had a chance to achieve some solidity through the drying of the mortar, the vault itself is laid over the formwork. In this case, any further building work on the walls above the level of the springing is not possible until the vault has been built in the second season. If, however, the first three voussoirs are laid flat, as at Crossraguel, then the side walls can be built up to full height if required *before* the vault is constructed (Figure 13.13). This has a very obvious advantage that those walls then have the same effect as the pinnacles on church buttresses, deflecting downwards the lateral thrust of the vault as it is built. With such a facility, the walls on which the vault actually leans can be somewhat thinner than if no such weight was bearing down from above. The walls at Crossraguel are indeed thinner than most others in the survey and, as mentioned earlier, Dérand's vector falls well beyond their outer surface. On the face of it, there must be a strong case for this building method being the reason why. Whilst this seems a logical conclusion in this instance, is it justifiable to apply similar logic more generally? As ever, can such reasoning hang on a single example? Fortunately, one other has been found: the mid-sixteenth century kitchen range at Aberdour in Fife. With a wall thickness of only 0.8 metres, the vault in this structure is in serious need of some alternative means of achieving stability. Again Dérand's vector falls beyond the outer surface. There are only two springing courses laid horizontally here but that was probably sufficient to allow the side walls to be built up prior to vault construction.

Although we only have two examples of this phenomenon of the *tas-de-charge* in a two storey domestic structure, the fact that it coincides with the wall thickness being too thin to accommodate Dérand's vector, suggests that there may be more significance in the use of this device than is immediately obvious. There are two ways of looking at the actual process of vault construction in relation to the *tas-de-charge*, again, given that in the survey sample the latter feature only occurs in those buildings where the walls abutting the vault are *thinner* than is required by Dérand's vector. Let us first look at the problem in reverse: if the abutting wall is *thicker* than required by

Figure 13.13 Vault construction where abutting walls are too thin to accommodate Dérand's vector since, presumably for economy, they are to be as thin as the walls of the storey(s) above, which are only to bear a timber truss roof. To enable the upper walls to be built up before the construction of the vault itself and thus provide counterweighting to the lateral thrust of the vault, the *tas-de-charge* has been used to provide an angled 'bed' on which to lay the first voussoirs, which does not encroach on the progress of building up the walls.

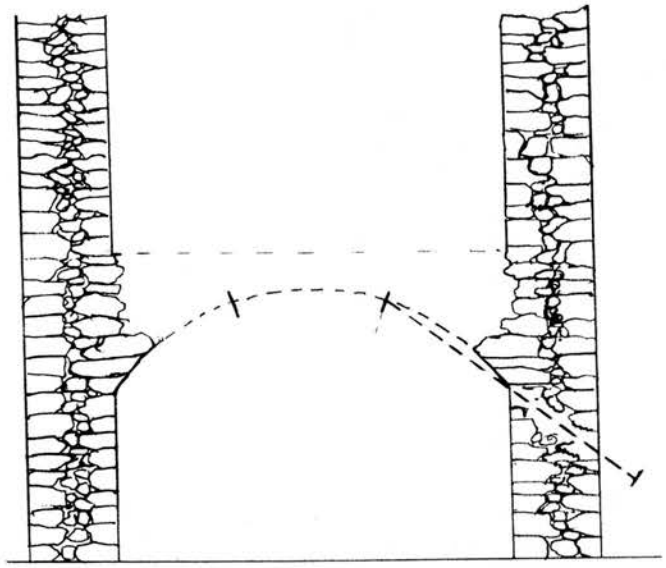
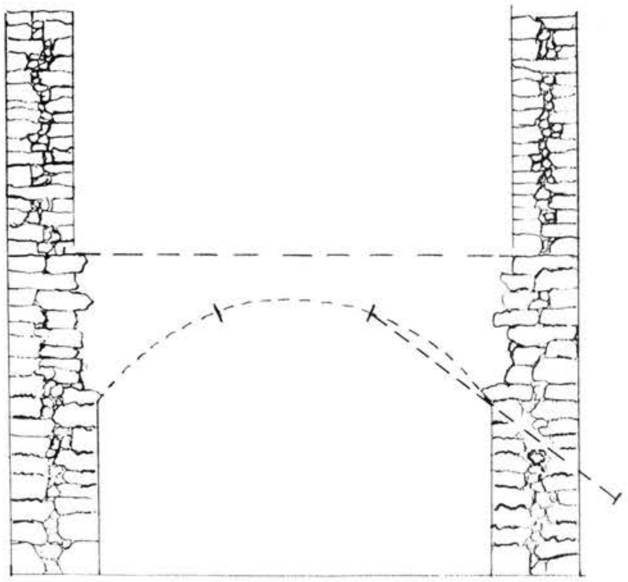


Figure 13.14 Vault construction where abutting walls are too thin to accommodate Dérand's vector, but thicker than the upper walls. Here there is no need for a *tas-de-charge* since the upper walls can be built up leaving sufficient 'bed' for the first voussoirs when the vault is finally built.



Dérand's vector, then it should be able to support the vault *on its own* during the vault's construction; that is, to support the vault *without* the counterweighting effect of building up the walls above prior to vault construction.

Alternatively, if counterweighting is required in order to compensate for abutment insufficient to accommodate Dérand's vector, it may be possible to build up the walls higher than the ground floor, prior to vault construction in order to provide that counterweight, if the upper walls were to be *thinner* than those on the ground floor, sufficient only to support a timber truss roof (figure 13.14). This is the case with most structures surveyed. As can be seen from the diagram, these upper walls can easily be built up leaving a sufficient bed for the first voussoirs of the vault below.

On the other hand, for whatever reason, the abutting wall may be designed for maximum economy, that is no thicker than the walls above which only have to support a timber roof, as in the case of Crossraguel and Aberdour. In being so economical, the abutting walls are too thin to accommodate Dérand's vector, but furthermore, are too thin also to enable building up the walls above ground floor level to counterweight the lateral thrusts of the vault during and immediately following construction. Another device must be found to enable the walls to be built up *before* vault construction in this situation, and the *tas-de-charge* appears to have been the answer (Figure 13.13). In other words, the *tas-de-charge* actually enables the much more economical use of masonry in support of vaulting, as well as greatly facilitating the construction process.

If this is the case in these few Scottish examples, then there are significantly wider implications for the history of medieval building generally. Although in post medieval times the existence of the *tas-de-charge* has been known at least since Viollet-le-Duc, and various dictionaries and encyclopaedia have attempted descriptions, apart from Shelby and Mark's work (II 1979), there has been no real analysis of this feature, particularly as an aid in the *process* of construction. If indeed what has been found in these few Scottish examples is representative of wider and earlier practice, then our understanding of the construction of Chartres and other major European cathedral buildings requires considerable re-examination. It would seem that the *tas-de-charge* may have played a much more significant role in the construction process, and in the reduction of masonry mass in gothic structure generally than has hitherto been recognized. Some further research is urgently needed in this direction!

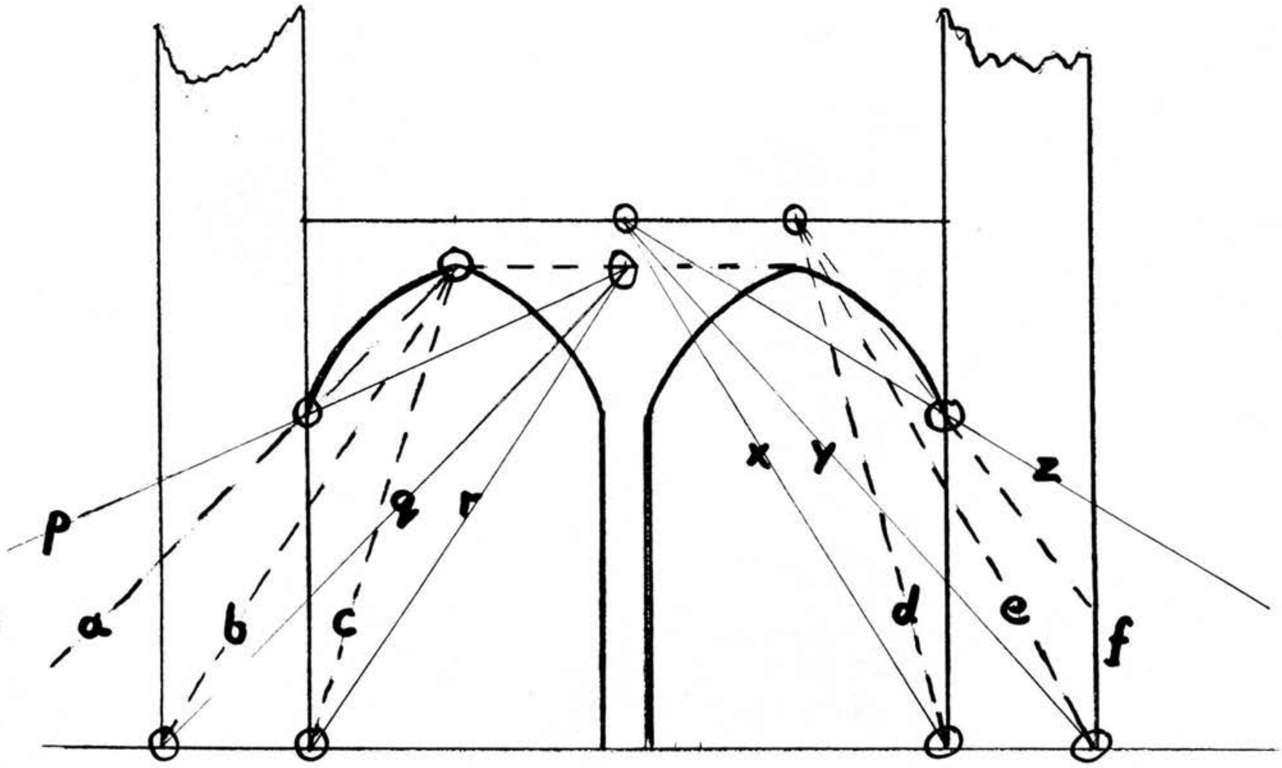
There are two other structures from the survey sample which defy explanation: a little courtyard building outside Houston, West Lothian, has a relatively shallow vault and walls so thin that Dérand's vector terminates about 0.5 metres outside. The first floor vaulted strong-room at Culross 'Palace' presents similar cause for concern, although the overlap by Dérand's vector here is only about 0.12 metres. The only characteristic which links these two buildings is that they both date to sometime in the first quarter of the seventeenth century. Were they both constructed using the *tas-de-charge* process just described? Unfortunately we may never know. Their walls are variously panelled or well daubed with plaster and harling, and must remain for the moment unexplained. Alternatively, by this date, other ingenious methods of overcoming such problems may have been developed in response to the demands for economy and efficiency in building during the period of increasing volume of construction carried out since the mid sixteenth century. Only a great deal more painstaking research will bring any such developments to light.

To briefly summarize, it seems possible, though as yet unprovable, that the overall form of these domestic vaults was loosely based on triangulature in section at least, but the wall thickness was more likely to have been derived from quadrature in plan and, as in vaulted churches, using Dérand's vector to ensure that the minimum thickness required was provided. The use of this device, or some other with similar effect, is again strongly suggested both by general conformity to the level of abutment demanded by it, by the Dryburgh pilaster buttresses, by the failure of the Crichton stables vault, and by the appearance of the *tas-de-charge* which enables walls too thin to accommodate it, to be built up above the level of the vault prior to its construction.

13.6 MULTIPLE PILLARED RIBBED GROIN VAULTED UNDERCROFTS

It is not intended to engage in a full and conclusive analysis of ribbed groin-vaulted undercrofts in this research: the complexities involved would justify a separate project. The possibilities for the application of triangulature alone are many more than for simple longitudinal barrel vaults: Figure 13.15 shows the twelve options available. In several of the examples surveyed one side wall is thicker than the other, for no immediately apparent reason and this doubles the number of possibilities for triangulature in those cases to twenty four! To this task is added the job of accounting for buttresses on both side walls of some structures, on only one side wall of some others. Some also are sited on a slope with one side effectively acting as a retaining

Figure 13.15 The possibilities for application of triangulature to ribbed groin-vaulted structure with central columns



wall, in some cases its thickness unknown and unmeasurable. In few cases is the difference between the internal and external apex dimension known or measurable. To all of this must be added the sobering thought that no survey or analysis of ribbed groin-vaulted vaults will be valid, let alone complete without including the vaulted aisles of major church buildings, and in order to do that satisfactorily, the entirety of those churches would require survey and analysis. That is a task of monumental complexity and falls well outside the scope of this research.

In spite of all this, some basic measurement and tests were carried out where possible to achieve some comparison at a very general level with the barrel-vaulted category. Predictably perhaps, the results revealed possibilities of geometric constructions having been used in both the overall design and also in the sizing of individual elements. Figure 13.16 shows the similarly random possible occurrence of the four elemental triangles, though it seems to be different triangles which occur most frequently from the barrel-vaulted variety.

Figure 13.16 RIBBED GROIN-VAULTED UNDERCROFTS: TRIANGULATURE SUMMARY

Date	Site	*a*	*b*	*c*	*d*	*e*	*f*	*p*	*q*	*r*	*x*	*y*	*z*
12C	Dryburgh calefactory & novices	58.5	63	55	74.5	63.5	58.5	38.5	51	60	62.5	53.5	42
12/13C	Melrose dorter range	47	52.5	65	68	56	53	25	36	45	48	39	30
13/14C	Arbroath gatehouse range*	47	58	67	68	60	51	-*	-*	-*	-*	-*	-*
13C	Glasgow chapter house GF	51	56	70	72	59	57	30	42	52	54	45	33
15C	1F	53	67	77	?	?	?	30	54	62	?	?	?
14C	Dunfermline reredtr. 1.1m. wall	54	60.5	73	74	62	59	34	48	57	59	50	38
	0.85m. wall	54	73	73	74	65	59	34	50	57	59	52	38
14C	Dunfermline kitchen range	55	47	67	68	50	59	33	35	49	50	38	37
14C	Dunfermline refectory rg	37	39	55	58	42	42	21	27	35	38	30	25
14C	Tulliallan Castle	54	51	69	70	54	58	33	40	51	54	42	38
15C	Crossraguel	54	62	73	75	64	60	32	48	56	59	51	38.5

* Arbroath has a single span vault, therefore lacking a central row of columns

Totals of possible elemental triangles:

	a	*b*	*c*	*d*	*e*	*f*	*p*	*q*	*r*	*x*	*y*	*z*	Totals
Equilateral (60 degrees)	0	1	-	-	2	4	-	-	1	3	-	-	11
Egyptian (51 degrees)	1	1	-	-	1	1	-	2	2	1	3	-	12
Right Angled (45 degrees)	0	0	-	-	-	-	-	-	1	-	1	-	2
Egyptian Variant (39 degrees)	0	1	-	-	-	-	1	1	-	1	2	4	10
Totals	1	3	-	-	3	5	1	3	4	5	6	4	35

Here the 45 degree triangle seems to be almost entirely absent, when it appeared to be the most popular in barrel-vaulting, whilst the situation for the equilateral triangle is the reverse. Either way, it must be emphasized again that these figures are all very approximate, and can at best be taken as general indicators of possible trends rather than of individual examples. At worst, the indications of the use of triangulature may be merely coincidental.

That said, there are two examples worthy of closer scrutiny before moving on from this brief look at triangulature. In the calefactory and novices room at Dryburgh Abbey the angles p, q, and r are respectively 39, 51 and 60 degrees, thus appearing to use three different elemental triangles in both the overall form and in the definition of the wall thickness. A similar characteristic can be found in the reredorter and possibly the kitchen undercroft at Dunfermline but here based on the angles x, y and z. However , it is the Dryburgh figures which are particularly interesting, since it was at the chapter house there that a case could be made for the use of both triangulature and quadrature. Can the same be found in the calefactory and novices room? And generally, can quadrature be found with more certainty than triangulature?

Experimentation with rotation on the plans of the rib vaulted undercrofts produced some illuminating results. First, there are a number of cases where the wall thickness appears to have been determined by rotation of the core square. This applies at the dormitory range at Melrose Abbey, but only in the thicker of the two side walls which measure 1.25 and 1.75 metres. The calefactory and novices room at Dryburgh is probably an instance of this also, but with a variation: the actual relationship of internal to external width is 1: 1.36. The 'root 2' ratio of 1: 1.4142 indicative of rotation applies if pilaster buttresses 20 centimetres thick are added to both side walls. At Dryburgh however they only appear on the outer wall. Ignoring this irregularity for a moment, this is the same situation as found at Duddingston and Cockpen Churches. Here it should be recalled that the Dryburgh chapter house walls also appeared to have been designed by rotation, but then the pilaster buttresses were *additional* to the thickness so defined, possibly in order to enable the total vault abutment to accommodate Dérand's vector. It is possible, even probable that these two buildings were designed by the same architect, and if that was indeed the case, whilst on one hand it might be considered odd that there is no consistency in the relationship between rotation and use of pilasters, it seems on the other hand to be just one more indication that geometric manipulation was in many cases merely a standard means of achieving the overall design, a "help-diagram". The fine tuning of the size of structural members then followed.

There is, however, one other possibility at Dryburgh's calefactory and novice room: each bay is 4.5 by 3.5 metres. The phenomenon of rectangular, often nearly square bays in medieval ribbed groin vaulting is very common. It is difficult to quantify precisely without a laborious nation-wide headcount, but it is probably more common than exact square bays. Now, if the diagonal of each bay is rotated, not about the *centre* of the bay as usual, but about *one corner* (figure 13.17) then it happens to define the wall thickness to within about 5 centimetres, without the pilaster buttresses. Of course this may just be a coincidence. In order to give some credence to this as a valid method of structural design, further examples are required. Interestingly, the gatehouse range at Arbroath is one such instance. A similar manoeuvre at the chapter house of Glasgow Cathedral comes within 10 centimetres of defining wall thickness and buttress projection combined, and the huge refectory at Dunfermline may also be designed on this basis with a similar discrepancy. All this does suggest a trend but, again, some of these are very difficult buildings to measure accurately and ideally much more work is needed on this structural type. Nevertheless if this truly was a method of wall thickness definition, it still follows the simple logic of being achievable using no more than pegs and string on the ground. If those were indeed the principal tools of the structural designer's trade then there may be yet other ways in which they were used.

When faced with no obvious solution for wall thickness in triangulature, or in rotation of the core square about its centre, or in rotation of the diagonal of the rectangular bay about its corner, there is one more logical step to take which combines the principals of both these last, and it is this: rotation of the diagonal of the entire rectangular bay about its centre. This variation has already been encountered earlier in the sacristy of Seton Collegiate Church. On the face of it, this seems an entirely logical manoeuvre: if there was a practice of rotating the core square where there was no bay system, it might only be deemed common sense where such a system did exist, to simply rotate the bay itself instead. Such may have been the logic of the medieval mind. But was such logic actually used? It appears to be so in the Dunfermline reredorter block, and also at Tulliallan Castle, whose wall thickness is based on the dimensions of the rotated main north east vaulted chamber (Figure 13.18).

Figure 13.17 Dryburgh Abbey, Calefactory & Novices room: definition of wall thickness by (left) rotation of the core square about its centre; and (right) rotation of the diagonal of the bay unit about one corner

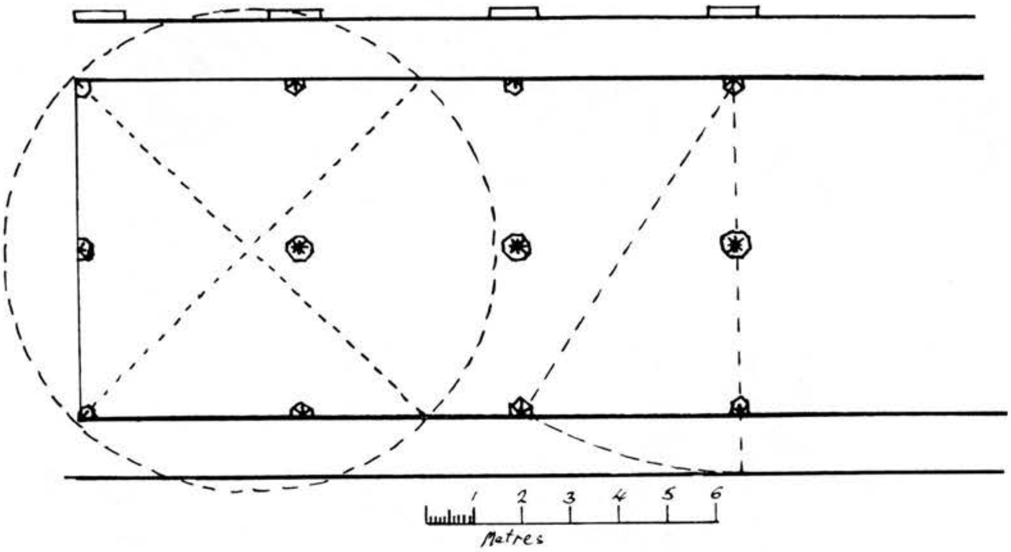
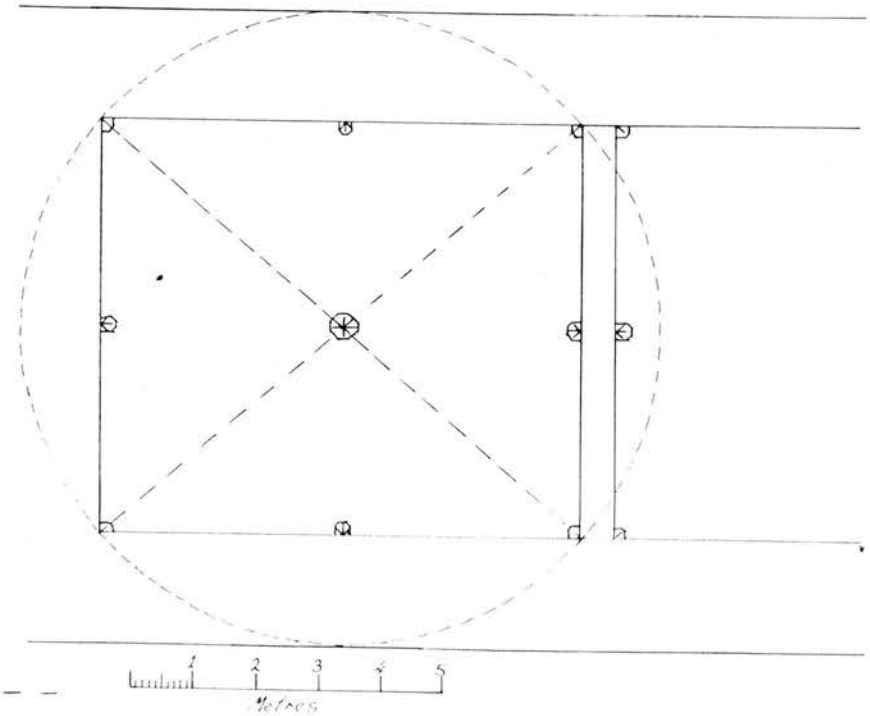


Figure 13.18 Tulliallan Castle: definition of wall thickness by rotation of the entire bay about its centre



At neither of these sites is the bay square. The reasons why these and so many other bay systems are not based on exact squares need not concern us here - that was often the manifestation of some integrated system of modular measurement. What is of significance in this research is that, whatever proportions used in the ground plan, it was the act of rotation of the whole bay unit that determined the wall thickness. The problem for this research is, as ever, that there are so few examples. Does it occur elsewhere?

13.7 CONCLUSION

Whilst it is possible that triangulature of whatever forms may have been used in guiding builders of domestic vaults and, from the data gathered, the 45 degree triangle would have been the most common, it has been simpler to make a case for the use of quadrature in the design of the ground-plan, or at least some rule of thumb based, for example, on a simple ratio of internal to external width as 2: 3. In the absence of any other sectional method of vault design, the case for the use of Dérand's 'vector' has become ever stronger. It is perhaps almost too easy in view of all the evidence presented to believe in its existence as a design tool in the medieval architect's hand. It does indeed become difficult to judge which of these methods generally played the key role in the task of structural design. But to over-generalize is dangerous. Taking a circumspect view, it does seem that many ground plans were based in quadrature, or some other proportion obtainable by simple methods of constructive geometry, and for the vault section an elemental triangle was chosen which was appropriate to the height required. Dérand's 'vector' perhaps constituted a substitute for such a triangle if none suited that particular job, but also a useful safety device to check that the chosen triangle was structurally suitable, in the event that one was chosen. These various systems were not necessarily mutually exclusive.

The possibility of a logical explanation for the *tas-de-charge* feature in vaults may constitute something of a revelation in our understanding of gothic architecture and requires following up with more research both in these relatively simple structures, and in the major cathedrals and abbey churches of Europe.

One structure of more specific interest which bears repeating are the various parts of Dryburgh Abbey claustral complex. The possible combination of more than one triangle together with different types of quadrature, the accommodation of

Dérand's 'vector', and the incorporation of all this with pilaster buttresses results in a design of no mean sophistication.

14 CHURCH TOWERS

14.1 INTRODUCTION

It is difficult to be precise about the role of the church tower. Generally they were thought to have performed a multiplicity of different functions: symbolic, a vehicle for bells to call the faithful to prayer, to sound the alarm in time of danger or to celebrate anything from a wedding to a military victory. In some parts, it was supposed to have been able to afford some protection to refuge seekers when the locality was subject to military attack. There are occasional references to a church tower as the most secure stone building in a community and being used as a prison (e.g. St. Giles and Corstorphine) or as an armoury (St. Giles) and powder magazine (Greyfriars). The list is probably endless. Regarded by the Cistercians as an unnecessarily lavish and inessential piece of structure, the tower was certainly held in high esteem by the builders of cathedrals, parish and collegiate churches as symbolic or representative of the wealth and pride of their benefactors. Embellishment on occasions certainly exceeded the bare essentials, whether for the western elevation of a great cathedral or for the crown spire of a parish church. Just how much constituted these 'essentials' will next be the subject of scrutiny.

It should be mentioned perhaps that this section includes only full western towers and, with a single exception (South Queensferry), not crossing towers to which access is invariably difficult to obtain, and whose crossing pier supports invariably prove difficult or impossible to measure.

Of the structural variations of church towers, there are many: in most, the ground floor is vaulted: in the simpler, a barrel vault - with ribs or without; in the more prestigious a complex ribbed groin vault; rarely a second vault at higher level. Some structures have buttresses, terminating at various different heights - some level with the ground floor vault, others and more commonly, reaching to the wall-head. Stairs to access both the various levels of the tower, and also often the roof or other levels of the nave of the church, were incorporated usually in one corner of the tower, protruding either inside the structure or outside in a round or polygonal jamb. Occasionally the stair would ascend in one or other of these to a certain level, then change to an alternative site. Often in small towers the tortuous ascent from first floor upwards was only by ladder. Many are styled with pseudo-military features, mainly from the late fourteenth century - crenellated parapets, corbelled out corner bartizans - and astride the wall-head is sometimes a very domestic looking ridged roof with crow stepped gables. Alternatively a timber-framed and slated or a stone spire of either simple pyramidal or broached form were chosen. Where flat leaded roofs appear there may have been the intention of a grander spire, as at Elgin.

Original intentions are often difficult or impossible to read at this distance in history and this can cause considerable problems when attempting to interpret a building type of this nature. The church western tower was often the last structure of the complex to be erected and if there was any shortage of finance or willpower, for whatever reason, the original intentions may never have been carried out. In that case it is difficult for any retrospective research to comprehend what load the lower storeys of such a tower will have been designed to carry. So whilst a tower may bear no more than a flat leaded roof, it may come down to educated guesswork to ascertain whether or not something of grander status and greater weight was intended and, conversely, where a full stone spire is found, it may be difficult to know whether that was envisaged from the outset, or if it was the result of a surplus of funds, or fresh aspiration for grandeur at a late stage in the building project. Analysis of these structures is by no means straightforward, so it seems logical to begin with the most fundamental aspects. First of all let us take a look at the geometry of church tower plans.

14.2 CHURCH TOWER GEOMETRY

14.2.1 *The Dimensional Basis*

Figure 14.1 sets out the towers surveyed together with some overall dimensions. It had to be ascertained first whether the design of any particular tower was based on internal or external dimensions. Logic dictates that the former were of greater importance in a structure intended to house some activity or other. A church tower does not ordinarily house any particular activity, apart from ringing bells and a session room in a few cases, and is a structure whose external dimensions should in many cases be at least influenced, if not dictated by other considerations, the church nave width for instance, with which it is aligned and, in some cases, with which it is

Figure 14.1 CHURCH TOWERS : DIMENSIONS, SLENDERNESS & SIDES RATIOS BY PERIOD

SITE	VAULT	WALL THICKNESS (M)	HEIGHT (M)	FOOTPRINT AREA (Sq.M)	SLENDERNESS RATIO 1 :	SIDES RATIO 1:
ANGLO-SCOTTISH - NORMAN generally 11th & 12th centuries						
Restenneth	-	0.8	? (altered)	22.9	?	1.04
St Rules	-	.75	32.9	37.8	43.9	1.04
Markinch	-	0.8	20	25.7	25	1.05
Muthill	-	0.96	20.6	21.6	21.4	1.03
Dunning	-	1.1	22.8	27.9	20.7	1.05-1.09
Dunblane (lower)	RBV	1.25	17.5	46.4	14	1-1.03
Monymusk	BV	1.1	18.7	45.9	16.9	1
Kirkliston	-	1 + pil. butts	14.5 + ?	34.9	14.5	1
Uphall	-	1.1	? (altered)	31.7	?	1.04
Stobo	-	1.45	? (altered)	36.7	?	1.1
Dunblane (entire)	RBV	1.25	26 full ht.	46.4	20	1
ANGLO-SCOTTISH - GOTHIC generally 13th century						
St Vigeans	BV	0.75	15	24.1	20	1.13
Cambuskenneth	-	1.3 + butts	13	89.3	10	1
Elgin	RV	1.57 + butts	25 spire	64	15.9	1
Brechin	RV	1.35 + butts	20	60.8	14.8	1
Crail	-	0.8	19.2	37.2	24	1
WARTIME 1296-1370						
Inverkeithing	-	0.95 + butts	15	42.6	15.8	1
EARLY SCOTTISH 1370-1480						
Cambuskenneth	RV	1.3 + butts	19	89.3	14.6	1
Dalkeith	?	1.2	20	46	16.7	1.02
Aberlady	2 BV	1.1	12	33	11	1.09-1.06
Corstorphine	BV	1.1	10 spire	35	9.1	1.05
Dundee	RV	1.95 + ½ butts	50.3	144	25.8	1.04
Cupar	2 BV	0.85	20	33.3	23.5	1.13-1.27
St Salvator's	BV	1.3	29 spire	61.2	22.3	1.07
Linlithgow	WRV	1.24	25 crown sp.	51.5	20.2	1.02
St A's Holy Trinity	-	1.2	22.7	41.1	18.9	1.13-1.27
Stirling (entire)	WRV	1.35	25 (18 + 7)	63.3	18.5	1.37-1.73
TRANSITIONAL 1480-1560						
Ab'd'n St Machar	BV	1.5 + butts	16.75 spire	55	11.2	1.1
Dunkeld	RV	1.2 + butts	26.8	54.7	22	1
Culross	RV	1.2	23.6	65.8	19.7	1.15-1.0
Stenton	-	0.85	12	23.3	14.1	1.05
Peebles Cross K.	BV	1.2	15.7	38	13.1	1.1
Kirkaldy	-	1.4	17.5	54.7	12.5	1.05
Aberdeen King's	-	1.55 + butts	17.7 crown sp.	64.7	11.4	1.06
POST-REFORMATION 1560 -						
Dirleton	BV	0.8	16	25.2	20	1.04
Dunfermline	WRV	1.55 + ½ butts	29 + spire	46	18.7	1.1

BV	barrel vault
RBV	ribbed barrel vault
RV	ribbed (usually quadripartite) vault
WRV	webbed ribbed vault
butts	buttresses to the full height
½ butts	buttresses to only part of the height
pil. butts	Norman pilaster buttresses

structurally integrated. Alternatively, as the Stieglitz's treatise suggests, overall dimensions may be based on the choir width (X Gwilt 1889: 1010). As mentioned in Appendices II and III (metrology), church towers were the only building type where *external,* instead of internal dimensions were commonly specified in building contracts, at least in the few examples which survive. Figure 14.2 summarizes all the towers surveyed, categorized in chronological sequence by period with a note of whether the overall dimensions of western towers are, or appear to be in some way related to those of the main body of the church, or some part of it. Although in about one third of the cases the original church structure has been too drastically altered to bear comparison or been lost altogether, the remaining statistics speak for themselves: an overwhelming majority of eighteen, against a mere four, seem to be based on the width of the nave, aisle or choir, either exactly or in a 'root 2' relationship. There seems to be sufficient evidence to confirm that, excepting abnormal circumstances, the starting point for the design of all church towers must be the external dimensions.

Figure 14.2 CHURCH TOWERS: DERIVATION OF OVERALL DIMENSIONS FROM OTHER PARTS OF THE CHURCH

DERIVATION	ANGLO-SCOT NORMAN	ANGLO-SCOT GOTHIC	WARTIME	EARLY SCOTTISH	TRANS-ITIONAL	POST-REF
= NAVE				11	1	1
√2 NAVE	1	1			11	
= AISLE		1		111	1	1
√2 AISLE						
= CHOIR/ CHANCEL	11					
√2 CHOIR/CH.	11			1		
NOT RELATED	1	1		1	1	
LOST	1111	11	1	11	1	

DERIVATIONS:

= NAVE	Overall width of tower equal to, and in some cases structurally integrated with width of nave / nave arcade.
√2 NAVE	Overall width of tower related to nave width by root 2.
= AISLE	As for nave above.
√2 AISLE	ditto
= CHOIR/CHANCEL	ditto
√2 CHOIR/CH.	ditto
NOT RELATED	There does not appear to be any dimensional relationship between the tower and any other parts of the church.
LOST	Either the original church with which the tower was coeval has been demolished, rebuilt or altered so drastically that dimensional comparison is impossible or unsafe.

14.2.2 *Dimensional accuracy*

Superficially it might reasonably be expected that the square would form the basis for any design, and generally this appears to be the case. However, as we look closer at the 'sides ratio' list on the right of figure 14.1, that is the ratio of each pair of sides of the tower to the other, a pattern becomes increasingly evident: of the ten earliest towers, those of Norman design of the twelfth century, only three have exactly square floor plans. The other seven vary in ratio between 1: 1.03 and 1: 1.09 with a majority around 1: 1.05. Then, in the thirteenth century, from the relatively few examples which were built and survive, there is a remarkable trend towards geometric exactitude in Scotland. Of the five towers listed, only St. Vigeans at 1: 1.13 is not a square and is obviously not even intended to be a square. As Gothic linearity begins to predominate, there seems to be a more precise approach to building. Figure 14.3 summarizes the pattern.

Figure 14.3 CHURCH TOWERS : RATIOS OF SIDE LENGTHS SUMMARY

RATIO	ANG-SCOT NORMAN	ANG-SCOT GOTHIC	WARTIME	EARLY SCOT	TRANS-ITIONAL	POST-REF
1: 1	**111**	**1111**	**11**		**11**	
1: 1.01 *(de minimus)*						
1: 1.02				**11**		
1: 1.03	**11**					
1: 1.04	**111**			**1**		**1**
1: 1.05	**11**			**1**	**11**	
1: 1.06				**1**	**1**	
1: 1.07				**1**		
1: 1.08						
1: 1.09	**1**			**1**		
1: 1.1	**1**	**1**			**11**	**1**
1: 1.11 - 1.15				**11**	**1**	
1: 1.16 - 1.2						
1: 1.21 - 1.25						
1: 1.26 - 1.3				**1**		
1: 1.31 - 1.35						
1: 1.36 - 1.4				**1**		
1: 1.41 +				**1**		

Care must be taken in interpretation here: the surviving twelfth century examples are, possibly with the exception of Dunblane, part of small or relatively less prestigious buildings or groups of buildings - mainly parish churches or small monastic foundations. Even at Dunblane the original church building may have been relatively insignificant. The thirteenth century examples are undoubtedly more important: cathedrals or major parish churches. The comparison may be unfair. To begin with, at the greatest twelfth century monuments of Kelso, Jedburgh and Dunfermline there are no equivalent surviving towers. Also, of course, the later period was characterised by tremendous economic prosperity, and what appears relatively insignificant earlier in the twelfth century may actually be of an equivalence that is difficult to quantify and evaluate in relative terms - a subject which would benefit from further research. The thirteenth century does not appear to have seen the construction of many church towers, at least not of the parish church category. Braun has noticed a similar situation in England over the thirteenth and fourteenth centuries (I 1985: 227).

That aside, the thirteenth century does of course boast a wealth of high status religious building and its quality and sophistication traditionally is evidenced by the ever finer and more complex carved stone work - tracery, finials, pinnacles but most significantly groin and rib vaulting, pointed arches and buttresses. The more scientific equilibrium of thrusts and their controlled descent to a number of tightly defined points in the foundations pioneered mainly in France appeared in diluted form in Scotland in the late twelfth and early thirteenth century. The well known predilection for verticality and ever greater height to which French builders aspired was not shared this side of the Channel and the English penchant for relative horizontality was generally assimilated in Scotland. However, it does appear that greater attention was paid to precision in architectural design and possibly draughtsmanship, resulting at last in towers of accurately laid out squares.

The mason craft has been traditionally regarded as being predominantly town based, and the decimation of its ranks in the plague of 1349 throughout Britain because of this has been remarked on (IV Crossley 1941: 39). There were some changes in the way in which building design was approached and that may have been a factor in this. The reduction in influence from English sources and the appearance of a different and recognisably Scottish way of building later in the fourteenth century after the Wars of Independence also may be assumed to have had some effect, perhaps even on the geometric basis for building. What do we find by measuring the surviving towers? Fortunately there is a wealth of structures of all shapes, sizes and different levels of sophistication from this period.

The examples of the fifteenth century are not easy to evaluate; they rarely appear to fit neatly into any particular pattern. Openly apparent to the observer are two different approaches to church tower design. At the often more prestigious end of the scale are characteristics reminiscent of the previous era: buttresses, ribbed groin vaults, some pointed arched windows with Gothic tracery, etc. and occasionally a true square plan or a direct square derivative. All this might appropriately be labelled 'old Gothic'.

At the other end of the spectrum was what might be described as 'domestic vernacular', consisting of solid thick wall structures with plain, even severe, external elevations and with simple round or pointed barrel vaulting. Wall-head parapets and ridged roofs ending in crow stepped gables provide the basis for a fortified aesthetic and, possibly a predictable characteristic, geometry is hopelessly imprecise: the near-square abounds. These are the two extremes. Now, how do the surviving buildings measure up to these models?

Few buildings were constructed in, and survive from the fourteenth century: Inverkeithing tower is now badly weathered but obviously in its time was of some sophistication, even boasting light and comfortable session room at top floor level (figure 14.4). With its buttresses and fine traceried windows it appears on the surface to have been the work of those who remembered the old way of building. When measured, the dimensions of its plan seem to confirm this: it is an *exact* square. So is the magnificent *campanile* tower of Cambuskenneth.

The fifteenth and sixteenth centuries to the reformation can be taken for the moment as a whole since little seems to change over the period. Again it is hard to pin down any generalities or patterns. There are 13 towers with a vaulted ground floor and only three without. Of the latter, Kirkcaldy has walls amply thick enough to bear a vault. Perhaps one was intended. So this feature, if none other, has become almost universal, although the manner in which it was designed could hardly be more diverse - but that will be discussed later. Often are elements of 'old Gothic' freely intermixed with those of 'domestic vernacular' and, in that spirit, it is quite common to find towers with vaulted ground floor geometry differing from that of the level above: in six cases there is a true square on one level and a near-square on the other - no particular trend of which level each appears, and there does not seem to be any obvious explanation. There is, however, one trend which seems to apply: the more sophisticated buildings, often evidenced by more of the 'old Gothic' elements than 'domestic vernacular' are more likely to have true squares, very near true squares or derivatives thereof: for instance, the plans of Linlithgow, Dunfermline Abbey (north-west tower), Dunkeld, Culross are all true squares, at least at one level; that of Cupar is an auron; of Stirling a root-3 rectangle. In contrast the towers of the relatively vernacular Aberlady, Corstorphine, Holy Trinity (St. Andrews), Kirkcaldy, Crail (figure 14.5), even St. Salvator's, are near-squares and in each case the ratio of their sides falls between 1: 1.04 and 1: 1.09, except Holy Trinity which is 1: 1.27.

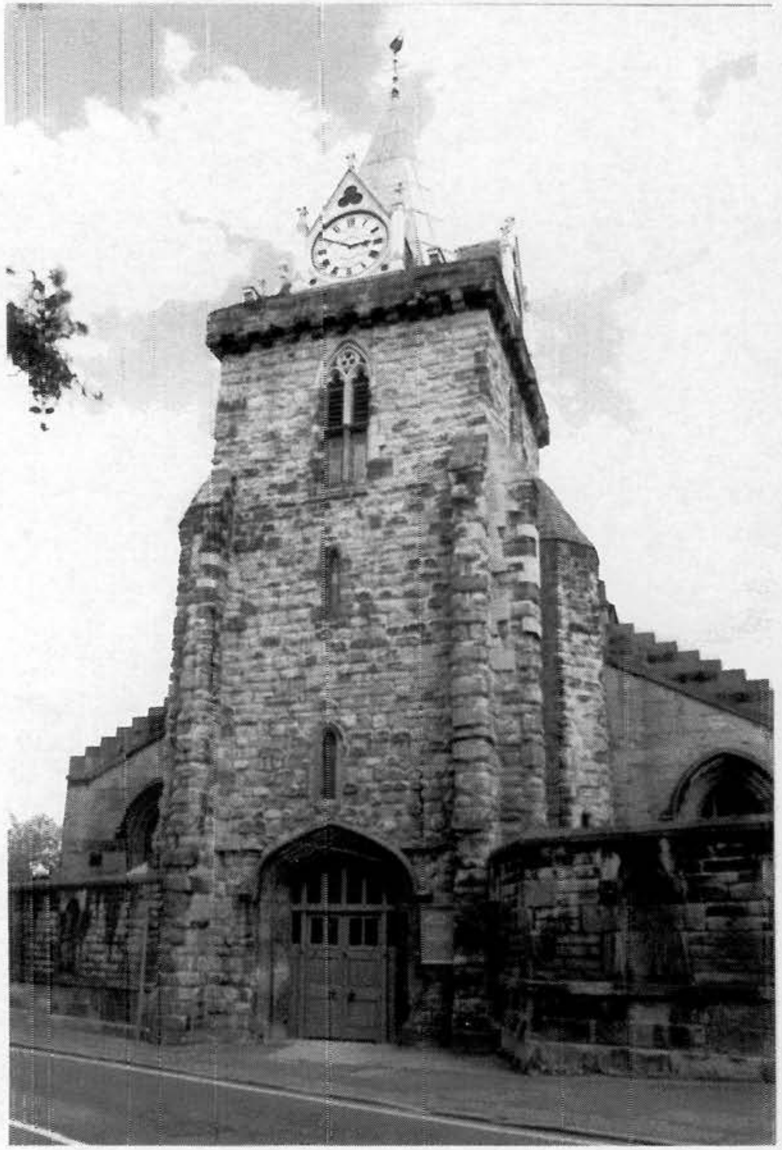


Figure 14.4 Inverkeithing Church tower

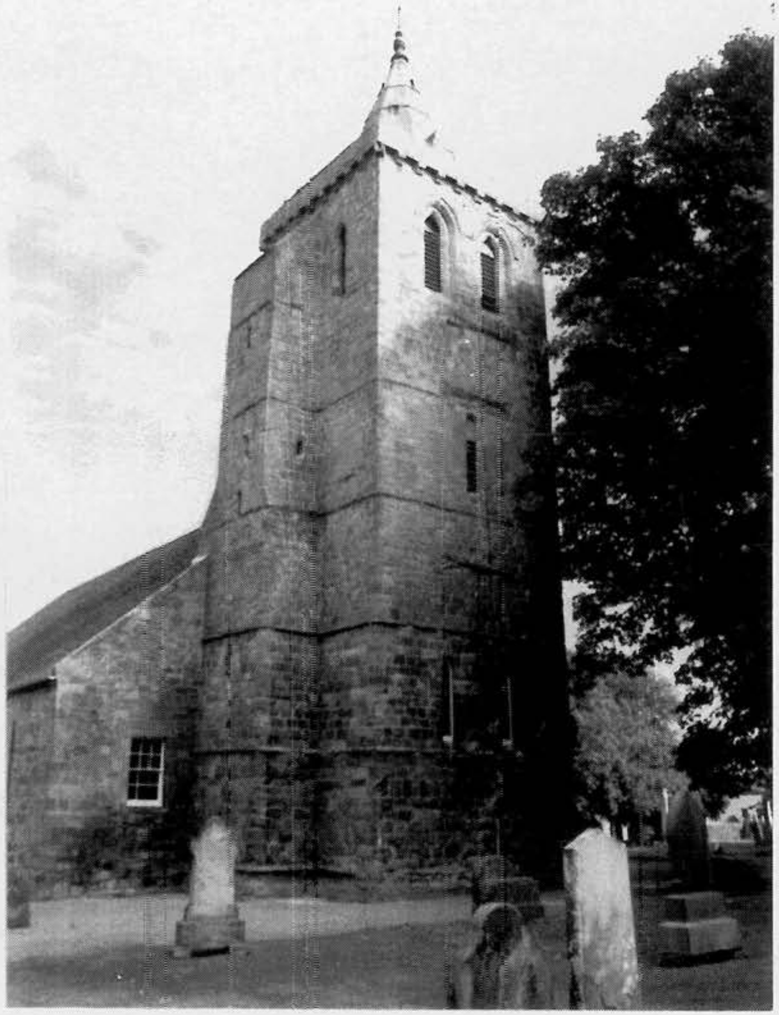


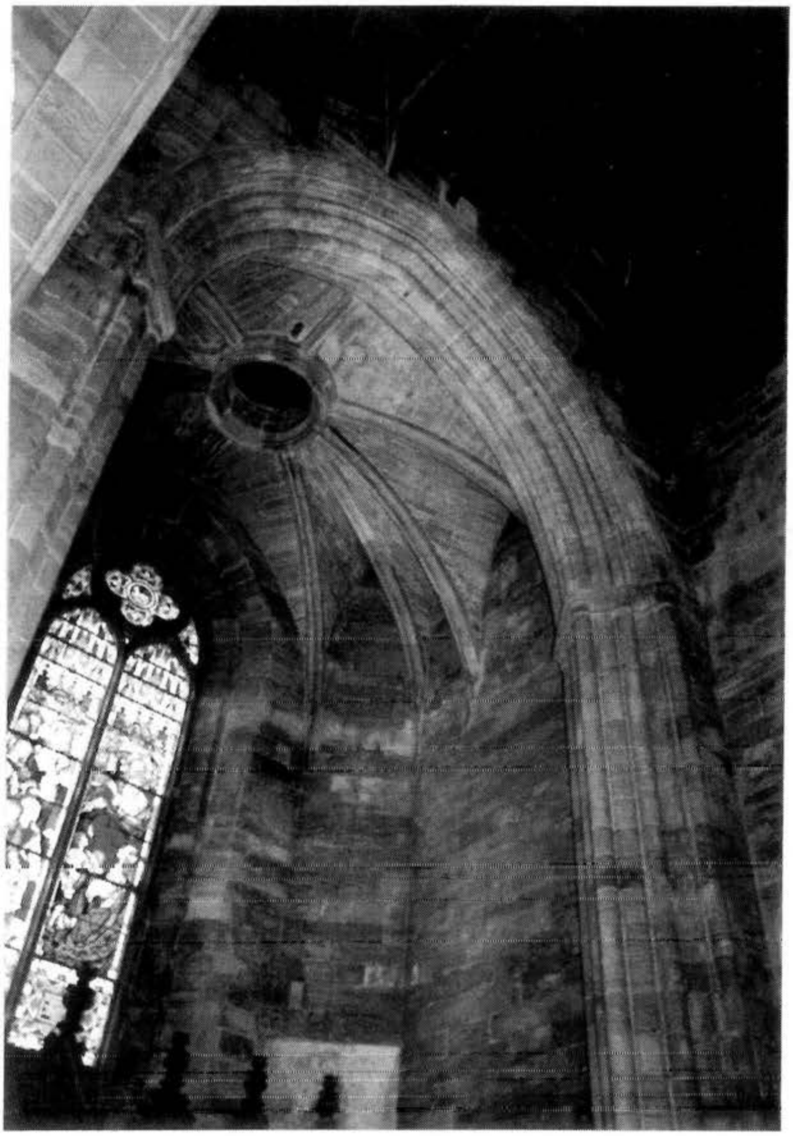
Figure 14.5 Crail Church tower

Another exception is the very vernacular-looking Cross Kirk tower (Peebles) which turns out to be an exact square. This church turns out to be exceptional in more than one respect, as has become evident in the unvaulted church chapter. Despite these there is an undeniable connection between the Scottish 'domestic vernacular' way of building and the near-square.

Some reasons why this may be so are not hard to discern. On the one hand, both complex ribbed groin vaults, and buttresses, are very expensive in terms of skilled stone-cutting, dressing and laying, the tower also requiring the costly input of carpenters in the fabrication of complex formwork. The design and execution of both features requires the same geometric precision that is involved in the setting out of an exact square. On the other hand a simple rectilinear-planned tower with barrel vaulted ground floor will require much less time, skill and finance.

There is another issue worthy of passing mention here, that of structural logic in the abutment of different types of vault. Individual buttresses should logically be used to support the thrust from ribbed groin vaults which is directed down to relatively tightly defined locations in the wall. The abutment of a barrel vault is an entirely different matter: thrust is evenly distributed along a continuous length of wall, and will only be directed to more tightly defined points by the interruption of arched window or other openings. Church towers have few, if any, windows, especially at ground floor level; perhaps at most a west door. So if a barrel vault is used, it would be logical to support it using thicker walls, at least on the sides of the tower receiving the thrust of that vault. If a ribbed groin vault is used, it is logical to afford extra abutment to the points from which the ribs and groins spring: usually with corner buttresses. A hybrid type of ribbed groin vault poses something of a problem for structural logic in just three cases: Holy Rude (Stirling), Culross and Linlithgow boast a multiplicity of ribbed groins, a sort of web (figure 14.6) Obviously to buttress these ribs individually on the external elevations would appear ridiculous; hence perhaps the thicker smooth walls where such webbed vaults occur.

Figure 14.6 Webbed vault in the tower of Holy Rude, Stirling



14.3 FINDING THE BASIS FOR WALL THICKNESS

What is eminently noticeable about the wall thickness of the church towers surveyed is that they all appear to be very similar, most displaying not much variation on around 1.2 metres, or 4 feet (Figure 14.7), and many of them are also are of a not dissimilar footprint area. There are some obvious exceptions, but when so little variation is found amongst so many, the problems of unravelling such seemingly insignificant deviations from any norm that might be found can be disproportionately large.

Figure 14.7 CHURCH TOWERS: WALL THICKNESS SUMMARY

Thickness CM.	Anglo-Scot Norman	Anglo-Scot Gothic	Wartime	Early Scottish	Trans-itional	Post-Ref-ormation
- 75	1	V(?)				
76 - 80	11	1				V
81 - 85				V	1	
86 - 90						
91 - 95			1			
96 - 100	11					
101 - 105						
106 - 110	11V			VV		
111 - 115						
116 - 120				V1	VVV	
121 - 125	VV			V		
126 - 130		1		VV		
131 - 135		V		V		
136 - 140					1	
141 - 145	1(?)					
146 - 150					V	
151 - 155					1	V
156 - 160		V				
161 - 165						
166 - 170						
171 - 175						
176 - 180						
181 - 185						
186 - 190						
191 - 195				V		
196 - 200						

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1 Unvaulted structure
V Vaulted structure

Some generalisations can be drawn from the above. Every tower that is vaulted and was originally vaulted has a wall thickness of between 1.2 and 2 metres with several exceptions: the massive St. Mary's (Dundee) of the fifteenth century: 2.4 metres; St Vigeans where the vault may possibly be a later insertion, or even a complete rebuild; Dirleton where the heavily abutted ground floor vault is of entirely different character from the relatively economical structure above, which is all fairly typical for its late date (early seventeenth century); Monymusk, of the twelfth century: c.1.05 - 1.1 metre thick which will be discussed in more detail later, and Cupar, of the fifteenth century, 0.85 metres which sat astride the north aisle of the church, and seems to be of inexplicably precarious structure. Unvaulted towers are characterised by wall thicknesses of between 0.7 and 1.4 metres, but commonly no more than 1.1 metres. In view of this and our earlier review of towers where the vaulted ground floor has, in a majority of cases, thicker walls at that level than above, it is reasonable to conclude at this stage that the presence of a vault did generally result in thicker walls for towers. Obvious perhaps, but worthy of statement nonetheless. However, this could be at least partly explained by the simple observation that unvaulted examples tend to be found amongst the smaller structures averaging between around 30 and 40 square metres footprint, the largest being the exceptional King's, Aberdeen and Kirkcaldy at 54.7 square metres (Kirkcaldy's great wall thickness of 1.4 metres might indicate an intention to vault, taking it out of this category). This smaller group is also characterised by consisting mainly of earlier, twelfth century examples. The vaulted cohort embraces all sizes up to the huge examples such as Elgin's 64 square metres and St. Mary's (Dundee) 144 square metres.

A look at the relative wall thickness at ground and first storeys does not always necessarily appear logical as structural logic is understood today. Out of 20 towers, ten had thicker walls at ground (vaulted) floor level than above, which is perhaps the format that might be expected. Such an arrangement might indicate a conscious attempt to differentiate the size of wall needed for the abutment of a certain form and size of vault from that needed for the rest of the tower where economies could be made. It may seem unreasonable, therefore, that in the cases of Aberlady and Corstorphine the wall thickness is the same on each storey. There is much to connect these two: the relative vernacular simplicity of their design and build, their date of construction - both in the fifteenth century, and their geographical proximity. Unvaulted towers, one might expect, would also be found to have the same wall thickness at all levels, but of the thirteen examples surveyed, only seven have the same wall thickness most or all of the way up. In some cases this is due to later rebuilding such as at Stobo, but at others such as Dunning there are intakes at higher levels.

Perhaps most surprising in the sample of church towers surveyed were five (out of the total of 20 vaulted examples) where the wall thickness was actually greater on the storey above the vault than below it, although only by a structurally insignificant margin: St. Machar's, Cupar, Dalkeith, Holy Rude, Dunfermline Abbey (NW tower). All that can be said to unite these are their age, again all bar Dunfermline of the fifteenth century, and their relatively high quality. Is there any concept of structural logic in these apparently widely divergent practices?

14.3.1 *Slenderness Ratio*

At this point several tools or yardsticks were used to test aspects of tower design. First, let us suppose for now that wall thickness was based on the height of the tower; and let us refer to Alberti's prescription (X Book VIII, V: 170-171) which amounts to a slenderness ratio of 1:20. These walls would be slender indeed by any standard, but then they have only a few metres horizontal length between the abutment that each provides for its neighbours at the corners. Alberti may have been referring to unfortified towers, ornamental status structures, but also perhaps the very tall fortified urban towers such as survive in San Gimignano. Although unspecific on the matter of building materials, he may have assumed the use of brick or accurately shaped stone. It is possible also that these structures were unvaulted. Further research in this subject is required. Of course Alberti was writing in the fifteenth century and in a different, and very distant, country but it is quite likely that he was merely reflecting current and even historic building practice at a quite mundane level. Coincidentally the Stieglitz treatise specifies the same ratio (X Gwilt 1889: 1010). How does Scottish medieval practice match up to these recommendations? There are several problems with analysis here which have already been mentioned but bear restating, and one note which should be added concerning the interpretation of towers in modern terms.

The design of towers in modern engineering terms requires calculation of wall thickness not so much in relation to *total* height, but the height between each storey, the floors providing some stiffening to the whole structure. For the purpose of this analysis, however, the entire height alone is used on the basis of evidence from these two contemporary documentary sources, Alberti and the Stieglitz treatise. The notion of floors having a stiffening effect is, however, an interesting one, and there may be a requirement for a wider survey of towers with their original floors to ascertain what relevance this may have been.

Of other problems in the analysis there are several worth mentioning. Most towers in Scotland are vaulted at ground level but this need not necessarily invalidate a comparison which may be made using the towers from the first floor upwards. Unfortunately though, some towers are only two storeys high above the vault and a test in respect of only two unvaulted storeys would hardly be satisfactory. Secondly, some towers have been cut down from their original height, which, together with the reasons for doing so, has gone unrecorded. Thirdly, some towers have been heightened, the original height and any embellishment - parapet, spire, etc. - again being unrecorded. Fourth, it may not be known if the original design for a tower was worked through to completion consistently conforming to that design. For instance, does the wall thickness reflect the intention to erect a stone spire that was, in the end, never built? As if all this is not difficult enough the wall thickness of many church towers differs slightly between the north/south walls and the east/west walls.

Taking all this into account are any valid examples available at all? Actually the situation for meaningful analysis may not be as bleak as these provisos would imply. Assuming for a moment that medieval builders recognised the relevance of slenderness ratio in their work, when adding extra storeys or a spire to an existing tower they might well look carefully at the earlier wall structure to ascertain whether any safe limits determined by slenderness ratio might be exceeded by the additions. In any event there is nothing to be lost by making an objective assessment based on what evidence is available.

With all these provisos in mind, a remarkably diverse picture emerges. Figure 14.8 shows the towers in descending order of slenderness, while figure 14.9 summarizes the data by chronological period. Some towers have been omitted where insufficient information on the original dimensions is to hand. Where the tower is fully or partly buttressed, or where it bore or was intended to bear a pointed or crown spire, this is indicated by arrows on the right hand side of figure 14.8 to show which way up or down the 'scale' such features would probably move that particular structure. Where structures are vaulted and the ground floor walls are thicker than above, only the upper wall thickness has been used, but the *whole* height to the wall-head is taken as the basis for calculation. This is justified by an assumption that if there had been no vault, then the wall thickness of the upper levels would probably have been used on the ground floor also.

Figure 14.8 CHURCH TOWERS: SLENDERNESS RATIO COMPARISON

SITE	PERIOD	VAULT	WALL THICKNESS (M)	HEIGHT (M)	SLENDERNESS RATIO 1:	
St Rules	1	-	.75	32.9	43.9	
Dundee	3	RV	1.95 + ½ butts	50.3	25.8	↓
Markinch	1	-	0.8	20	25	
Crail	1a	-	0.8	19.2	24	
Cupar	3	2 BV	0.85	20	23.5	
St Salvator's	3	BV	1.3	29 + spire	22.3	↑
Dunkeld	4	RV	1.2 + butts	26.8	22	↓
Muthill	1	-	0.96	20.6	21.4	
Dunning	1	-	1.1	22.8	20.7	
Linlithgow	3	WRV	1.24	25 + crown spire	20.2	↑
St Vigeans	1a	BV	0.75	15	20	
Dirleton	5	BV	0.8	16	20	
Dunblane (entire)	1	RBV	1.25	26 full height	20	
Culross	4	RV	1.2	23.6	19.7	
St A's Holy Trinity	3	-	1.2	22.7	18.9	↑
Dunfermline	5	WRV	1.55 + ½ butts	29 + spire	18.7	↑↓
Stirling (entire)	3 & 4	RV	1.35	25 (18 + 7)	18.5	
Monymusk	1	BV	1.1	18.7	16.9	
Dalkeith	3	?	1.2	20	16.7	
Elgin	1a	RV	1.57 + butts	25 + spire	15.9	↑↓
Inverkeithing	2	-	0.95 + butts	15	15.8	↓
Brechin	1a	RV	1.35 + butts	20	14.8	↓
Cambuskenneth	2	RV	1.3 + butts	19	14.6	↓
Kirkliston	1	-	1 + pil. butts	14.5 + ?	14.5	↑
Stenton	4	-	0.85	12	14.1	
Dunblane (lower)	1	RBV	1.25	17.5	14	
Peebles Cross K.	4	BV	1.2	15.7	13.1	
Stirling (lower)	3	WRV	1.35	18	12.8	
Kirkaldy	4	-	1.4	17.5	12.5	
Aberdeen King's	4	-	1.55 + butts	17.7+ crown spire	11.4	↑↓
Aberdeen St Machar	3	BV	1.5 + butts	16.75 + spire	11.2	↑↓
Aberlady	3	2 BV	1.1	12	11	
Cambuskenneth	1a	-	1.3 + butts	13	10	↓
Corstorphine	3	BV	1.1	10 + spire	9.1	↑
Restenneth	1	-	0.8	? (altered)	?	
Uphall	1	-	1.1	? (altered)	?	
Stobo	1	-	1.45	? (altered)	?	

BV	barrel vault
RBV	ribbed barrel vault
RV	ribbed (usually quadripartite) vault
WRV	webbed ribbed vault
butts	buttresses to the full height
½ butts	buttresses to only part of the height
pil. butts	Norman pilaster buttresses
↑	possible movement up the scale to compensate for spire
↓	possible movement down the scale to compensate for buttresses

PERIODS:	1	ANGLO-SCOTTISH - NORMAN generally 11th & 12th centuries
	1a	ANGLO-SCOTTISH - GOTHIC generally 13th century
	2	WARTIME 1296-1370
	3	EARLY SCOTTISH 1370-1480
	4	TRANSITIONAL 1480-1560
	5	POST-REFORMATION 1560 -

Figure 14.9 CHURCH TOWERS: SLENDERNESS RATIO SUMMARY

RATIO 1: (rounded)	ANGLO-SCOT NORMAN	ANGLO-SCOT GOTHIC	WARTIME	EARLY SCOT TISH	TRANSITIONAL	POST-REF
9				Y		
10		B				
11				V	ZC	
12						
13					VA	
14	V				A	
15	B	X		X		
16		Z	B			
17	V			V		
18						
19				AV		Z
20	V	V	*Alberti's recommendation*	Y	V	V
21	AA					
22				Y	X	
23						
24		A		V		
25	A					
26				X		
27						
28						
29						
30						
31						
32						
33						
34						
35						
36						
37						
38						
39						
40						
41						
42						
43						
44	A					
?	AAA					

A	Unvaulted,	no buttresses,	no spire
B	Unvaulted,	with buttresses,	no spire
C	Unvaulted,	with buttresses,	with spire
V	Vaulted,	no buttresses,	no spire
X	Vaulted,	with buttresses,	no spire
Y	Vaulted,	no buttresses,	with spire
Z	Vaulted,	with buttresses,	with spire

? Towers whose original height, or intended height not known

NB Alberti's ideal of 1:20 has been underlined for purely academic interest

Fairly self-evident from these tables is the very consistency of the diversity of ratios, extending as they do from 1: 9.1 all the way up to 1: 25 with the exceptional St. Rules at 1: 43.9 included merely for interest. There is hardly any specific concentration around Alberti's recommended 1 : 20. Any other pattern or trend is curiously elusive. All that can be found is a very generalised and rather loose relationship between height and slenderness: higher buildings generally tend to have more slender walls. This is, of course, not particularly logical in Albertian or in modern engineering terms: the slenderness ratio should ideally be the same for all the towers, except perhaps where walls are stiffened by buttresses or a heavy stone spire distorts the picture. If anything, taller towers should be built with proportionately greater strength to resist the disproportionately stronger winds at higher altitudes. This does not seem to have been an issue. As with other building types, a minimum wall thickness of 0.75-8 metres is noticeable, and perhaps of equal interest is the maximum wall thickness (excepting that of the massive St. Mary's, Dundee) of around 1.6 metres and the mode of nearer 1.2 metres.

One point to which attention should perhaps be drawn is the role, if any, of buttresses. Theoretically, it should be the slenderest of walls that would require additional stiffening by this means. The examples on the chart reveal that this simply is not the case, further proof perhaps if it is needed that slenderness ratio, certainly on its own, was not the determinant factor in church tower structural design. So in what direction can it be found?

14.3.2 *Dimensional Congruity*

It has already been noted that at least one, if not both external dimensions of many church towers are based on some other part of the main body of the church, the nave arcade, the choir, or an aisle. What if the tower wall thickness were also based on that of some other part of the church structure? Furthermore, if the overall dimensions could be related to the nave or choir either equally, or by a root 2 relationship, might not the same be possible for wall thickness? Figure 14.10 shows a summary of findings. A relationship of the wall thickness to that of the nave (which in many cases was the same also as the choir) was very common in the Norman period, but seems to have been replaced as, amongst other considerations, ground floor vaulting became more common and the wall thickness drawn from elsewhere proved to be inadequate. At that point structural expediency demanded a more appropriate solution, and that will be dealt with in the next section. In the meantime, there are some other unvaulted towers which are obviously not designed on this basis.

Figure 14.10 DERIVATION OF TOWER WALL THICKNESS FROM THAT OF OTHER PARTS OF THE CHURCH

DERIVATION	ANGLO-SCOT NORMAN	ANGLO-SCOT GOTHIC	WARTIME	EARLY SCOT TISH	TRANS-ITIONAL	POST-REF
= NAVE	11111	1		111		
√2 NAVE	11					
= AISLE				1		
√2 AISLE						
= CHOIR/ CHANCEL						
√2 CHOIR/CH.					1	
NOT RELATED		11		11	11111	11
LOST	111	11	1	111	1	

DERIVATIONS:

= NAVE	Tower wall thickness equal to, and in some cases structurally integrated with that of nave / nave arcade.
√2 NAVE	Tower wall thickness related to that of nave by root 2.
= AISLE	As for nave above.
√2 AISLE	ditto
= CHOIR/CHANCEL	ditto
√2 CHOIR/CH.	ditto
NOT RELATED	There does not appear to be any relationship between the wall thickness of the tower and that of any other parts of the church.
LOST	Either the original church with which the tower was coeval has been demolished or rebuilt to the extent that dimensional comparison is impossible or unsafe.

14.3.3 *Quadrature*

Of perhaps a modicum greater structural logic, in medieval terms, than directly 'lifting' the wall thickness dimension from that of the nave or choir, is the concept of quadrature. Taking the external dimensions of the tower as the starting point for the design, the inscription and rotation of a square for the internal dimensions, giving a root-2 relationship, at least ensured that the wall thickness was consistently related to the overall footprint area. This method was found to have been used at a few sites, including St. Vigeans and Dirleton where it was found only on the upper floors, the ground level being thicker due to its having been vaulted.

A variation on the quadrature idea is to be found at Holy Rude Stirling, which is web-vaulted. Here the diagonal of the core square of the internal rectangle is rotated about its end point, rather than its mid point, and this defines the west wall thickness (Figure 14.11).

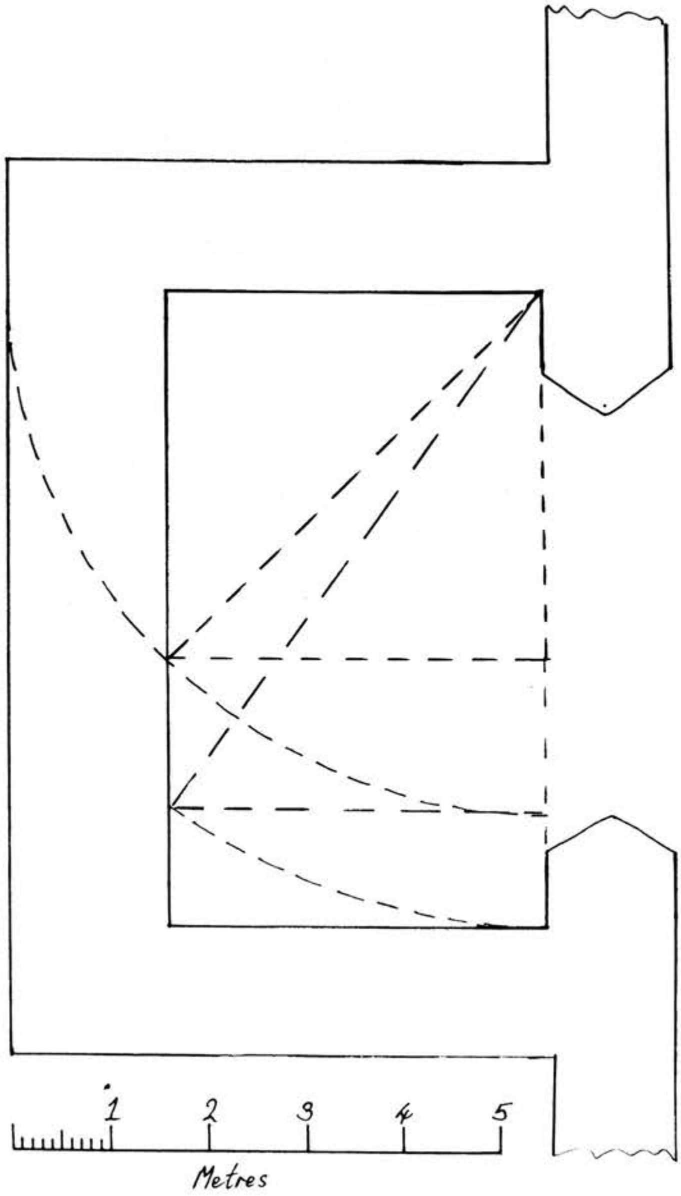


Figure 14.11 Church of the Holy Rude, Stirling: geometry of the tower plan

14.3.4 *Span Ratio*

Where vaulted towers are concerned the problems of design should perhaps be thought of in the building's section rather than plan, for we have here the problem of lateral thrusts from the vaults and these should theoretically condition the solution. As mentioned earlier, there are several different kinds of vault found in Scottish church towers: plain barrel, ribbed barrel, quadripartite ribbed groin, and multiple ribbed groin or webbed. Now there may well have been different ideas on solutions for each of these in the medieval age, but there are none that immediately present themselves. In this research they have been treated as the same.

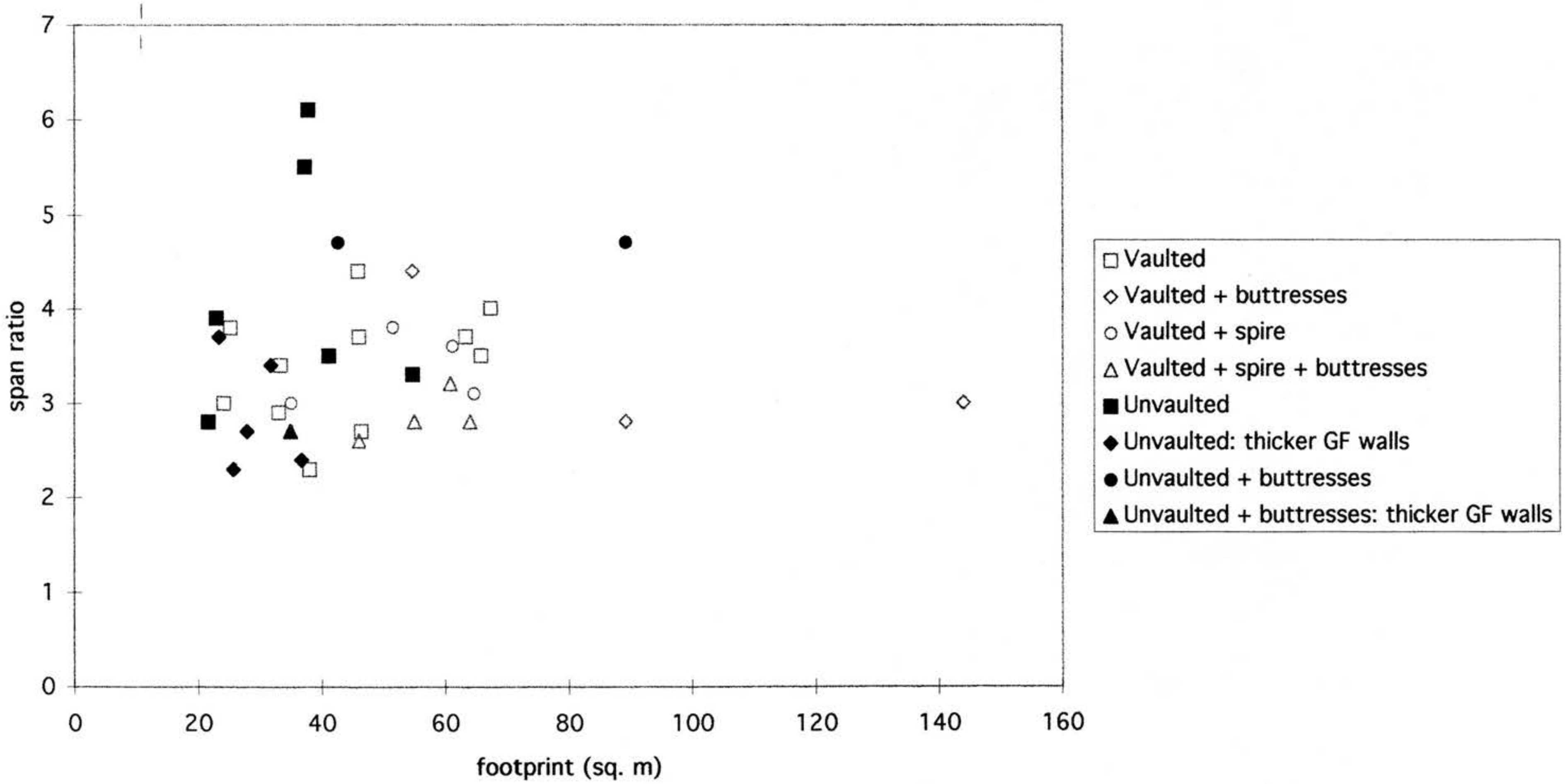
Span ratios were a logical starting point for an examination of towers requiring abutment for vaults at whatever level, but appeared at first to produce little in the way of meaningful results. Figure 14.12 shows a very general trend for a few unvaulted towers to have a higher ratio than all those that were vaulted. The latter were calculated ignoring the use of buttresses. Their inclusion in the figures, even to the extent of adding just one third of the buttress projection, would bring ratios down considerably in the columns pertaining to towers with buttresses. Even so, the unbuttressed vaulted towers still show a remarkable parity with many of the unvaulted examples. This seemed illogical and called for further enquiry. The graph shown in figure 14.13 demonstrates the true situation more clearly. If span ratio is examined in conjunction with the overall footprint area of each tower, it becomes evident that in general it is the smaller towers that are unvaulted. In smaller towers also span ratio tends to be disproportionately high for the simple reason that, as footprint decreases, wall thickness does so at a lesser rate as the minimum safe dimension of around 0.80 metres, or a measurement taken from some other part of the church, is approached.

To return to the subject of buttresses, three instances where a valid reason for their employment could be found is where the tower is, or was intended to be, capped by a spire: Elgin, Aberdeen St. Machar's and Dunfermline. It is particularly noticeable that these have amongst the lowest span ratios. Only a little higher at 1: 3.2 is King's Aberdeen which, although not vaulted at ground floor level, bears a weighty crown steeple and this has been treated for analysis purposes as tantamount to a vault.

Figure 14.12 Church Towers Span Ratios

Ratio 1:	Vaulted	Vaulted + butts	Vaulted + spire	Vaulted + spire & butts	Unvaulted	Unvaulted + butts
2						
2.1						
2.2						
2.3	1					
2.4					1	
2.5						
2.6				1		
2.7	1					1
2.8	1			1	1 1	
2.9						
3	1	1	1	1		
3.1						
3.2				1		
3.3		1				
3.4	1				1 1	
3.5						
3.6			1			
3.7	1 1					
3.8	1		1			
3.9					1	
4	1				1 1	
4.1						
4.2						
4.3					1 1	
4.4	1	1				
4.5						
4.6						
4.7						1
4.8						
4.9					1	
5						
5.1						
5.2						
5.3						
5.4						
5.5					1	
5.6						
5.7						
5.8						
5.9					1	
6						

Fig. 14.13 Church Towers - Footprint:Span Ratio



At the other extreme, there are three cases of uncharacteristically higher span ratios amongst vaulted structures which are worthy of comment. The crossing tower at the Carmelite Church in South Queensferry is above average at 1: 3.8. The tower of St. Michael's, Linlithgow was the same. Above average for any vaulted tower, this figure is very exceptional for a tower with spire or in this case a crown steeple which it once bore. This was demolished in 1821, reputedly after being found to be dilapidated and unsafe. It would be interesting to find out whether its condition was entirely due to decay of the structure itself, or if inadequacy of its support was in any way a contributory factor.

Monymusk is a plain building by any standards, the history of this structure is subject to differing opinions: MacGibbon and Ross think it almost entirely rebuilt apart from the doorway in the west wall (1896: I 217). This is quite possible. The following comments are therefore offered with reservation. Of twelfth century origins, the foundations form an almost exact square: any discrepancy is negligible. The ground floor is barrel-vaulted. If this feature is original, it would be one of the earliest in the country. It has to be acknowledged that it may be a construction or reconstruction of perhaps the fifteenth century. The span ratio at 1: 4.4 is relatively high, and perhaps therefore it comes as little surprise to learn that the spire added to the tower in 1822 had to be removed in 1891 and that, according to the present minister, the tower has constant structural problems, primarily that the four walls are gradually parting company at the corners.

Dunkeld Cathedral's tower boasts a wildly high span ratio (1: 4.6) compared with the others, but it does benefit from buttresses to compensate. Further examination of these structures was necessary to ascertain more precisely what methods might have been used in their design.

14.3.5 *Dérand's Vector*

The application of Dérand's vector as a tool for testing the design method of vaults seems appropriate at this stage and produced very significant results: the 'vector' line terminated in the majority of towers surveyed well inside, or at least on the outer wall surface of each tower. However, in the three cases just mentioned, it fell outside. Significantly these are the three cases just mentioned. At Dunkeld, if this method of vault thrust measurement was used by the architect, he was at least aware that he at least aware that he would have to add buttresses. At South Queensferry and Monymusk it would seem that the masons were either over-enthusiastic in their pursuit of economy, inexperienced or incompetent. Here perhaps is another indication that Dérand had found a method which either was the same as that used by earlier mason's, or at least had the same effect as some other rule of thumb employed by them. This leaves the question, just how had these three towers been designed?

Back at the drawing board, the answer soon became obvious: the wall thickness of Dunkeld and Monymusk had both been drawn up using quadrature, the method more usually employed for unvaulted towers. At Monymusk, if the vault was of the twelfth century, this may be explained by the culture of that era as proposed by Bucher: that design was naively restricted to the use of quadrature, unrefined by the rules of thumb which followed the collapse of Beauvais. If on the other hand it was of fifteenth century construction, it could be surmised that the builders were thoughtlessly building a vault on foundations where there had been *none* previously, where the foundations had been designed by quadrature for an unvaulted tower because that had been a customary method in the twelfth century. Small wonder the tower has suffered structural problems ever since!

At Dunkeld also quadrature had been used, and not just to derive the wall thickness. The buttress projection was defined by the rotation of the external dimensions, the only case of this found in Scotland, and perhaps an indication of a much more sophisticated design approach altogether (figures 14.14 and 14.15). This is possibly amplified by the fact that it might well have been known by the architect that buttresses were actually necessary, if the test of Dérand's 'vector' is indeed valid.

Figure 14.14
Dunkeld Cathedral Tower

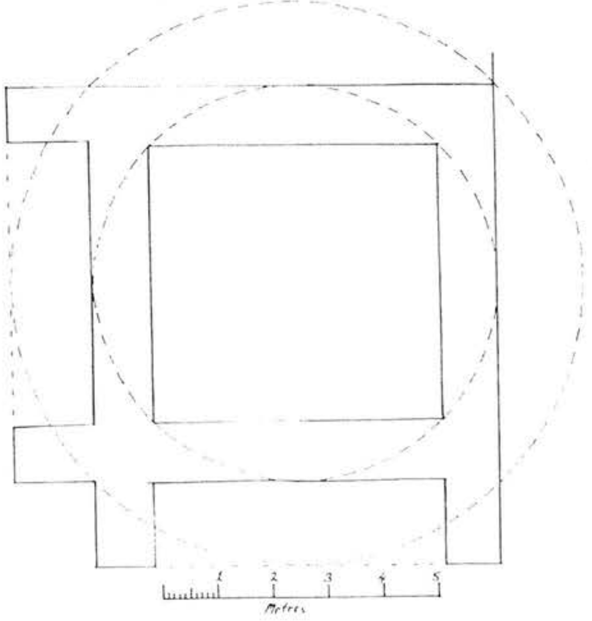
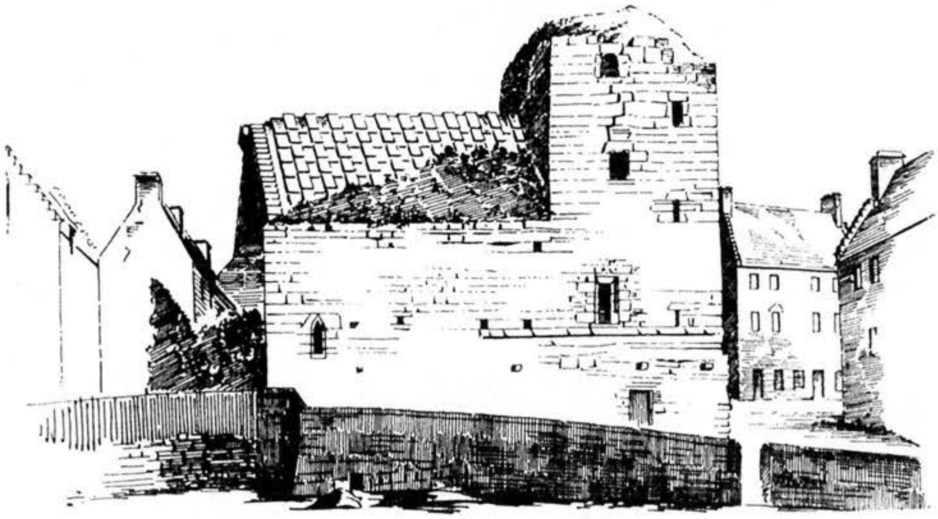


Figure 14.15 Dunkeld Cathedral Tower

South Queensferry church defies all attempts at explanation, and not just concerning the tower, from whose walls Dérand's vector oversails. It will be recalled that this church has thrown up some other exceptional characteristics: the walls of the unvaulted transept are almost thick enough to bear a vault, while the walls of the vaulted choir are too thin to accommodate Dérand's vector. The tower itself appears to have had an uncertain structural history. MacGibbon and Ross's drawing of the tower shows a substantial crack as though the stresses of the vault thrust have not been sufficiently abutted (figure 14.16). A site visit confirmed this, although the structure seems to be stable enough now. Of course it is impossible at this distance in time to make any rash conclusions about the cause of this damage without much more research and analysis, but this may turn out to be further evidence of the efficacy of Dérand's vector as having been a design tool originally (though not at South Queensferry!), and as being a highly useful analytical tool in our own time.

Figure 14.16 South Queensferry Church, showing structural fault in the tower. (MacGibbon & Ross III p298)



14.4 CONCLUSION

From all the foregoing, it becomes obvious that over-generalisation in this subject can be a mistake . In what is a mere introduction to a very complicated subject, it is appropriate to at least attempt an explanation of the design basis of each tower surveyed. Figure 14.17 sets out what in some towers seems a reasonably safe conclusion, in others can only be educated guesswork. Any of these solutions could of course be mere coincidence, it is admitted. The list is organised in order of chronological period, but not necessarily in the correct order within each period, since that is often simply not known, and in any event is not particularly important for the purposes of this research. In some instances more than one solution seems possible, and there both are indicated. The solution will have depended on whether towers were vaulted, whether they were to bear a spire, what were the contemporary practices elsewhere, and also on the experience and intuition of the architect. There does seem to have been a reliance in earlier times on a structural relationship with the main church building, both in overall dimensions and in wall thickness; then the occasional use of quadrature in unvaulted towers. With the increasing use of vaults there seems to have been a rule of thumb that span ratio, especially if bearing a spire, should be up to 1: 3, more generally at least between 1: 3 and 1.38 for safety unless buttresses were to be used. These figures are interesting to compare with those of other vaulted church units, and vaulted domestic work. The mode for towers falls within the range from 1: 2.6 - 1:4, excluding outliers. This is almost identical to the range in which vaulted churches fell taking into account half the buttress projection. This, however, is a lower range than that of vaulted domestic buildings which fell into the bracket 1: 3.7 - 1: 5.4. This would probably be explained by the fact that, at a general level, the wall thickness of the towers is generally as thick or thicker than the domestic work, but the span is less.

Perhaps what is most surprising is the apparent lack of interest in slenderness ratio, though the difficulties of actually deciding on how to calculate these, given the wide range of variables possible, may have resulted in data which does not accord with the way these structures were conceived. Further refinement of analytical techniques may produce different results. An overall picture emerges of disparate attempts by different architects from the Gothic period to address the problems of vault abutment with something approaching a rational method based on span ratio or another method such as Dérand's vector, with a few exceptions which have shown up in inadequate structure in later times. In the light of the findings of this section, it is also possible to draw up a number of standards by which more consciously designed architecture is differentiated from the vernacular: geometric exactitude (the square as opposed to the near-square; precise use of geometric manipulation, in this case, rotation; in certain circumstances, the consistent use of a common wall thickness, or related wall thicknesses, throughout the church.

Perhaps the two most memorable structures to come out of this survey are, on the one hand, South Queensferry with its obviously inadequate abutment, and on the other, Dunkeld Cathedral. The use of quadrature for the wall thickness, of span ratio, Dérand's 'vector' or other rule of thumb, and then quadrature again for buttress projection is possibly unique in Scotland. Whilst it does not represent a move towards structural sufficiency, or even logic in the use of quadrature for sizing of the structural elements, the possible referral to a more logical method in order to determine that buttresses would actually be necessary, combined with this two stage use of the *scientia geometria* makes Dunkeld a most interesting example.

Figure 14.17 CHURCH TOWERS: POSSIBLE WALL THICKNESS DERIVATIONS

SITE	VAULT	SOLUTION	
ANGLO-SCOTTISH - NORMAN generally 11th & 12th centuries			
Restenneth	-	= ?	
St Rules	-	=	
Markinch	-	=	
Muthill	-	?	
Dunning	-	√2	
Dunblane (lower)	RBV	SR	
Monymusk	BV	O	
Kirkliston	-	?	Upper floors: =
Uphall	-	=	
Stobo	-	F/V?	
ANGLO-SCOTTISH - GOTHIC generally 13th century			
St Vigeans	BV	SR	Upper floors: O [entire rectangle]
Cambuskenneth	-	O	
Elgin	RV	SR	
Brechin	RV	SR	
Crail	-	=	
WARTIME 1296-1370			
Inverkeithing	-	O	
EARLY SCOTTISH 1370-1480			
S. Queensferry	2BV	?	
Dalkeith	?	SR	
Aberlady	2 BV	SR	
Corstorphine	BV	SR	
Dundee	RV	SR	
Cupar	2 BV	=	
St Salvator's	BV	SR	Upper floors: =
Linlithgow	WRV	SR	
St A's Holy Trinity	-	O [entire rectangle]	
Stirling (entire)	RV	SR / O / =	
TRANSITIONAL 1480-1560			
Aberdeen St Machar	BV	SR	
Dunkeld	RV	O	
Culross	RV	SR	
Stenton	-	SR	
Peebles Cross Kirk	BV	SR	
Kirkaldy	-	F/V?	
Aberdeen King's	-	SR	
POST-REFORMATION 1560 -			
Dirleton	BV	SR	Upper floors: O [entire rectangle]
Dunfermline	WRV	SR	

=	same as nave / choir wall thickness
√2	√2 relationship with nave / choir wall thickness
O	Rotation resulting in √2 relationship between internal and external dimensions
SR	Vaulted and possibly determined by span ratio, Dérand's 'vector' or other method with similar effect
F/V	Uncharacteristically thick wall at ground floor, possibly intended to be fortified or to carry a vault.
?	Does not appear to fit any particular method or pattern, or insufficient data to hand.

15 TOWER HOUSES

15.1 INTRODUCTION

We come finally to the building type which theoretically at least, should incorporate elements of wall thickness calculation of all those types which have been examined until now:

- the management of height;
- the management of thrust from vaults both at low and, more particularly, at high level;
- the consideration given to fortification and security.

This presents a truly formidable task of analysis.

To set the scene a fundamental aspect of size requires some qualification. It might be reasonable to assume that the primary dimensions of a tower house as specified in a building contract and therefore from which others might derive, would be those of the main *interior* space. Such contracts as survive, as mentioned before, almost invariably specify dimensions "within the walls". But we have no contracts for tower houses. Perhaps the nearest we have to this is the contract for Partick Castle which does specify internal measurements, but this is late: 1611. Warning bells ring when the only indicator of possible earlier custom in this respect is the contract for a tower of Carlisle Castle, where overall external dimensions are expressed first. This is dated 1378, much nearer to the era of the great fortified Scottish tower houses, but then again, it does constitute a part of a larger composite structure, already partly built, which may have dictated these external dimensions. Whilst the early Scottish towers were undoubtedly often surrounded by barmkin walls and other outbuildings, it seems unlikely that these would have necessitated the contractual quotation of the tower's external dimensions in the same way. We will proceed, therefore, under the assumption that *internal* dimensions were pre-eminent, but with caution.

15.2 OVERALL SIZE

Figure 15.1 shows the tower houses surveyed, together with some basic dimensions: internal span and wall thickness at first floor level, and height measured to the side wall-head, that is at the *base* of the parapet.

Figure 15.1 TOWER HOUSES: The survey sample

Site	Height [m]	Span (1F)[m]	Wall Thickness [m]
Early Scottish			
Balgonie	17.75	6.2	2.2
Dunnottar	12	4.76	1.52
Sauchie	14	5.6	1.6
Blackness	16.7	4.83	2.55
Tolquhon	13.25	4.45	2.2
Lennoxlove	16.5	6.45	1.95
Lincluden	17	4.75	1.3
Lennox	(ruined)	5.85	2.25
Balwearie	15	4.8	1.8
Cardoness	15.5	5.2	2.1
Early Scottish with upper vault			
Neidpath	16	6.55	2.55
Hallforest	15	5.1	2.1
Clackmannan	16	5	2
Crichton	(ruined)	5.9	2.2
Craigmillar	16	6.3	2.7
Dundas	16.6	6	2.3
Almond/Haining	15	4.9	1.95
Falside	12	4.95	2.2
Preston	14	4.95	1.8
Spynie	19.5	6.5	3.2
Transitional			
Red Castle	11	6.5	1.8
Castle Campbell	16	4.92	2
Piteadie	8	5.41	1.7
Smailholm	14	5.4	2.2
Newark [Renfrew]	12	4.8	1.1
Newark Gatehouse [Renfr.]	9	4.1	1.05
Seafield	14	4.85	1.65
Dysart	22	3.85	1.5
Balvaird	15.5	5.7	1.8

Cairns	10.25	4.1	1.5
Lordscairnie	13	6.5	1.8
Craiglockart	(ruined)	5	1.2
Creich	11	5.8	1.35
Denmylne	8.55	4.45	1.45
Burleigh	12.5	5.25	1.5
Edzell	17	7	1.7
MacDuff	12.25	5.4	1.35
Carsluith	9.75	5.1	1.25
Crossraguel	12.25	4.6	1.5
Drumcoltran	11	5.2	1.5
Galdenoch	9.25	4.5	0.95

Transitional with upper vault

Scotstarvit	15	5	1.75
Carberry	13.2	5.3	2.1

Post Reformation

Dunskey	10.5	5.65	1.3
Cas. Stewart	11.5	5.7	1.5
Fenton	12	5	1.2
Greenknowe	11	4.9	1.07
Brunstane	7.75	3.3	1.1
Buckholm	9.5	5	1
Bandon	9.5	4.6	1.1
Midhope	15	6	1.3
Tranent	9.55	4.5	0.87
Moncur	8	6.25	1.1
Sorbie	13	5.1	1.1
MacLellans	11.5	5.8	1.35
Uttershill	(ruined)	5.18	0.85
Houston	12.3	5.1	1
Redhouse	14.25	5	0.9
Inch	11.5	6.2	1
Cluny Crichton	(ruined)	5.25	1

Figure 15.2 shows the internal span at first floor level, which was almost invariably the same as all levels above, but slightly wider than the vaulted basement below in some cases where that level had thicker walls. The survey sample is divided into chronological categories, and those towers which have a vault at an upper level, that is on the top or second to top storey, are shown with a "V" in this and subsequent tables.

Figure 15.2 TOWER HOUSES: INTERNAL SPAN

SPAN (metres)	EARLY SCOTTISH c1370 - 1480		TRANSITIONAL 1480 - 1560		POST-REFORMATION 1560 -
3.3					1
3.4					
3.5					
3.6					
3.7					
3.8					
3.9			1		1
4					
4.1			1 1		
4.2					
4.3					
4.4					1
4.5	1		1 1		1
4.6			1		1 1
4.7					
4.8	1 1 1 1		1		
4.9		V	1 1		1 1
5		V V V	1	V	1 1 1
5.1		V	1		1 1
5.2	1		1		1
5.3			1	V	1
5.4			1 1		
5.5					
5.6	1				
5.7			1 1		1
5.8			1		1
5.9	1	V			
6		V			1
6.1					
6.2	1				1
6.3		V			1
6.4					
6.5	1	V	1 1		
6.6		V	1		

KEY: 1 Tower house ***without*** upper storey vault
V Tower house ***with*** upper storey vault

The survey sample shows that in general the size of accommodation on each level within tower houses between the late fourteenth and early seventeenth centuries did not alter appreciably. In the early period there were a very few untypically large towers and from the late fifteenth century the number of smaller towers being constructed increased. However, there does seem to have always been a most popular width of between around 4.6 and 5.4 metres. In contrast to this there was a marked trend for later towers to be less tall than earlier ones as figure 15.3 shows, usually because they had one less storey. Zeune's assertion that earlier towers were both larger and taller (VII 1990: 21) was therefore correct in the latter dimension, and also in overall footprint area due to the thicker walls but, if this sample is representative, then he was incorrect with regard to the internal living space on each level which remained broadly the same.

Figure 15.3 TOWER HOUSES: HEIGHT

HEIGHT (metres)	EARLY SCOTTISH		TRANSITIONAL		POST-REFORMATION
	c1370 - 1480		1480 - 1560		1560 -
--					
6					1
6.5					
7					
7.5					
8			1		1
8.5			1		
9			1 1		
9.5					1 1 1
10			1 1		
10.5					1
11			1 1 1		1
11.5					1 1 1
12	1	V	1 1 1		1
12.5			1		1
13	1		1	V	1
13.5					
14	1	V	1 1		1
14.5					
15	1	V V		V	1 1
15.5	1		1		
16		V V V	1		
16.5	1 1 1	V			
17	1		1		
17.5					
18	1				
18.5					
19					
19.5		V			
20					
20.5					
21					
21.5					
22			1		
Unknown/lost	1 1 1		1		

KEY: 1 Tower house ***without*** upper storey vault
V Tower house ***with*** upper storey vault

15.3 WALL THICKNESS

As for wall thickness, this also decreases over time. Figure 15.4 illustrates the thickness of the survey samples taken at first floor level which, again, is taken to be representative of all storeys, although that of the basement was sometimes marginally thicker. In the early period what is most obvious, and indeed logical, is the greater wall thickness of towers which have an upper storey vault, as against those which do not. Also evident is a progression over time from a great diversity of wall thickness to a situation in the post reformation period where there is relative homogeneity. Most buildings by that time have walls only around one metre thick, or in the language of the day, between 3 and 4 feet, perhaps one ell, with variations dependent on precisely what length of foot was used. There is also a marked difference over the whole period in the way span and/or height only seem to affect wall thickness in the early periods. Again the issue must be confronted, was wall thickness determined more by height or by span?

Figure 15.4 TOWER HOUSES: WALL THICKNESS

WALL THICKNESS (metres)	EARLY SCOTTISH c1370 - 1480		TRANSITIONAL 1480 - 1560		POST-REFORMATION 1560 -
0.9					1 1 1 1 1
1			1		1 1 1 1
1.1			1 1		1 1 1 1 1 1
1.2	1		1		1
1.3	1		1		1 1
1.4			1 1		1 1
1.5	1		1 1 1 1 1 1		1
1.6	1				
1.7			1 1 1		
1.8	1	V	1 1 1	V	
1.9					
2	1	V V	1		
2.1	1	V		V	
2.2	1 1	V V	1		
2.3	1	V			
2.4					
2.5					
2.6	1	V			
2.7		V			
2.8					
2.9					
3					
3.1					
3.2		V			

KEY:	
1	Tower house ***without*** upper storey vault
V	Tower house ***with*** upper storey vault

15.4 SLENDERNESS RATIO

Given that both wall thickness and overall height are generally less in later periods, there is a possibility that slenderness ratio is a significant element of tower house structural design. This needs to be tested. Figure 15.5 shows the ratios for all these buildings, again using the wall thickness above the usually vaulted ground/basement storey which is thicker in some cases.

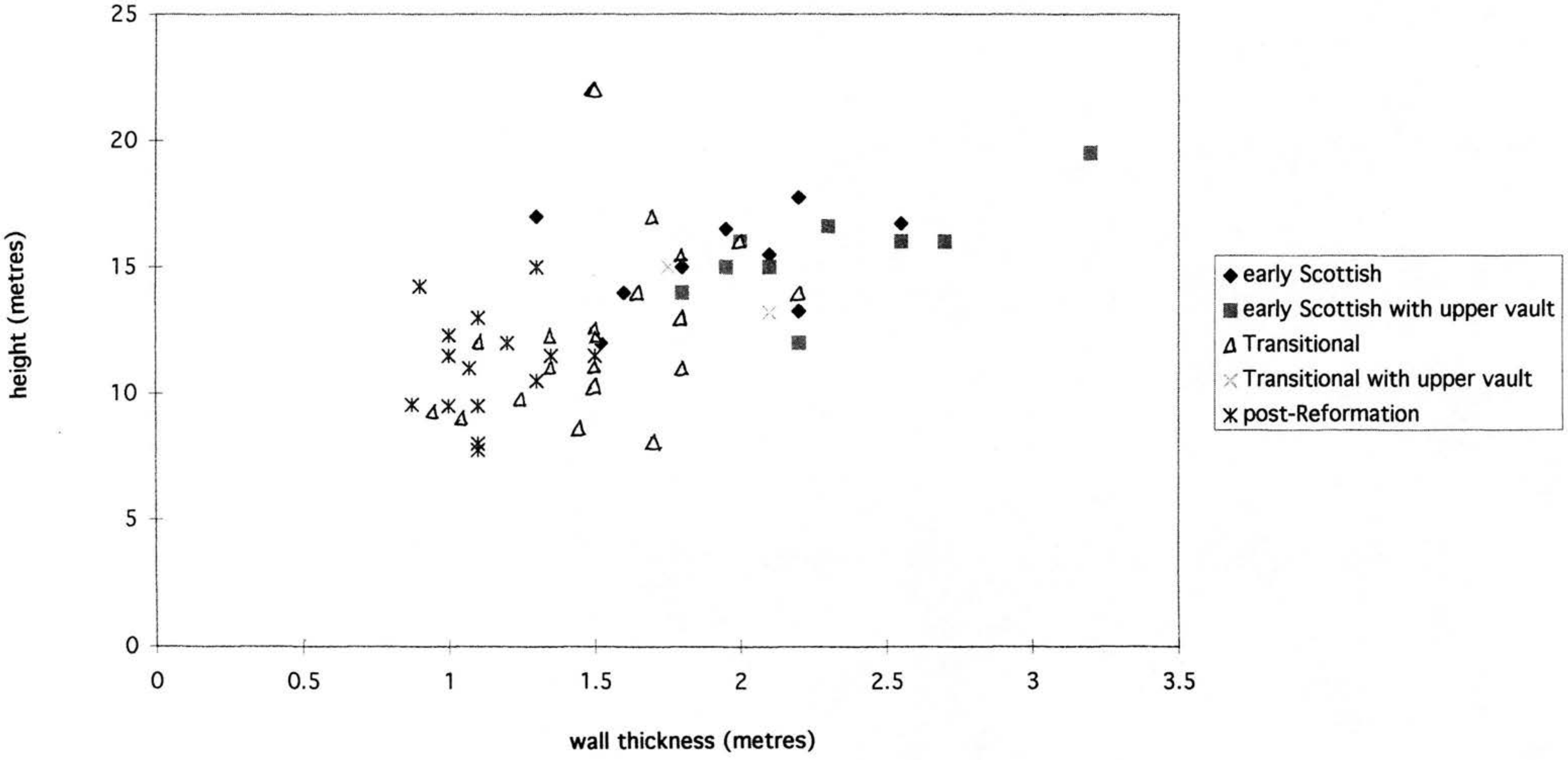
Figure 15.5 TOWER HOUSES: SLENDERNESS RATIO (Based On *Total* Height)

SLENDERNESS RATIO 1:	EARLY SCOTTISH c1370 - 1480		TRANSITIONAL 1480 - 1560		POST-REFORMATION 1560 -
4					
4.5			1		
5					
5.5		V			
6	1	V V V	1	V	
6.5	1	V	1 1		
7		V	1 1		1 1
7.5	1	V	1 1		1 1
8	1 1 1	V V	1 1 1 1		1 1
8.5	1		1 1 1	V	1 1
9	1		1		
9.5			1		
10			1		1
10.5	1				1
11			1		1
11.5					1 1
12					1
12.5	1				1
13					
13.5					1
14					
14.5			1		
15					
15.5					
16					
16.5					1

KEY: 1 Tower house ***without*** upper storey vault
V Tower house ***with*** upper storey vault

Figure 15.6 shows the same data arranged graphically, and demonstrates by the roughly linear cluster that generally just as in the case of unvaulted churches, as height increased, so did wall thickness, until the post reformation period. Then the same rounded cluster appears in the tower house chart as does in the former category. There is just the same late trend for most buildings to be a similar wall thickness regardless of height.

Figure 15.6 Tower Houses - Height:Wall Thickness (based on total height)



Clearly there is very little difference between the figures through from the late fourteenth to the mid-sixteenth century. Slenderness ratio does indeed appear to be a fairly significant factor in the majority of towers through these two earlier periods, and even after 1560 at least half the examples still fall into the same range. This is perhaps a little odd in view of the fact that almost half the earlier examples are vaulted at high level, but only two of the 'transitional' examples share this feature and yet they all share a very similar range of slenderness ratio. The later transitional structures lacking a high vault might be expected to have been more slender. They are indeed thinner in absolute terms (see figure 15.4) but it seems that that was more the result of their lower height. Indeed six of the ten unvaulted structures in the earlier period alone share similar slenderness ratios with the vaulted examples. High vaulting *per se* does not appear to have been the reason alone for thicker walls. From these figures, the incidence of extraordinarily thick walls appears to be merely coincidental with upper storey vaulting when combined with above average building height.

For a moment, it is worth drawing a comparison between the slenderness of tower houses and that of free-standing and curtain walls discussed earlier. Here the average rose from around 1: 4 to 1: 6 with a maximum of about 1: 7. It is immediately noticeable that it is only around 1: 6 - 7 that tower house slenderness ratios start. In a sense the comparison is flawed because the side walls of tower houses are obviously abutted at the corners by the adjoining gable walls. In the light of that there seems to be no relationship. However, if the vaulted basement is subtracted from the height of each tower for the purposes of assessing slenderness ratio, an entirely different set of figures appear (figure 15.7) and their averages conform very closely with standards applicable to free-standing walls until the mid sixteenth century. It has already been noted that in many domestic ranges with vaulted basements, the wall thickness of basement and first floor could be different. The same was sometimes the case with tower houses. Those in the surveyed sample in fact show in each period almost exactly the same number had different wall thicknesses as had homogenous thickness throughout. It would appear from this that the medieval architect often applied one set of standards to the design of the vaulted basement, and another to the walls above, more in common with free-standing walls.

Figure 15.7 TOWER HOUSES: SLENDERNESS RATIO (Based On Height From 1st Floor Only)

SLENDERNESS RATIO 1:	EARLY SCOTTISH c1370 - 1480		TRANSITIONAL 1480 - 1560		POST-REFORMATION 1560 -
2					
2.5			1	V	
3		V			
3.5	1	V V			
4	1		1 1		1
4.5	1 1	V			1
5	1 1 1	V V	1 1	V	
5.5	1	V V	1 1 1 1 1 1 1		1
6		V	1		1
6.5			1 1		1
7			1 1		
7.5					1 1 1 1
8			1 1		1 1
8.5					1 1
9	1				1
9.5					
10			1		

KEY:		
	1	Tower house ***without*** upper storey vault
	V	Tower house ***with*** upper storey vault

15.5 SPAN RATIO

Figure 15.8 sets out the figures for the survey sample and shows an obvious trend for span ratio to increase over time both in magnitude, and also in diversity. The same situation is shown graphically in figure 15.9. The implication of the latter means, of course, that wall thickness became progressively less responsive to changes in span in the later periods. We shall return to this point later. Before that, let us look at the situation regarding towers with upper storey vaults.

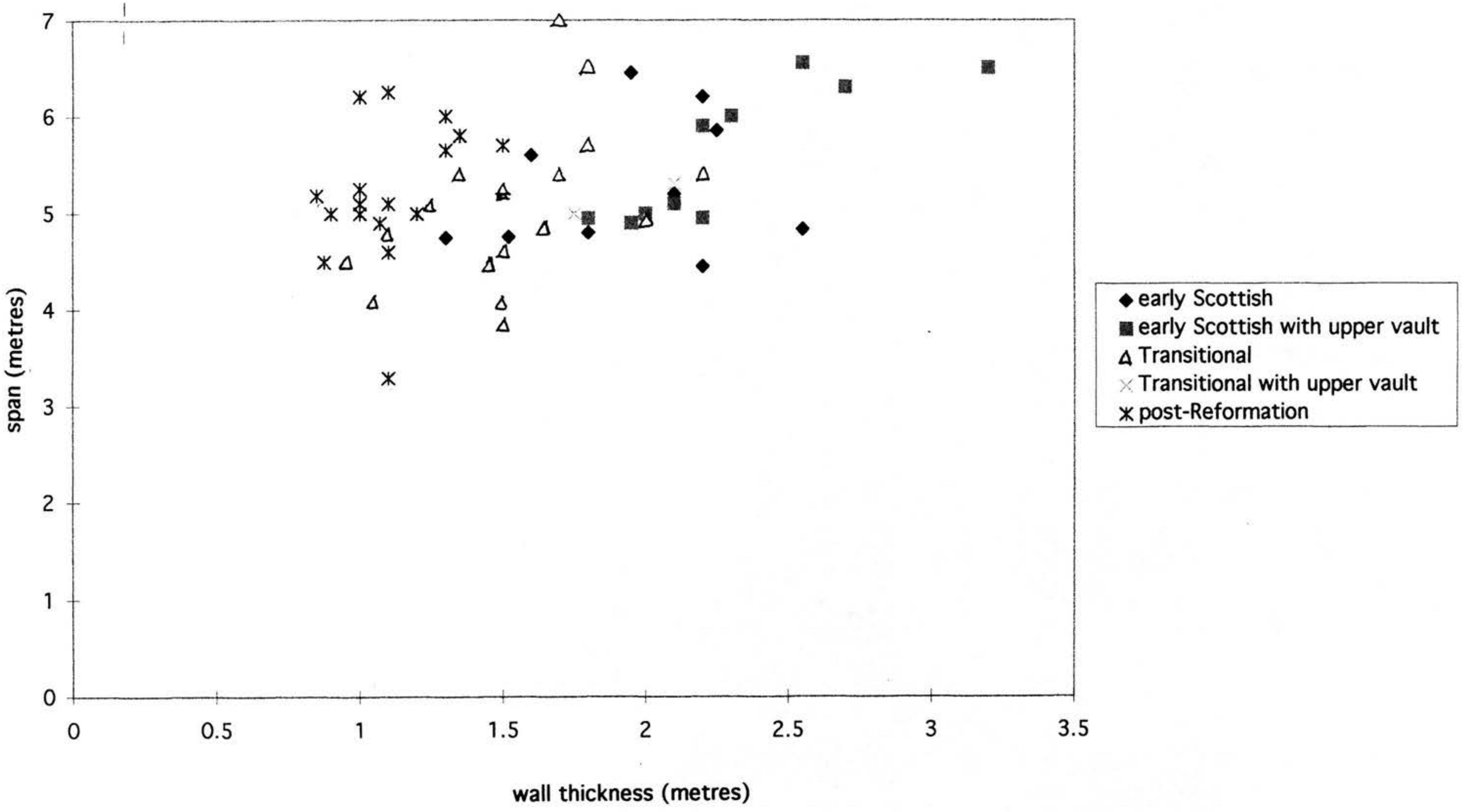
It is significant that on the cluster chart the early structures with upper vaults form a much more consistently inclined linear group than the early unvaulted towers which are much more randomly scattered. Indeed, even the two transitional period examples also fall into the early vaulted line, the unvaulted of this period forming a similarly diverse cloud to the corresponding earlier group. These loose 'clouds' of unvaulted structures do, however, both show some relationship between span and wall thickness compared with the post reformation groups. As was the case with slenderness ratio, these simply form a rounded cluster indicating no particular relationship between wall thickness and span. It would appear then that span was particularly influential over wall thickness of earlier and vaulted towers, and this of course accords with findings in the vaulted church category.

Figure 15.8 TOWER HOUSES: Span Ratio

SPAN RATIO 1:	EARLY SCOTTISH c1370 - 1480		TRANSITIONAL 1480 - 1560		POST-REFORMATION 1560 -
2	1	V			
2.1					
2.2					
2.3		V V			
2.4		V	1		
2.5	1	V V	1	V	
2.6	1	V	1		
2.7	1	V V	1	V	
2.8		V			
2.9	1		1 1		
3					1
3.1	1		1 1		
3.2			1		
3.3	1				
3.4					
3.5	1		1 1		
3.6	1		1 1		1
3.7					
3.8					1
3.9			1		1
4			1		
4.1			1 1		
4.2			1		1 1
4.3			1		11
4.4			1		
4.5					
4.6			1		1 1 1
4.7					
4.8					
4.9					1
5					1 1
5.1					1
5.2					
5.3					1
5.4					1
5.5					
5.6					
5.7					1
5.8					
5.9					1
6					
6.1					
6.2					1
6.3					1

KEY:		
	1	Tower house ***without*** upper storey vault
	V	Tower house ***with*** upper storey vault

Figure 15.9 Tower Houses - Span:Wall Thickness



Generally the early and transitional tower houses have a much lower span ratio than almost all other structures. Span ratio was a factor which, it will be recalled, was probably most influential in the sizing of walls of simple barrel-vaulted churches. The diversity of internal span dimensions of tower houses with upper storey vaults is very evident from the data in figure 15.2 but the contrasting contiguity of their span ratios invites the conclusion that this was indeed a factor, possibly even *the* defining factor in the wall thickness of earlier vaulted tower houses also. This is perhaps supported by the contrasting way in which slenderness ratio (figures 15.5 & 15.7) does not divide the vaulted from the unvaulted groups to the same extent as span ratio (figure 15.8). There is a generally higher equivalence of slenderness ratio between the two types in the early period. Again, surviving documentary evidence also supports this conclusion: it was always principally the relationship with *span* which was discussed in the masonic craft, as evidenced by the writings of, for instance, Lorenz Lechler and Rodrigo Gil, when recommending levels of vault abutment.

Drawing individual comparisons amongst the vaulted cohort is difficult since they are almost all of similar height (c. 16 metres), span (c.5-6 metres) and wall thickness (c. 2-2.7 metres). Perhaps the only comparison which might be instructive is between Falside and the remainder. The height of the former is only 12 metres, about 4 metres less than the others. This lower height does not result in any diminution of wall thickness which, at 2.2 metres, accords very much with the trend. Falside's internal span of 4.95 metres is also typical, and so we may deduce that this comparison lends some confirmation that span is a more influential factor in the wall thickness of early tower houses with upper storey vaults.

If span ratio formed the basis for upper storey vault-abutment 'calculation', then it perhaps comes as little surprise to find that in towers without such vaults, span ratio seems to play an ever decreasing role as times moved on. But there is one other major factor at the heart of tower house design which has yet to be mentioned.

15.6 FORTIFICATION

This must be one of the principal factors affecting the wall thickness of tower houses, and the changes to it through the period under review. It was governed by changing perceptions of what constituted an adequate or desirable level of security. Much ink has been spilt, and continues to be spilt over this subject, with varying degrees of seriousness and sanity but often little in the way of circumspection. It is time that the subject received a fresh approach. What is required at this stage is a comparison of defensive walls in general - the free-standing curtain and barmkin walls dealt with earlier; also the outside walls of the domestic courtyard ranges. It will be recalled that a comparison of the latter two groups has already been made in Chapter 8, which also included a few fortified towers.

Taking the early Scottish period first, figure 15.10 shows the combined wall thickness statistics for these three classes of building. What is immediately clear is the agreement on the range of thickness deemed suitable for fortification which centres around the range 1.5 - 2 metres, about 5 - 6 feet, but the walls of tower houses tend to be a little thicker on average than free-standing walls. The figures also confirm that the extra thickness afforded to vaulted structures appears in some cases to be in excess of what is required for defence in tower houses, and is therefore presumably at least partly for vault abutment.

Figure 15.10 TOWER HOUSES: Levels of fortification in wall thickness compared with other building types

EARLY SCOTTISH c1370 - 1480

WALL THICKNESS (METRES)	CURTAIN WALLS	COURTYARD RANGES	TOWER HOUSES	
0.7	1 1			
0.8				
0.9				
1	1 1			
1.1	1 1			
1.2	1 1 1		1	
1.3	1 1		1	
1.4	1 1	1		
1.5	1 1 1 1 1		1	
1.6	1 1 1	1	1	
1.7	1 1 (AVG.)	1 1 1		
1.8	1 1 1		1	V
1.9	1		(AVG.)	
2	1 1 1	1 (AVG.)	1	V V
2.1	1 1 1	1	1	V
2.2			1 1	V V
2.3	1 1 1		1	V (AVG.)
2.4	1			
2.5		1		
2.6			1	V
2.7	1			V
2.8		1		
2.9	1			
3				
3.1				
3.2				V

KEY: 1 Tower house ***without*** upper storey vault
_ _V Tower house ***with*** upper storey vault

In the transitional period (figure 15.11) there is a shortage of courtyard range buildings but, nevertheless, the trend towards slightly thinner walls is carried through both free-standing and tower house walls, the latter again tending to be marginally thicker, as they had been in the earlier period. A trend towards less diversity becomes evident. However, that ignores the statistics for structures that are obviously primarily artillery fortifications rather than domestic, and this is possibly the most significant factor. With the use of firearms becoming more widespread, some structures were being consciously designed as artillery fortresses, others for a lesser level of domestic security. For both types the basis of design was entering uncharted waters. There were no well-tried ground rules, other than a naive return to a revised version of the medieval curtain wall with round bastion towers, and gun ports in place of arrow slits.

Figure 15.11 TOWER HOUSES: Levels of fortification in wall thickness compared with other building types

TRANSITIONAL 1480 - 1560

WALL THICKNESS (METRES)	CURTAIN WALLS	COURTYARD RANGES	TOWER HOUSES
0.8	1		
0.9	1 1		
1			1
1.1	1		1 1
1.2	1 1 1		1
1.3	1 1 1 1 1 (AVG.)		1
1.4	1 1 1 1		1 1
1.5	1		1 1 1 1 1 (AVG.)
1.6	1 1 1		
1.7	1 1		1 1 1
1.8	1 A	1	1 1 1 V
1.9			
2	A		1
2.1		1	V
2.2			1
2.3	A	1	
2.4			
2.5			
2.6			
2.7			
2.8			
2.9	A		
3	A		
3.1			
3.2			
3.3			
3.4			
3.5			
3.6	A		

KEY: 1 Tower house ***without*** upper storey vault (AVG.) Average
V Tower house ***with*** upper storey vault A Artillery fortification

Excluding those artillery fortresses, figures for post-Reformation walls (figure 15.12) show the characteristic of decreasing diversity brought to its logical conclusion with few walls falling outside a bracket 0.8 to around 1.2 metres, but where domestic security is more obviously an issue, such as at Noltland, the previous standard of around 2 metres still prevails. From this it would seem that the owners of many later towers regarded security as more a matter of appearance - height and gunports - and where these would suffice in the place of masonry mass, considerable economies could be achieved.

Figure 15.12 TOWER HOUSES: Levels of fortification in wall thickness compared with other building types

POST-REFORMATION 1560 -

WALL THICKNESS (METRES)	CURTAIN WALLS & BARMKINS	COURTYARD RANGES	TOWER HOUSES
0.6		1	
0.7	1 1		
0.8	1 1 1 1	1	
0.9	1		1 1 1 1 1
1	1 (AVG.)	1 1	1 1 1 1
1.1	1 1 1 1	1 1 (AVG.)	1 1 1 1 1 1 (AVG.)
1.2	1 1	1	1
1.3	1		1 1
1.4			1 1
1.5			1
1.6		1	
1.7		1	
1.8			
1.9			
2			A

KEY:	1	Tower house ***without*** upper storey vault
	V	Tower house ***with*** upper storey vault
	A	Artillery fortification
	(AVG.)	Average

This is all very well but, apart from the last point, it only compares trends of one sort of fortified wall with another. A consensus is achieved which is useful in itself but it still does not illustrate precisely how much of the earlier wall thickness in particular was mere self-supporting structure, and how much additional to that for security purposes. In the earlier analysis of curtain walls in isolation, it will be recalled that maximum slenderness and minimum thickness in any one period were used to ascertain what was merely structural, and what was added for fortification. Kisimul on the coast of Barra in the Outer Hebrides was noted as having the highest slenderness ratio (1:7.5) with walls only 1.2 metres thick. Perhaps Kisimul's situation surrounded by the sea, which would utterly confound any attempts to bring siege equipment to bear, presents us with an example of walls designed purely for structural stability and to impress at a safe distance.

There are other walls of that period with similar thickness which bear out the validity of this case. The structures of Kisimul and these other thinner walls create a benchmark against which most of the early tower houses are, without any doubt at all, heavily fortified. Indeed it does appear that there was an accepted norm for an unfortified wall of around 0.8 to 1.2 metres right through from the early period to post-reformation times and, generally, anything over and above that constituted some form of fortification or vault abutment. Similarly, there does seem to be consensus throughout that adequate domestic security in thicknesses of around variously 1.5, 1.8, 2 and 2.2 metres, probably in whole numbers of feet.

15.7 PROBLEMS IN FINDING WALL THICKNESS DETERMINANTS

All this provides an idea of some of the influences bearing on the particular wall thickness chosen for a tower house, but so far all that has been found is a very general correlation between span and wall thickness, and this is more pronounced in towers with upper vaults. Also we have vague notions of what was an appropriate thickness for an unfortified, and a fortified wall at a most general level. There must be something more definitive, particularly for the early vaulted towers. Perhaps there may be some ideas in common with the barrel-vaulted churches reviewed earlier.

It will be recalled that for the most part the design of barrel-vaulted church structures was founded in triangulature applied to the buildings' sections. In a smaller number of cases, quadrature was applied to the ground-plan. In most cases, whatever geometric method was used, the wall thickness and any further abutment was found to be subject to some further guiding process, to which Dérand's 'vector' was found to be tantamount. In many ways the upper parts of full vaulted tower houses resemble the essential structure of those churches. There are, however, several obvious and significant differences: firstly, the vaults of the churches were all pointed, apart from that of the Archerfield aisle at Dirleton. In contrast, those of the tower houses are mostly round, and slightly segmental, resulting in lateral thrusts of a shallower incline which, of course, implies the need for greater abutment. Secondly, there was much greater value placed on the admittance of daylight in some, but by no means all, churches and where large and expensive windows could be afforded this might also require buttresses. The priority for fenestration was much less in tower houses and, furthermore, buttressing on a fortified building does not occur in Scotland. There are a number of examples of this phenomenon in England, but not north of the border. The only example that even begins to approach the concept is the Regalitie Tower of Arbroath Abbey but, whilst having some superficial resemblance to tower house architecture, it is really a high status ecclesiastical design and can hardly be classified as fortified. Buttresses would, in the event of a siege, constitute a potentially disastrous liability and open invitation for battering. Finally, of course, churches were not fortified, as tower houses obviously were. Given all these differences, is there even the remotest chance that there should be any common ground in design methodology between the two types?

15.8 DÉRAND'S VECTOR

The application of Dérand's vector is an exercise which, theoretically worthwhile in the light of all the interesting results it has thrown up in relation to other building types, seems totally superfluous in relation to any of the vaults of all but the latest tower houses. Its point of termination invariably lies safely wallowing somewhere in the masonry of the massive walls in the cases of both low vaults and high. The very few exceptions to this are, unsurprisingly, of the post-reformation period, for instance Buckholm (Borders), Houston (West Lothian) and Inch (Edinburgh).

15.9 TRIANGULATURE

Triangulature had very obviously been the basis of most church structure design so this should logically form an initial line of enquiry. However, such an exercise in the realm of tower houses is fraught with problems. It is very difficult to decide at what level such triangles might have been based. Every tower is different and many early examples have vaults not just at two, but at three levels. Access to all, or even some of these levels for the purposes of tolerably accurate measurement was either difficult, dangerous or impossible. From the measurements which were possible it is perhaps worth mentioning that, in six towers, angles of 53-55 degrees were found between the external apex of an upper vault and the exterior wall face at the level of the external apex of the next vault down. There may be some significance in this coincidence, but it would be hard to prove and, in any event, these do not constitute any of the 'elemental' triangles obtainable by constructive geometry.

In reviewing the problems of analysis of the sections of buildings in terms of triangulature, it was decided there was little point in attempting a similar exercise on the tower houses in detail. The vast range of possibilities encountered in other building types (notably groin-vaulted undercrofts with piers) would no doubt also arise in such a study and, for the time and resources available it was considered not to be worthwhile. An assumption is made that, in line with previous findings, the possibility of triangulature having been used cannot be ruled out. That may be a subject for further research at some future date. For now, we are thrown back on seeking to identify forms of geometrical manipulation in the *plans* of tower houses.

15.10 QUADRATURE

First of all it is instructive to see whether or not the basic rectangles of the internal dimensions represent any geometric derivatives of a square. Figure 15.13 lists all the geometric figures found in variously ground/basement level, first floor, or both, in all the towers measured. It is a complicated table and attention is drawn to the key which explains most of the complexities. One of these is, because the wall thickness is sometimes different on each of these ground and first floor levels, there may be different geometric figures on each level, or there may be a geometric figure on only one level. Where in later towers the ground/basement level is divided into several vaulted rooms, sometimes with a passageway, it has been difficult to measure that level as a whole and in these cases the proportions have been taken to be the same as on the first floor, a not unreasonable assumption given that this is the case for most towers anyway.

Several interesting trends are apparent from figure 15.13. In all periods a substantial number of towers feature some sort of square derivative on both ground and first floors, and, despite many cases of slight wall thickness differences between these levels, these geometric figures are mostly the same on both levels.

Figure 15.13 TOWER HOUSES: Geometrical basis of internal room proportions

	*	Sq	Nr Sq	1¼sq	Dgn	Hmln	Aurn	√3	√5
EARLY SCOTTISH									
BF									
1F		2			2		1		
Both		222		1	12	11	11	11	
Each diferent				1		1	1	1	
TRANSITIONAL									
BF									
1F					1111				
Both	11111		112	11	11	11	1	11	1
Each diferent						1			
POST-REFORMATION									
BF									
1F									
Both	111	113	22333		2		1	1	
Each different							1		

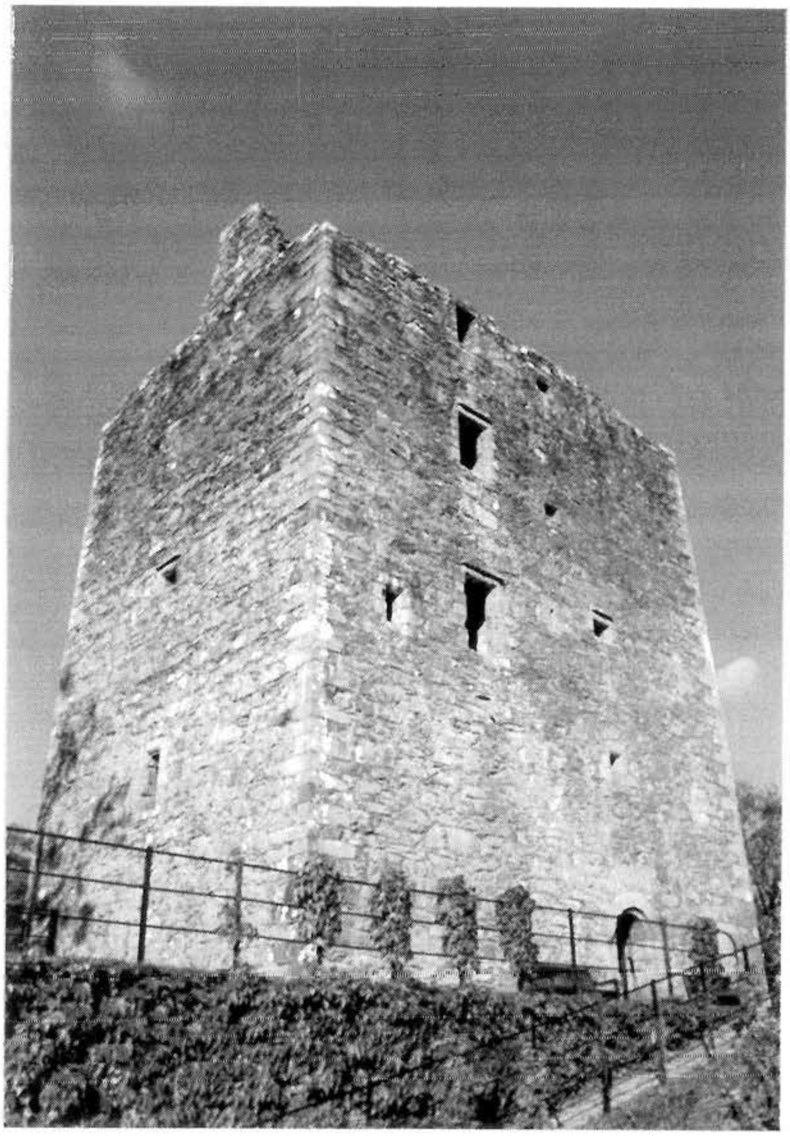
KEY	BF	basement floor	
	1F	first floor (and usally above also)	
	*	no apparent geometry	
	Sq	square	1: 1
		if "2" shown, then proportions are a double square 1: 2; if "3", then triple square 1: 3.	
	Nr Sq	near square	1: 1.05-1.1
		if "2" or "3" then as for multiple squares above	
	1¼sq	1¼ squares	1: 1.25
	Dgn	diagon	1: 1.4142
		if "2" then proportions are a double diagon 1: 1.828	
	Hmln	hemiolion	1: 1.5
	Aurn	auron	1:1.618
	√3	√3 rectangle	1: 1.732
	2 Sq	double square	1: 2
	√5	√5 rectangle	1: 2.236

In the early period there is an obvious preference for square derivatives achieved by geometric manipulation and this trend continues in the transitional period. However, there are also an increasing number of towers where identification of geometric figures becomes difficult: five where nothing seems identifiable, four where combinations of 'near-squares' are a possibility. The post-Reformation tower is a contrasting nightmare for analysis with only a few precise square derivatives, and a majority turn out to be combinations of squares, mostly near squares and other figures. No mean level of educated guesswork has had to be used in unravelling some of these plans. By the post-reformation period, it appears from these examples that the use of geometry in semi-vernacular building was becoming perfunctory, if not consummately careless. It will be recalled that a similar situation was noticed in church building.

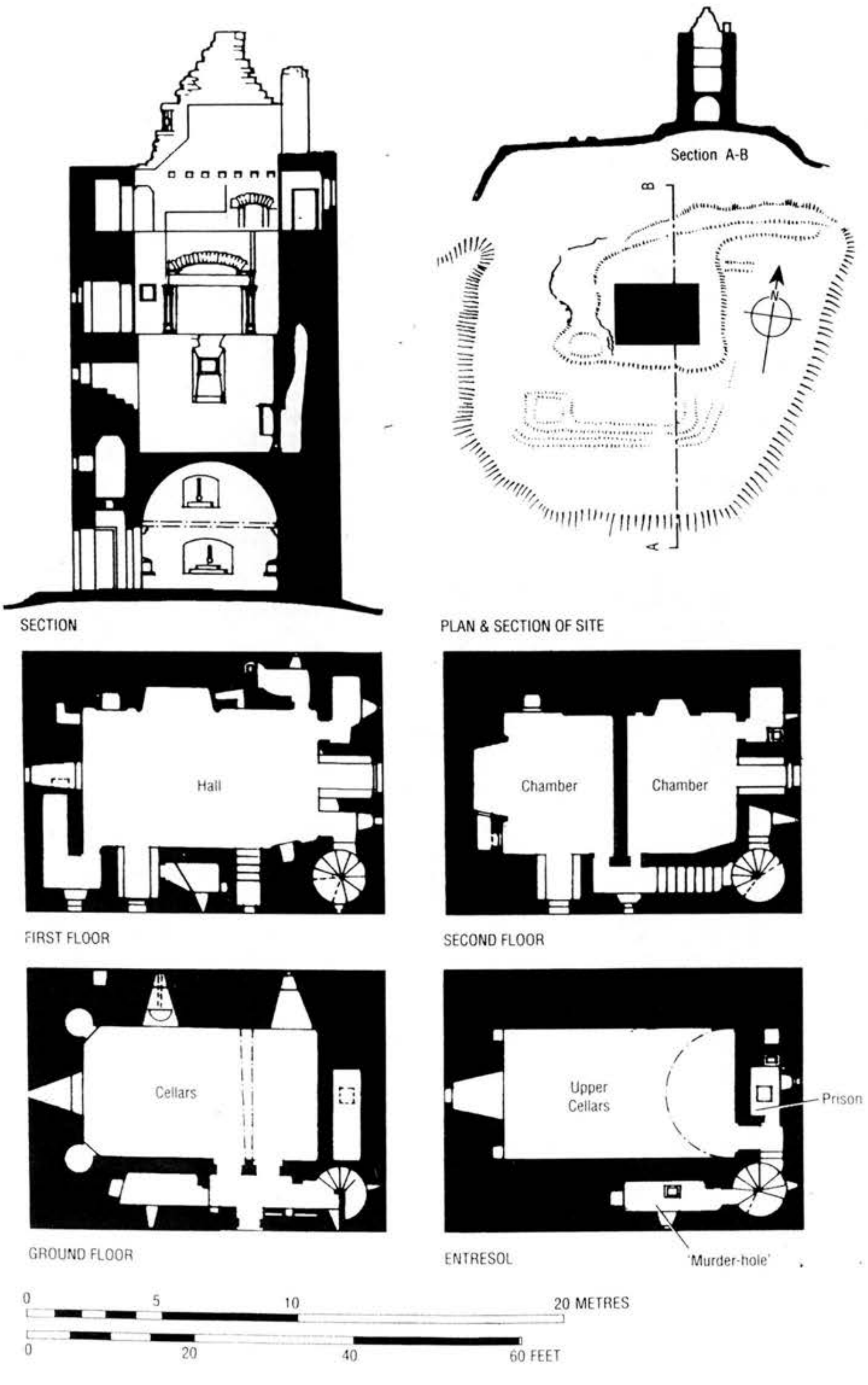
Finally it is evident that only in the early period was there some use of two different geometric figures on each of the ground and first floor, obviously because of the greater differential in wall thickness between those levels.

With some tower houses there is a fairly intractable problem with attempting to decipher what geometric figure forms the basis for their plan design. The difficulty arises when one wall of the structure is deliberately thicker than the others in order to accommodate within its thickness various spaces for what might be described as 'services': chimney flues, stairs, garderobe closets and aumbries - the 'service wall' which was first encountered earlier when assessing the tall accommodation tower at Crichton, and the gatehouse tower at Tantallon (cf p.77). To take the example of Cardoness Castle (figure 15.14a), both the south and east walls are service walls, the former 2.65 metres thick, the latter 2.4 metres. The others are only 2.1 metres (figure 15.14b). The internal dimensions constitute a root-3 rectangle (figure 15.14c). That appears to be satisfactory enough. However, if the internal width is altered to disregard the extra thickness of the south and east walls, a very different picture appears (figure 15.14d). The internal figure is almost exactly an auron, but for a discrepancy of about 17 centimetres. Admittedly this could invalidate any geometric solution but, nevertheless, the question that arises in cases such as this is whether the actual proportions of the *internal* space are 'as designed' by the use of some geometric figure, or whether they have been encroached upon and altered by the service wall. If the former, then the service wall may be deemed rather to have encroached *outside* the basic overall footprint of the tower house. To make matters more complicated at Cardoness the exterior dimensions do not, as they stand, form any recognisable square derivative. If, however, they were altered to omit the extra thickness of the service walls, then they would be within about 15 centimetres of a diagon (figure 15.14e). In many towers with one or more service walls it is far from obvious which was intended.

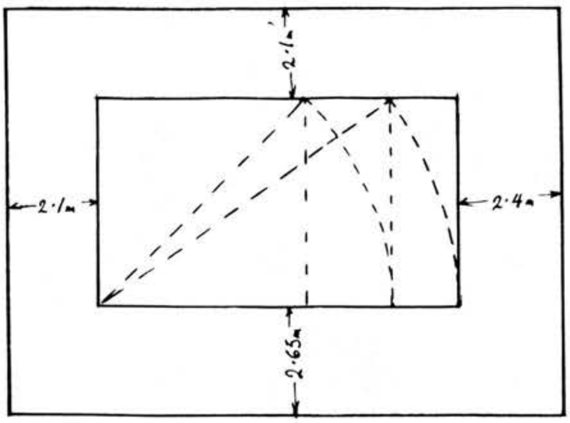
Figure 15.14 (a) CARDONESS CASTLE, Galloway, Mid 15th Century



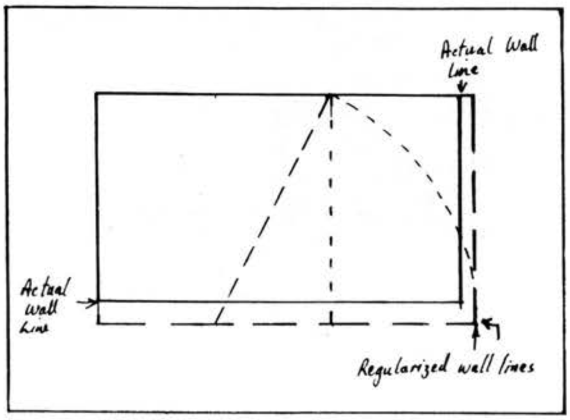
(b) Plans of the tower house showing details of the 'services' within the wall thickness
(Historic Scotland guide book)



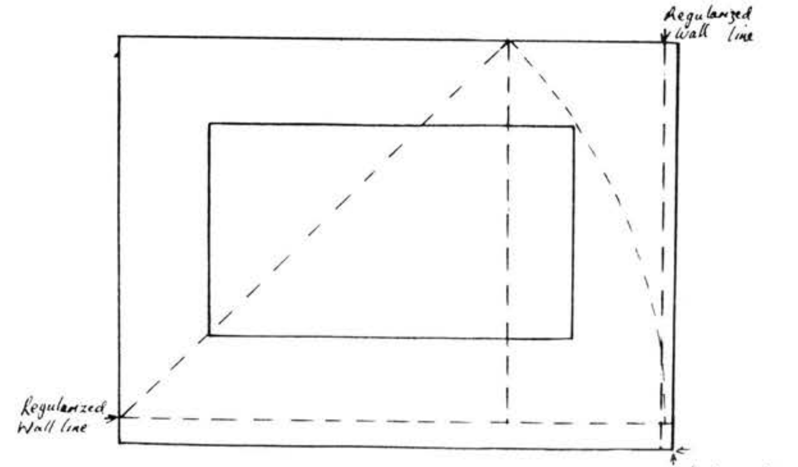
(c) Schematic plan showing the internal room space as a root-3 rectangle



(d) Schematic plan showing conjectural reordering, with south and east 'service walls' reduced to same thickness as the others from the *inside*, and resultant near auron internal proportions



(e) Schematic plan showing conjectural reordering, with 'service walls' reduced, this time from the *outside* , and the resultant near diagon external proportions



So much for service walls. What about the definition of ordinary wall thickness? Could this be achieved similarly by geometric manipulation? It has been illustrated that indeed the structure as well as the internal space of some examples of other building types had been derived from quadrature. However, looking at some of the early, thick-walled tower houses, it can only be wondered how this could be so. The previous chapter on vaulted domestic ranges was concluded with a finding of wall thickness determination based on the rotation of an entire bay in a few ribbed groin-vaulted undercrofts. This in itself was not so surprising as the fact that the bays were not square. Apart from an apparently similar method used in the sacristy of Seton Collegiate Church, all other geometric manipulations discovered so far had involved regular and perfect forms, including exact squares. Could similar aberrations be found elsewhere, particularly in the tower houses currently under scrutiny?

Figure 15.15 shows the results of tests carried out on the plans of the tower houses surveyed, to ascertain what, if any, instances of constructive geometry appear to have been used to define wall thickness. Of course a problem has arisen in this exercise due to the occasional differing internal proportions, and also therefore wall thicknesses, between ground and first floor. To this can be added the problem of whether any manipulation should be based on the actual internal proportions, or a regularized internal space which ignores any aberrations such as service walls. Without wishing to be seen contriving solutions where they do not exist, I have used whichever internal figure appears to *convincingly* present a square derivative, and which has been used to derive wall thickness.

The results are highly instructive. In the early period, the thickness of the long side-wall of roughly half of the towers was derived from the rotation of the *entire rectangle* of the main internal room space, as had been the case in some ribbed groin vaulted undercrofts and the Seton Sacristy. For a similar number of towers, the wall thickness was achieved by taking the 'core square' from which the internal figure was derived, and from this square creating a diagon. It was the rotation of this '*core diagon*' that was then used to define wall thickness. In a minority of cases could no convincing or precise solution be found.

At the other end of the chronological spectrum there are absolutely no examples of the rotation of either the entire internal rectangle, or of the 'core diagon'. That entire approach has been replaced by an almost universal practice of rotation of the 'core square'. This implies a very neat and tidy explanation which is in fact very far from the case: In this later period inaccuracy abounded and the 'near-square' proliferated, resulting in wall thicknesses which all appear to be roughly the same, but are nearly all, significantly, slightly different.

Figure 15.15 TOWER HOUSES
Determination of wall thickness by quadrature

	EARLY SCOTTISH c1370 - 1480	TRANSITIONAL 1480 - 1560	POST-REFORMATION 1560 -
QUADRATURE USED ON BASEMENT FLOOR *ONLY*			
Internal Rectangle	1	1	
Core Diagon	1		
Core Square			1
Core fig + c20cms (SW)			
QUADRATURE USED ON FIRST FLOOR *ONLY*			
Internal Rectangle	11	111	
Core Diagon	11		
Core Square		111	11111111
Core fig +c20cms (SW)	1	11	111
QUADRATURE USED ON *BOTH* BASEMENT *AND* FIRST FLOOR			
Internal Rectangle	11111	11	
Core Diagon	1111	1	
Core Square		1	11
Core fig +c20cms (SW)		1	
No geometric solution found:	11	11111111111	1

There are a number of exceptions to this practice and they are principally to be found in the south-west of Scotland where what appears to constitute an entirely separate 'school' of building may have existed. In this area, to the thickness defined by the rotation of the core square was added a further 6-9 inches - generally around 20 centimetres. The reasons for this are not clear. Further research is needed, but it seems to have been a method used in that region right through the entire period under review.

So the two extremes of the timespan under review, together with one regional variation are easily accounted for. What happened in between? What is meant by ‘transitional’? This is something of a problem. A few towers follow the earlier tradition of rotation of the entire *internal rectangle*. Some others anticipate the later idea of just rotating the *core square*. Actually the chronological division between these two falls quite distinctly around the first decade of the sixteenth century. That must be qualified to the extent that the precise dating of many towers is impossible to within greater accuracy than about twenty years. Notwithstanding this, the transitional period throws up what appears to be an overwhelming sense of indecision on the part of masons and architects. We have already seen how the question of security or fortification was causing some headaches in view of the proliferation of firearms. It was also noted earlier that the choice of the internal proportions was becoming less reliant in this period on certain square derivatives and now sometimes based on mere ‘near-squares’, if identifiable at all. Coincidentally there are some examples where the *external* dimensions appear to constitute some geometric derivative of the square. If that was indeed the case, this may indicate a time of experiment from around the end of the fifteenth century, and uncertainty as to the way ahead. Further evidence of this can be seen in the indecision as to how to cope with an ever-increasing demand for convenience and services: two entirely different approaches to the problem are perhaps epitomised by, on the one hand Comlongon, where massively thick walls incorporated hollowed out spaces for chambers, garderobes, aumbries, flues and stairs: in effect *all* the walls had become service walls. On the other hand, Affleck illustrates the way forward eventually adopted, with thinner walls, the services being permitted to protrude and be expressed on the building’s exterior, at first only the stairs receiving this treatment. The methodological gulf between these different solutions could be seen as more visibly symptomatic of something of a crisis in the thinking of the building establishment at that time.

For whatever reasons, by around 1500 there was a perception that the rotation of the entire internal rectangle, or indeed of the ‘core diagon’, was producing a wall thickness that was greater than necessary. The lack of high vaults in transitional times obviated the requirement for such thick walls and, at the same time, rendered obsolete the geometric means by which their abutment was ‘calculated’. Now the concept of rotating the core square was certainly known and in common usage at this time in other building types, but it would have resulted in walls that were obviously deemed to be too thin at that time. Quite how the architects of transitional tower houses 'calculated' wall thickness remains a mystery, at least in geometrical terms. In about ten cases of the survey sample the solution lies somewhere between the result of rotating on the one hand the whole internal rectangle and, on the other, the core square. Suddenly it seems, the architects of this period seem bereft of method, of a 'rational' basis for their craft. There was simply a tendency to build walls thinner than previously, with a marked preference for dimensions of about 5 or 6 feet. Perhaps in the absence of an appropriate geometric method, architects were simply willing to settle for a round 'modular' dimension. This cannot be ruled out and, in a sense, these towers might possibly be compared with church towers of the fifteenth and sixteenth centuries. It will be recalled that the wall thickness of those structures seemed so difficult to justify in geometric terms, but which clustered suggestively round 1.1 - 1.5 metres. Perhaps on the other hand there was a tendency to opt for some diagonal coefficient of measure such as that of Rondelet, or even Dérand's vector.

15.11 CONCLUSION

To briefly summarize, it would appear that in the early period, most if not all tower houses were regarded as fortified. Ground plans were almost invariably created by means of constructive geometry - in particular derivatives of the square - using the required internal area as a starting point. But then, what is it that appears to be the *principal* determinant of wall thickness?

The evidence seems to point in the early period towards the use of quadrature applied to the building plan by one of two principal methods, rotation of the of the entire internal rectangle or of the core diagon. For early vaulted structures particularly this resulted in a roughly consistent span ratio: commonly 1: 2.3 - 2.8. They were possibly aiming at 1: 2.5, or perhaps expressed as 2: 5, which is obviously easy to remember, or a convenient basis from which to work. It is perhaps interesting to compare this with the span ratios of vaulted churches if their *entire* abutment, wall thickness and total buttress projection, is taken into account. The majority of these fall into the range 1: 1.7 to 1: 2.6. Against this should be set the figures for vaulted churches which were unbuttressed, in many cases lacking any significant fenestration. The span ratios for this group fell in the range 1: 3 to 1: 5, which straddles the 1: 4 which Rodrigo Gil tells us was customary at that time in church building for approximate total abutment. This also compares with Palladio's recommendation for bridge design of a pier to span ratio of between 1: 4 and 1: 6. All this of course also conforms closer to the ratio resultant from the application of Dérand's vector. The difference between the span ratios for tower houses and churches is simply due to the requirement for the domestic structures to be fortified. Combining the client's accommodation and security requirements, the art of quadrature and the constraints of span ratio cannot have been an exact science! But perhaps the contemporary perception was just this: that there was no requirement for an *exact* science. Perhaps there was a 'rule-of-thumb', and it was an elastic rule, that any ratio around 1: 2.5 would do, and a geometric method was chosen which produced the result nearest to that figure, at the same time satisfying the client's security requirement. The span ratio was paramount for structures with an upper vault, but it was deemed appropriate, even essential, to achieve it using some geometric manipulation.

As regards towers with vaults only at basement level, these compare with the span ratios of the fortified side of vaulted basement floors of the two storey courtyard ranges of similar period assessed in chapters 8 and 14. The situation is summarized in figure 15.16.

Figure 15.16 EARLY TOWER HOUSES
Span ratio compared with vaulted fortified courtyard ranges

SPAN RATIO 1:	COURTYARD RANGES	TOWER HOUSES EARLY SCOTTISH	
2		1	V
2.1			
2.2			
2.3			V V
2.4			V
2.5		1	V V
2.6	1	1	V
2.7		1	V V
2.8			V
2.9		1	
3			
3.1	1	1	
3.2	1		
3.3		1	
3.4	1		
3.5		1	
3.6		1	
3.7			
3.8			
3.9	1		

KEY: 1 Courtyard Range or Tower house ***without*** upper storey vault
_ _V Tower house ***with*** upper storey vault

With the falling from favour of upper vaults, and changes in approach and priorities in security, this method became obsolete, producing walls that were too thick, and probably uneconomical for the times. Indeed the entire geometric basis for creation of the internal ground plan proportions began to be called into question, resulting in some cases in quadrature being used instead for the *external* plan, in some others not being used at all. In the post-reformation phase the nature of quadrature changes: again in some structures there is no evidence of its use at all. After all, there had always existed a rough norm of 3 or 4 feet for an unfortified wall. In others, it is used inconsistently, even perhaps unprofessionally, with 'near squares' and combinations of squares or near squares being used in the internal proportions, the wall thickness being defined by rotation of these often less accurate figures, perhaps to derive what might have been regarded as a *minimum* safe thickness for high domestic walls.

16 CONCLUSIONS

16.1 INTRODUCTION

The research, it is admitted, has few certainties to offer. The results are a proliferation of possibilities and probabilities. The fact remains that, without documentary evidence such as building specifications and contracts, very little can be proved beyond all doubt. The buildings themselves in this case have been the documents, and in the twenty-first century we are only just beginning to learn the language in which they were written. The number of questions arising has possibly only increased but the surface has at least been scratched, and a number of reasonably safe conclusions reached. It only remains to draw together some of the strands from the studies of each building type.

16.2 THE ROLE OF GEOMETRY

From the study of twelfth century churches in particular, a naive and almost blind faith in geometric solutions is evident in the Norman era. The use of quadrature - the rotating diagonal of the choir/chancel square, long before this motif appeared in Villard's sketch book, appears to have been the basis of much, if not most early structural design. That, together with nominal 3 inch increments seem to have been common practice. In some cases even the structure of the adjoining church tower was found to be simplistically related to that of the choir in these ways. The Gothic era was a time of experiment: while French cathedral builders were striving for ever greater height and, no doubt, the means to support it, those involved in smaller scale work were also preoccupied with the development of new geometric formulae for the relationship of structure to space and indeed the sizing of structure itself. It was probably these experiments, developments in vaulting, together no doubt with the requirement for a more rational or scientific approach generally, that resulted in a much greater degree of geometric precision. This was also possibly aided by the development of architectural draughtsmanship. Also, right from early in this period there is evidence to suggest that some device for assessing the stability of barrel vaults such as Dérand's vector may have begun to be used, and this may be more than mere coincidence. We will return to this subject later.

The reasons for the obvious desire for a consciously geometric solution to spatial and structural problems are beyond the scope of this research. They must lie variously in a belief that this science was the basis for all science and creation, as mentioned by Villard, and also perhaps developed as a means of somehow systemizing the design process, though at a very individualised level.

After the Wars of Independence, the role of geometry seems to have been exploited and broadened with increasing use both in church barrel vault design and in the increasingly popular tower house. Ever greater flexibility had to be sought within 'the science' to accommodate both church and domestic vault construction, also the needs of security and irregularities such as the service wall in domestic work. No doubt the difficulties of adapting the geometric methodology to changing requirements from the late fifteenth century, together with the increasing pressures of economy and larger volume production were all instrumental, together with other factors, in eroding the earlier use and standards of geometry to a level that was increasingly inconsistent, perfunctory, imprecise, or abandoned altogether. By the late sixteenth century, whilst lip service may still have been paid to the science, the return of the near-square to the building site seems to have been symptomatic of changing priorities in the building design process, possibly even within the building trades generally. It was after all in the late sixteenth century that William Schaw saw fit to pass his famous statutes reforming the craft and its members. Though the reforms relate only to conventions of working practices, contract and so on, the fact that these herald a changing culture may be more than a coincidence. The use of geometry as the working mason's tool of the trade was dying out, to be replaced within a few generations by a new and more intellectual perception of the same art as the embodiment of universal order and harmony.

16.3 RULES OF THUMB

Whatever the interest and even excitement of finding the geometry underlying the overall design of a church or tower house, the question remains, to what extent was the geometry really the basis of the structural design? In the Norman era this indeed seems to have been the case. The research has shown that whilst geometric configurations may abound in both plan and section thereafter, they were invariably simply a means to an end. The ends themselves undoubtedly consisted of standards, canons, norms or rules of thumb, whatever one likes to call them, that constituted the perceived wisdom of the day on subjects such as fortification, vault abutment, wall stiffness or strength. They were measured respectively in terms of feet or ells for fortification, for vault abutment span ratio was of some significance as seems the case for slenderness ratio for free-standing walls from at least the early sixteenth century. Whilst geometric solutions are obviously non-applicable to the latter, it has been shown that a variety of different structural solutions for various levels of fortification and vault abutment were devised on geometric bases. When looking for definitive rules of thumb that are specific and precise, it is little surprise that none are found, but only areas of commonality within a range, for the variety of dimensions and ratios found simply reflects the various effects of the different geometric means used. These were, of course, limited, and architects had to choose the geometric figure which provided the dimension or ratio that was nearest to the perceived wisdom of the times. Perhaps the centrally-planned structures, both fortified and ecclesiastical, best illustrated this. If, as in the case of many church towers, there was no geometric method that provided what was perceived as a structurally rational solution, then none was used.

The one subject that is still left with so many unanswered questions, only generalities of the vaguest nature, is slenderness ratio. Of some interest perhaps in the free-standing wall group from the sixteenth century, its validity as a standard of structural design in other building types is still open to question. The test 'duos' of unvaulted churches suggested that here it was a more influential factor in structural design than span ratio. Likewise in the case of church towers, the group where slenderness ratio might be expected to be crucial, particularly in view of the attention devoted to the subject by Alberti and the Stieglitz treatise, again the survey sample threw up nothing more than inexplicable variety and inconsistency. More often than not an argument for span ratio in respect of the ground floor vault was more convincing.

One point that is worth reiterating about the general rules or conventions governing particularly vaulted churches in Scotland when compared with those of continental Europe, is what appears to be a relatively conservative approach to abutment in this northern kingdom. Span ratios are generally much lower in Scotland than those found in the recommendations of, for instance, Lechler and Rodrigo Gil, except in rare cases such as St. Salvator's and the chancel of Dalkeith Church. But this, of course, is an inappropriate comparison. The heavy pointed barrel vaults of the late medieval Scottish collegiate structures are, in effect, a different structural type altogether.

16.4 DÉRAND'S VECTOR

The result that was perhaps more surprising than anything else was the regularity with which Dérand's vector appeared to be a deciding factor in the determination of vault abutment. There were no less than five areas of evidence which suggest the consistent use of this construction, or of some other which had similar effect:

(a) accommodation of the 'vector' within the wall thickness in a majority of cases;
(b) where the 'vector' is not so accommodated within the wall thickness, then one of two solutions have been applied:
  - either buttresses have been added and it is accommodated within these. Furthermore, such abutment has commonly *only* been added where the 'vector' has fallen outside the wall thickness;
  - alternatively, the wall above the proposed vault would be built up prior to vault construction to provide a counterweight, leaving a *tas de charge* in place to eventually bear the vault; this was the more usual solution for domestic property where buttresses would not be so appropriate;

(c) commonality of Dérand's ratio in different parts of the same church;
(d) structural failure of buildings not falling into these categories.

It will be recalled that the earliest building amongst the survey sample whose structure appeared to reflect the use of this design tool was the chapter house at Dryburgh, which was one of the earliest buildings to be constructed after the Abbey's foundation in 1150. That is very early gothic, but the appearance of this phenomenon may coincide with the development of gothic and the concomitant art of architectural draughtsmanship mentioned earlier. It would indeed make sense that if there was an improvement and an increase in the use of drawing at this time, then it would only be logical that new perceptions of structure might have been achieved in diagrammatic form that might not have been so obvious without. The drawing of structures in *section* that might have never been done before, might now have been opening the eyes of architects to ways of assessing and calculating the management of lateral thrusts from vaults. That these thrusts might have been envisaged in linear terms cannot be ruled out, and the concept for which there is so much evidence in the fifteenth century must have been developed or evolved sometime. Whether it was Dérand's vector or some other device with similar effect is, at this stage, immaterial.

16.5 INCIPIENT RATIONALISM IN A WORKING RELATIONSHIP?

It thus appears that, after the Norman period, although the simple constructional geometry of quadrature and triangulature was still very much in use to determine the overall form of a building, and some structural members in some cases, other means were developed from a more scientific standpoint which incorporated some element of structural rationalism. In general the architects of Scottish churches and unfortified dwellings of this period appear to have been designing with an eye and mind to structural sufficiency and, at the same time, a certain simple elegance. For fortification there were obviously certain widely-held views on what levels of wall-thickness were proportional to various levels of risk or security.

To the problems of achieving structural stability, and then a degree of elegance and/or fortification, all by geometric means if at all possible, there could be various solutions, depending on the understanding, wisdom and experience of the architect. But this has always been known, from the instructions of Lorenz Lechler to his son, from the centrally-planned temple projects of Sebastiano Serlio, and particularly from the record that survives of Rodrigo Gil's consultations with others in his profession. From all these, it is evident that the experience and practice of Scottish medieval architects had much in common with others across western Europe. What has not hitherto been so clear is, firstly, the interaction or relationship of geometry with rules of thumb; secondly the extent of diversity in uses of these rules and of the geometric solutions within a defined geographical area; thirdly the nature and extent of their development over a specific period of time. There is still much work to be done, many gaps to be filled in the ground covered so far, and many as yet unexplored fields to enter. But by attempting to "enter the mind of the designer" ways have been indicated which do provide a better understanding of the meaning and significance of that enigmatic relationship that we know about from the famous debate over Milan Cathedral "*Ars sine scientia nihil est*".

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16.6 IN ADDITION...

Whilst the unravelling of the medieval architect's methods of structural design at a general level has been the principal aim of this research, several other interesting and possibly very significant discoveries have also been made, relating both to generalized matters not part of the core research, and to individual buildings. There are also a number of areas only partly covered, all of which are now the subject of review, both to assess conclusions that can be drawn, and to outline possibilities for further research in the future where appropriate. These are mostly disparate in nature, and this section therefore necessarily constitutes something of a catalogue of loose ends.

Means or standards have grown out of this research by which architecture might perhaps be distinguished from the vernacular. It is by no means a clear distinction: in some ways the two poles are little more than shades of grey. But the clearly higher geometrical sophistication of Dalmeny Church and Dunkeld Cathedral tower, or the expressive triangulature of Corstorphine Church, to name but a few, indicate at one specific level a greater conscious application of these design principles than elsewhere. However, it has also been shown that geometry at such a level was the luxury or indulgence of a relatively few builders. It would require more specifically aimed research to assess just what proportion of the country's stock of a particular building type could be categorized as any particular level or quality of design. This project does, however, reveal some standards by which the buildings can be judged, and it does also give some approximate idea of how common the various levels of those standards might be.

As far as it has been possible to work out the basis for wall thickness design and requirement for further abutment, methods have in effect been developed by which the original intentions of architects may be assessed approximately, and this in itself could be useful as a methodology for the conjectural reconstruction of the original building design where this has been lost. For instance, realistic estimates can be made of the originally intended height of Dunblane Cathedral choir; the long-lost lay brothers choir at Culross can be almost certainly claimed to have originally had buttresses and the approximate size of these may now be estimated. The possibility can be considered of an original intention to vault Kirkcaldy Church tower; also perhaps the transept at South Queensferry. With further analysis of small Norman churches, it can be envisaged that one day even the size and wall thickness of the lost chancel of Kirkliston Church might be calculable.

Another analytical methodology seems to lie in the application of Dérand's vector. Based on the assumption of its validity, reasons have been suggested for structural problems in at least three specific buildings: Crichton Castle stables, Monymusk Church tower and South Queensferry Church tower. It can only be wondered how many more might have collapsed over the last five or six hundred years for non-conformity to this particular design method. These three in particular deserve further attention to examine more precisely how close to failure they have come, and whether there are any less obvious factors at work in their structural inadequacy. The apparently ornamental purposes only of the buttresses at Whitekirk porch are also confirmed by this method.

On a more theoretical note, there is some structural logic to Dérand's vector. It does take account of both the direction and magnitude of the vault's thrust. However, this quality could itself be tested by modern methods in order to assess its validity.

On the subject of metrology questions have been set which require vast amounts of field work: just how many different foot measurements were being used at any one time in Scotland, and indeed elsewhere. Evidence has been found that a hitherto unrecognized unit was being used as late as the seventeenth century by the King's Master Mason. Documentary sources indicate the use of personalized 'natural' feet. Measurement suggests that, in Norman times at least, other units might have been in common use. Research of this nature ideally requires some surviving building where the original specified dimensions, either written into a contract or drawn on a plan, could be compared with those found on site. Unfortunately such hardly exist in Scotland until the seventeenth century and it is really the earlier medieval centuries which require investigation. This leaves two alternatives: firstly to attempt a study in Scotland relying purely on an assumption that overall internal dimensions will be in whole feet, as was done in the analysis of unvaulted churches (Chapter 10); alternatively to carry out surveys of buildings wherever they may be found in Britain and even further afield where some written evidence of intended dimensions exists. Perhaps the latter would be most appropriate initially, the principles behind any findings then being applied to a secondary Scottish study.

Although the survey sample of each individual building type has been examined in as great a depth as resources allowed, further studies each concentrating on a single building type and involving a greater number of examples would probably reveal more than the generalised fundamentals established here. A region by region survey of tower houses and of small unvaulted churches would establish the existence and extent of any practices that were localised, or were restricted to a particular stone type. Investigation into the type and quality of wall-build may reveal much in this direction. To what extent wall strength was dependent on the mix of lime mortar is another consideration worthy of research, and whether this affected the thickness chosen.

A large-scale typological enquiry of this nature could address such eccentricities as the tendency for wall thickness to be slightly greater in domestic work of the south-west. It would be interesting to look further into the possibility of this being due to the generally greater rainfall and stronger prevailing winds than in the east of the country. There may be other such regional variations awaiting discovery, including account taken of the effects of weather on the building stone of different regions.

Attention has been drawn to the 'service wall' in mainly domestic building, a feature that has perhaps hitherto been only subconsciously recognized. Found in fourteenth century Tantallon, and possibly earlier elsewhere, the importance of this concept in the evolution of tower houses especially, of reserving one or more walls in which to site stairs, garderobes, aumbries, flues etc. as the other walls were built progressively thinner, must be emphasized. Furthermore, as individual room-spaces became generally smaller while the numbers of rooms increased during the period covered, the complex relationship between the increasing economy of the outer load-bearing walls and the proliferation of abutting internal partition walls is also worth investigation. More detailed study of both these aspects should form an integral part of any attempt at a comprehensive history of tower houses in particular, but also of domestic building in Scotland generally.

This research has necessarily been restricted to the simpler building types. The monumental complexity of the larger aisled churches has been avoided but for another project would be particularly worthwhile. It is stressed that whilst studies of individual examples in isolation such as has already been done with many of the greater churches of Europe generally is all very well, few of these have focused on the basis of *structural* design and none, as far as can be seen, have sought to assess whether there was any commonality of approach to the problem. An obvious drawback of attempting a study of this nature in Scotland is the relatively small number of examples under construction at any one time. That, however, is not insurmountable. For the period up to the Wars of Independence comparisons may be made with English work, for there were surely the same masons in many cases operating both sides of the border. Once the practices of that era had been assessed the great parish churches in Scotland of the fifteenth century might then be juxtaposed against them.

A survey of some stone multiple-arched bridges was carried out as part of this research but not included in the report for lack of space and for the simple reason that it seemed to have little to add to the conclusions reached. However, further work on this subject would be eminently worthwhile, particularly an analysis of the relationship between the height of the voussoir arch ring, the span, and the pier thickness. The results would be interesting to compare with the upper vaults of some of the earlier tower houses.

Another more detailed aspect which would undoubtedly repay investigation is a study of foundations. Whilst it is widely recognised that many medieval and later buildings in Scotland simply do not have any, this is by no means universal and further work needs to be done to find out what considerations, if any, prompted builders to take the precaution of digging before building.

Quite apart from thus ‘finishing’ this study in Scottish buildings, there is scope for extending the work to similar or comparable building types elsewhere; for instance round bastion towers of castles in England, Wales, France and beyond; church towers outside Scotland; Irish tower houses and so on. It should perhaps be recognised to what end such studies may be directed; this thesis has been deliberately restricted to Scotland as a relatively isolated test-bed so that similar structural problems in a range of building types could be compared. A comparison of, for instance, Scottish and Irish tower houses would constitute little more than just that, until the research ventured into other building types in Ireland in order to ascertain the true basis of that building tradition. In view of the widespread tendency in Ireland towards battered walls and its possible origins in a traditional dry-stone walling technique, it would not be surprising to find some very different results from Scotland.

These would all be very generalised studies, designed to widen the statistical net in a search for a *general* idea of working practice in the design of structure and to what extent this was commonplace. More focused studies are also required to ascertain more precisely how some individual structural relationships were worked out. In particular, there was found to be some logic in the relationship between wall thickness, buttress projection and window size in barrel-vaulted churches of the late medieval period (pp. 228-29), but within the scope of this thesis there were resources for no more than a general and approximate understanding of the relationship. A more detailed study taking just a few examples of this building type with an accurately measured and calculated comparative analysis may reveal much more, though care should be taken to recognise that results should be viewed in the context that medieval architects would not have used modern arithmetic calculations, but rather simple whole number ratios or geometric relationships.

Another aspect which would benefit from further examination is the expense associated with different types of building. For instance, it would be interesting to compare a sophisticated (usually church) building using thin walls, buttresses, large windows with tracery and stained glass, as against the simpler type with thicker walls and small windows. The access to skilled labour, and the comparative costs of the cutting of many individual stones for buttresses, tracery etc, and the cost of glass, compared with that of quarrying and laying larger quantities of rubble would prove to be of great value in assessing economic priorities over this period. Obviously, complete surviving structures would be needed, together with full accounts of all stages of the works, though it is conceivable that a study could be carried out using costings carried out by a contemporary masons' firm and modifying to accord with known medieval conditions and values.

More detailed research is required also on aspects of vault construction, particularly a phenomenon not mentioned until now, the gradation of voussoirs from thick at the springing to much thinner by the apex, as seen for instance at Seton (Fig. 12.29). What is not known at present (because no suitable partly fallen vaults of this type have been found) is whether thickness is also representative of depth. So the question must be asked, is this type of vault designed in such a way that the upper sections are lighter than the lower? The answer to this, if it can be found, may have considerable ramifications for both the vaults as finished works and also for the construction process itself, and this points to another large of area of research possibilities, as will become evident.

Where either little explanation had previously been offered for the presence of ribs on ecclesiastical barrel vaults, or they had been passed off as merely decorative, the evidence has now been presented for their structural function, assuming the validity of Dérand's vector in the vault design. Previous writers have occasionally credited some ribs with a strengthening function, but even this has been misinterpreted. When analysed by Dérand's vector, the effect of the rib has been not so much to thicken the vault, but more simply to move the position of the vector towards the inside of the church by the same distance as the thickness of the rib, which has been just enough to bring its lower end point within the wall thickness. Any further investigation into the structure of ribbed *groin* vaults (as distinct from ribbed *barrel* vaults), usually found in major parish, abbey and cathedral churches, should take this into consideration.

A new interpretation has been suggested for the *tas-de-charge*. Where this feature was once only noted and described in great cathedrals and aisled churches, but never satisfactorily explained, analysis of its function in possibly enabling economies in wall structure during the actual *process* of construction may substantially develop our understanding of major gothic structure throughout western Europe.

Perhaps with more potential for further enquiry than any other lead is the whole question of the medieval perception of walls, colonnades and abutment. Initially, it will be recalled, it appeared that the Norman architect may have actually regarded the wall thickness as the combined measurement of the wall *plus* the buttress projection, rather than just the former on its own. This may be of great significance, and particularly in connection with Alberti's utterance that a colonnade is really just a vestigial wall that has been pierced at regular intervals. Has he given us a clue about the terms in which at least some medieval architects regarded structure? Did the Norman builders, and indeed the gothic builders after them, regard the *entire* abutment as, in effect, the wall thickness, and the spaces in between the buttresses as mere infill between what they understood to have been in archaic terms a colonnade? After all, even Rodrigo Gil had written in terms of the "buttress" meaning that element *plus* the wall thickness. This sets up a conundrum that is pregnant with possibilities. The work is only just beginning and there is obviously much still to be done. Again, are we perhaps only just beginning to understand the language of medieval architecture? How much more is there to the *scientia* than mere *geometria*?

In the light of these three points, concerning ribs, the *tas-de-charge* and the concept of wall / abutment, further large-scale studies on vaulting would seem to be called for. There would appear to be several ways forward in this: firstly, testing on large, but not full-scale workshop models using cut stone and lime mortar (or possibly computer-generated models) would establish some parameters and perhaps a theoretical basis. Secondly, any such theoretical basis would require to be assessed against what could be found in built examples, and the more of these used, the better, again with the object of finding out what was the *general* practice of architects. It is felt that the former (workshop model construction) would be of particular value, especially since it is possible to envisage that some processes of construction may be interdependent with those of structural design, particularly in the building of vaults. Studies in the historical processes of construction are still at a very early stage. Documentation of the building process survives in decreasing quantities with age and because it was effected very much at artisan level, few if any records exist of the duration of each stage and how it was carried out. Some aspects can only be surmised from building accounts and graphic images where they exist. Occasionally a contract will state an overall deadline for completion from which some deductions may be made. Where all these sources fall short answers may indeed be found in the construction of models in the workshop.

This two-fold research process will be variously expensive, potentially dangerous, hugely time-consuming and labour intensive. However, once the parameters for the groundwork have been set out and the objectives identified, there is the potential for savings by some carefully constructed technological aids. Ideally further research should be conducted on a team basis both in the workshop, and in the gathering of data from built examples. The latter will really need to be carried out in an international dimension, for the art undoubtedly then, as now, transcended international boundaries.

APPENDIX I

SOME STANDARDS FOR STRUCTURAL RELATIONSHIPS FROM DOCUMENTARY SOURCES

INTRODUCTION

The following is not a comprehensive list of every recorded theory or judgement on aspects of medieval structural design. It is merely a selection of those which, with the limited time available were most readily accessible. It is understood that several possibly useful remarks on the subject may exist in the lodge book of Wolfgang Rixner (1467-68) but unfortunately access to this source could not be obtained. However, the purpose of this appendix is not to provide a full list for its own sake, interesting and even desirable though that may be. It is rather to pick out several models with which to assist analysis of the Scottish survey sample. The question that is emphatically *not* being asked, is whether Scottish architects used the same methods as Francesco di Giorgio, or Alberti, or Rondelet, or anyone else. The enquiry centres objectively on what methods were used in Scotland, and these other architects and theorists are simply called on for models or tools to assist in the process of comparison and assessment.

1 WALL THICKNESS : HEIGHT
in
UNBUTTRESSED, UNVAULTED STRUCTURES

1.1 FOR FREE-STANDING WALLS

1.1.1 *Act of the Parliament of Scotland 1535*

(Acts of the Parliament of Scotland Vol. II Record Commission 1831 p346)
That every £100 landholder should
"big ane sufficient barmkyn...of stane and lyme contenand thre score futis of the square ane Eln thick and vj Elnys heicht"

Slenderness Ratio: **1 : 6**

1.1.2 *Jean Rondelet*

Traité Théorique et Pratique de L'Art de Bâtir Paris 1847

Alternative Slenderness Ratios: **1 : 8**
1 : 10
1 : 12

...depending on degree of stability required.

1.2 FOR BRICK WALLS IN GENERAL

Rowland J. Mainstone: "Developments In Structural Form"

(First published 1975, 1983: 170)

"Quite recently it was still the almost universal practice to give a wall a thickness that was not less than, say, 1/16th of its height."

Slenderness Ratio **1 : 16**

1.3 FOR TOWN HOUSE PARTY WALLS

1.3.1 *London Assize 1189*

(quoted in IV Knowles and Pitt : 1972, 6)

"... for the allaying of the contentions that at times arise between neighbours in the city touching boundaries made, or to be made, between their lands ...". For such allaying, each neighbour was required "to give one foot and a half of his land on which they shall build at their joint costs a stone wall three feet in thickness and sixteen feet in height." (quoted in Knowles and Pitt, 1972: 6).

We have here a notion that for a two-storey house, a stone party wall of three feet thick was what had by then become regarded as necessary and sufficient to provide structural stability, with some aumbries and presumably also fireplaces recessed therein, and in which joists and bressumers could be set. Presumably fire proofing at roof level was, at that time, not considered a priority since at sixteen feet, this party wall would probably only reach to the ceiling of the first floor.

Slenderness Ratio: **1 : 5.3**

1.3.2 *Edinburgh Improvement Act 1698*

Thickness of stone party walls, by implication whether rubble or ashlar:

First storey :	3'
Second storey:	2' 9"
Third Storey	2' 6"
Fourth Storey	2' 3"
Fifth Storey	2'

"all middle or transing walls wherein there is no chimneys shall be at least ten inches thick."

Assuming that each storey averages 9' in height, giving a total height of 45', a mean thickness of 2' 6" results in a mean slenderness ratio of : **1 : 18**

It has to be remembered that the quoted thickness of side or party walls was for buildings that were probably cheek-by-jowl with many others, all in a conglomeration that to an extent shared some mutual support one with another.

1.3.3 *Andrea Palladio*

(X Book I. Ch.XI, 11)

Palladio does not provide any prescription for wall thickness at all, let alone slenderness ratio but, in common with the above, he does specify "that walls should diminish in proportion as they rise". Foundations should be double the thickness of the wall above ground; thereafter thickness should diminish at the rate of a half brick thickness per storey, "but with discretion, that the upper part be not too thin."

1.4 FOR TOWERS

1.4.1 *Leon Battista Alberti*

(X Book VIII Ch.V p170-171)

For 40 cubits	(c. 77 feet) height:	not less than 4' thickness
50	(c. 96 feet)	5'
60	(115 feet)	6'

Assuming Alberti was using the Florentine Bracchio or cubits of about 23" Imperial, this gives a slenderness ratio of : **1 : 19.17**

1.4.2 *The Stieglitz Treatise*

(quoted in X Gwilt: 1889, 1010) This document is referred to in Gwilt as simply *Treatise on Architecture* , and is recorded as having been in the possession of C. L. Stieglitz who mentions it in his *Altdeutscher Baukunst* published in Leipzig 1820. Whilst anonymous, it is evident from the content mentioned in Gwilt that it is probably derived from Lorenz Lechler's instructions to his son Moritz, of 1516. Whether or not this is the case is actually of little consequence for the present research, and so any citations from it will simply be referred to as "The Stieglitz Treatise".

For every 100 feet of height, 5 feet in thickness: **1 : 20**

2 WALL THICKNESS : SPAN : HEIGHT

2.1 UNBUTTRESSED UNVAULTED SINGLE CELL STRUCTURE

2.1.1 *Jean Rondelet*

Rondelet (X Paris 1847) presumed quite logically that the thickness of a wall should depend not only on its height, but also on its length between adjoining walls which would lend it some additional stability. The greater length between such adjoining walls, the greater need for additional thickness. Thus in figure 1, let the rectangle ABCD represent the *elevation* of the long walls EF and GH in figure 2 which represents the *plan* of a simple rectangular building. The square ABC'D' likewise represents the elevations of the shorter end walls EG and FH.

The height AB should be divided into eight parts for great stability, nine or (as shown here) ten parts for mean stability; into eleven or twelve parts where less stability is required. Diagonals are drawn from A to D and D' . At the points at *d* and *d'* where these intersect with the tenth part of the wall height perpendiculars are dropped, giving the appropriate thickness for each of the long and short walls of the building.

Figure 1

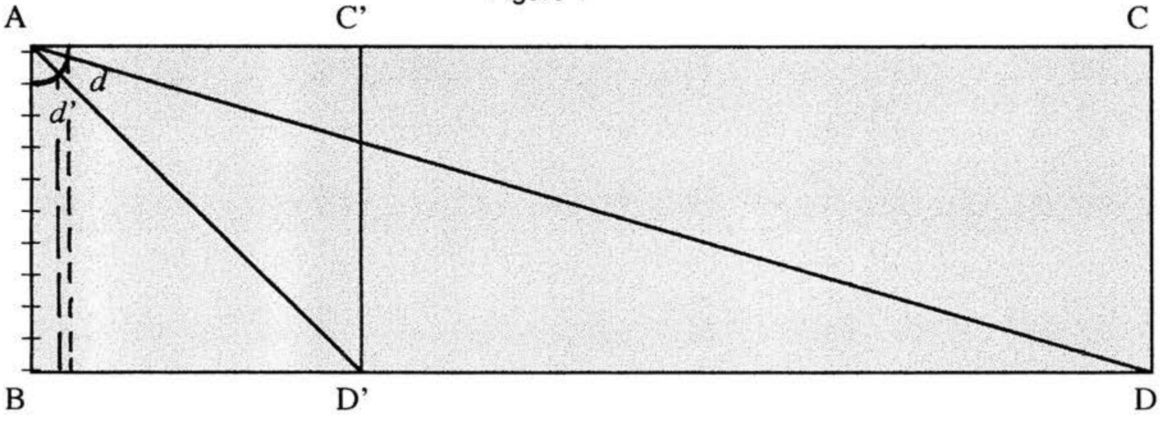


Figure 2

In practice, of course, the thickness will increase with the length in diminishing magnitude, and beyond some unspecified point, depending on the size and height of the structure, a judgement would no doubt have to be made on how much extra thickness might be needed, perhaps based on Rondelet's formula for free-standing walls described in section (1) (a) above.

This method also results in the end and side walls being of different thicknesses, and this can occasionally be found in practice.

2.1.2 *Ordinary Houses - Rondelet*

For ordinary houses Rondelet devised a variation on this principle. The method used for structures one room deep only will be described since structures with spine walls and therefore two rooms deep did not occur in Scotland until the early seventeenth century, and then rarely.

Rondelet describes the method using a hypothetical house, one room deep which measures 24' across, and 36' high to the wall-head. He adds to the span of 24' half the height, 18', totalling 42'. He then takes $\frac{1}{24}$ part of that, 21", for the least thickness of each of the external walls. For "mean stability" one inch extra should be added, for an even stronger wall, add two inches.

In this case the slenderness ratio based on 21" works out at : **<u>1 : 20.57</u>**
based on 23": **<u>1 : 18.78</u>**

At first sight this method seems to produce similar proportional relationships to those of the towers in Alberti's *De Re Aedificatoria* and the Stieglitz Treatise, and it possibly even compares with the stipulations of the Edinburgh Act of 1698. However, testing out the method against the latter produces a rather different story: if the building height is taken as 45 feet, and the width of the structure 24 feet, the result will be as follows:

$\left(20+\frac{45}{2}\right)\div 20=2.125$

or approximately 1' 9" **<u>1 : 25.4</u>**

for extra strength 1' 11" **<u>1 : 23.5</u>**

These wall thicknesses are, of course, somewhat thinner than those of the Edinburgh example. The method and its basis is a wholly different concept from that of the

Edinburgh Act and is also fundamentally different from the straightforward slenderness ratio principle at the basis of the Alberti and Stieglitz methods. In Rondelet's system the slenderness ratio increases with the wall height and the implications of this become more apparent if we take one further, slightly more extreme example:

A tower with walls 100 feet high and with a roof span of 24 feet:

$(24 + \frac{100}{2}) \div 24 = 3.08$

or	3' 1"	**<u>1 : 32.5</u>**
for extra strength	3' 3"	**<u>1 : 30.8</u>**

It quickly becomes evident why Rondelet restricted this method to domestic property of probably no more than three storeys.

2.1.3 *Structures Stiffened by Trussed Roofs - Rondelet*

Rondelet also prescribes a related system for determination of wall thickness where the walls are, in effect, braced or stiffened by the timbers of the roof, assuming the use of a simple triangulated truss:

NOT TO SCALE

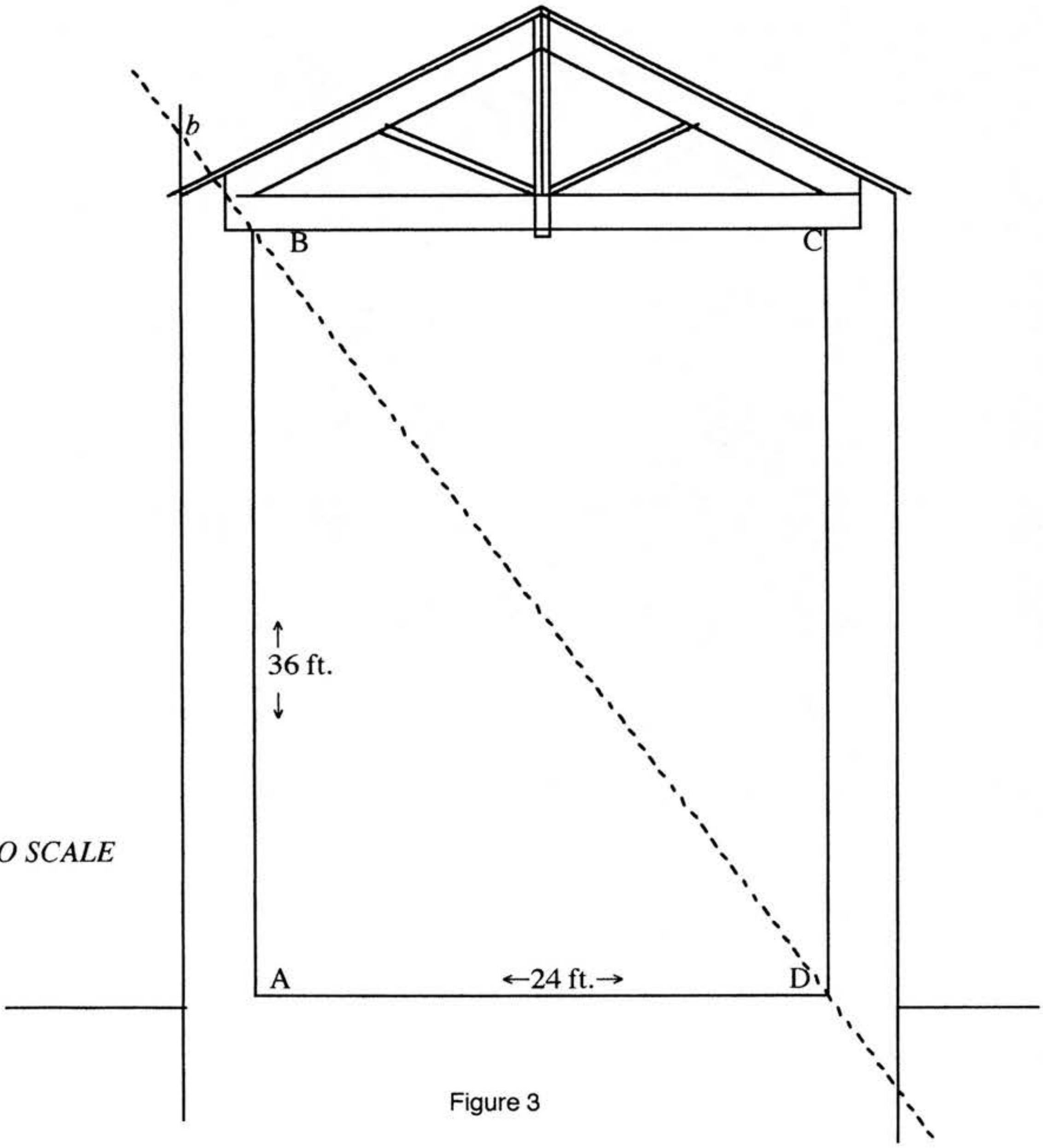


Figure 3

At its simplest, this method can be worked using geometrical means alone, bringing it within the capability of a jobbing mason. It starts from the internal dimensions of the building, in particular, span AD and height AB and, when these are known, a working approximation can be achieved without further calculation: a diagonal is drawn from one lower corner D to the opposite wallhead B, and then extended beyond that by a twelfth part of the internal height, to b . This point is then taken to define the external wall surface and this may then be drawn in on both sides.

The method can also be worked by calculation: the diagonal BD can be found thus: $BD = \sqrt{\overline{AB}^2 + \overline{AD}^2}$
If the span AD is 24 feet and height AB 36 feet, then BD will be: 43 feet.
If Bb is a twelfth part of AB, 3 feet, then the wall thickness will be found by

$$\frac{AD \times Bb}{BD}$$

Thus the wall thickness will be $\frac{24 \times 3}{43} = 1.674$ feet (c.1' 8")

The slenderness ratio achieved by this method is thus **<u>1 : 21.5</u>**

Again this appears to compare with the ratios recommended by Alberti and the Stieglitz Treatise for the walls of towers which, of course were stiffened by each other in relatively close proximity. However, if the wall height of 45 feet is substituted, we end up with a wall thickness of 1' 9" and a daring slenderness ratio of **<u>1 : 25.57</u>**

With this system, again, the slenderness ratio increases with height, which at some stage must be a recipe for disaster, no matter how much the structure is stiffened by the roof assembly.

3 VAULTED STRUCTURE PLANS
based on
CONSTRUCTIVE GEOMETRY

3.1 FRANCESCO DI GIORGIO

(II Betts: 1993, 5-25)

Francesco is an architect of immense interest for this research since he was heavily preoccupied with the problem of abutment of large barrel vaulted structures in the fifteenth century. Betts has interpreted a plan in his second treatise (Magliabecchianus II.I.141, fol.41v. of c.1490-92) (Figure 5) which shows his possibly unique method of working up by quadrature a module AB for the whole building, but specifically to define its wall thickness.

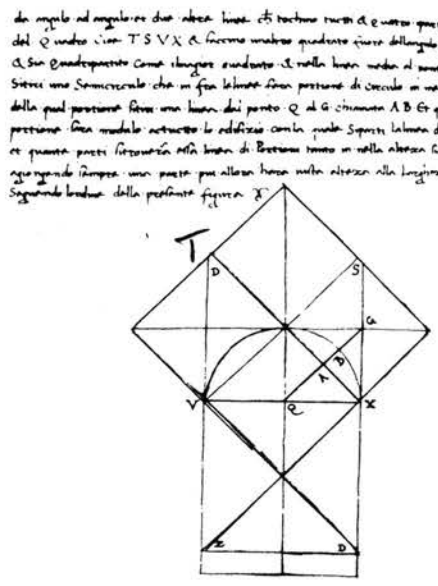


Figure 5 (Betts)

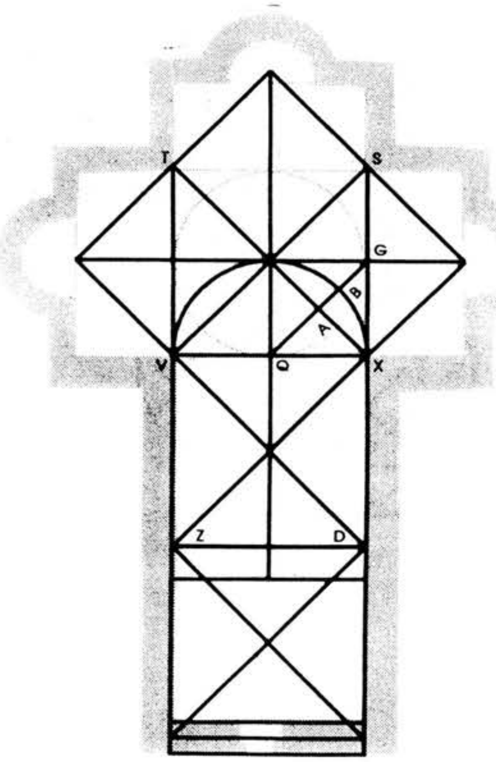


Figure 6 (Betts)

The method is designed to relate wall thickness directly to the span of the barrel-vaulted nave roof. When the diagram is superimposed over a plan of an ideal church from his earlier treatise (Saluzzianus 148, fol. 11v.) and the diagram is extended by one square, the end of the latter falls precisely along the mid-line of the west end wall, as does the opposite end of the diagram over the east wall. (Figure 6). Here, at the west end of the church the wall thickness is given by the module AB. (Interestingly the relationship of the side of this last square to the side of the near-square created by adding half of the module to it in the manner shown is about 1 : 1.08, similar proportions to a medieval near-square.)

At first sight Francesco's module appears to be a somewhat arbitrary dimension, but its origin is actually quite logical: it is the difference between half the span of the church, and half the side of the square, the diagonal of which forms that span. As such the wall thickness module can be either geometrically constructed, or calculated: $AB = \left(VX - \frac{VX}{\sqrt{2}} \right) \div 2$

The ratio of wall thickness to span emanating from this method is a daring **1 : 6.83**

3.2 NORWICH CATHEDRAL

(II Fernie: 1976, 77-86)

Eric Fernie has demonstrated how proportions of the overall plan and right down to the detail of individual pier design are permeated by root 2 relationships. In particular he shows how from the square nave bays the nave arcade wall thickness is defined by simple rotation of half the diagonal (Figure 7). Similarly the aisle wall thickness is found by rotation of half the diagonal of that unit (Figure 8). The wall thickness to span ratio in both cases is **1 : 4.8**

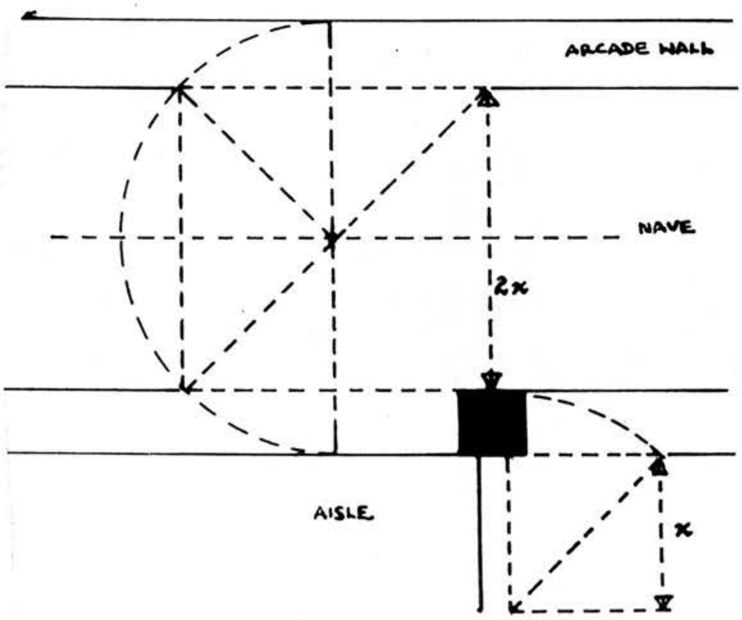


Figure 7 (Fernie)

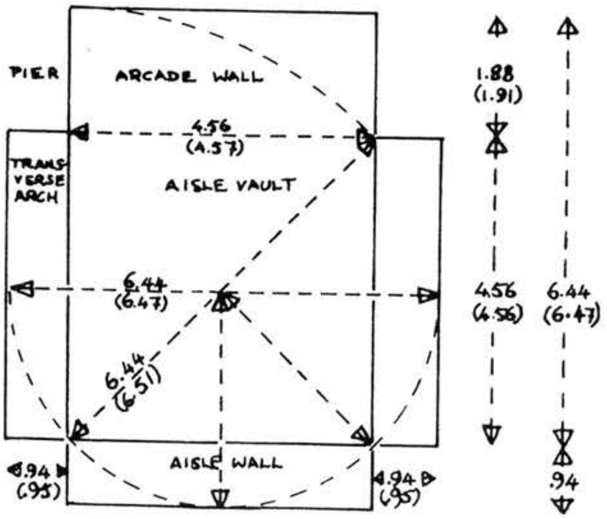


Figure 8 (Fernie)

3.3 ELY CATHEDRAL

(IV Coldstream: 1991, 37-38)

Again, the overall plan of Ely is shown to be based on a series of squares, and then the aisle width, and the nave arcade wall thickness derived through a progression of root 2 relationships (Figure 9). The overall span of the aisle (A) is half the width of the nave and it is also root 2 times the distance between the aisle responds (B). This in turn is root 2 times the maximum depth of the nave piers (D), which is root 2 times the thickness of the nave arcade wall (C).

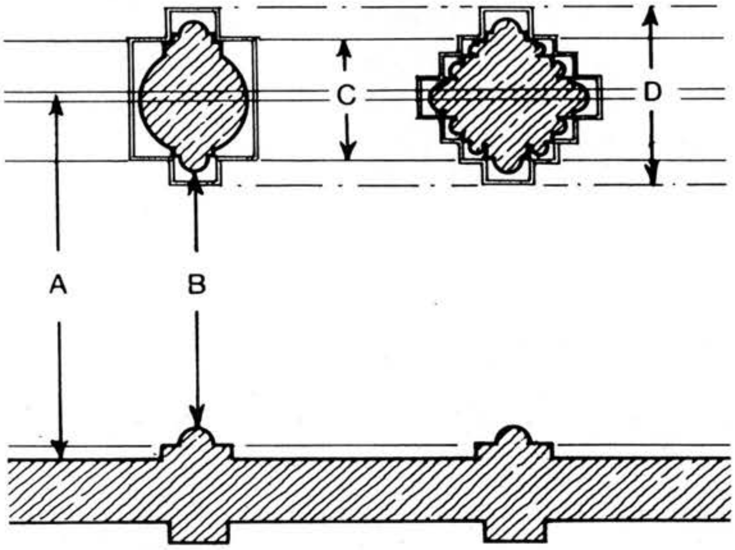


Figure 9 (Coldstream)

The wall thickness can easily be found using constructive geometry, or it can be calculated from the nave span thus:

$$X = \left(\frac{Y}{2} \div \sqrt{2}\right) \div 2$$

Where X is the wall thickness and Y is the span of the nave. This formula results in a wall thickness to span ratio of **1 : 5.66**

However, it is not clear whether, in order to find the aisle width , that is half the nave span, the latter has been measured in the same way as the former, i.e. up to the *mid-wall* line of the nave arcade wall. If this is the case, then a further calculation must be made in order to find the true span ratio; that is the ratio relating to the nave span as measured just up to the line of its *inner* wall surface. Half the wall thickness of both nave arcade walls must be subtracted from the nave span. In this instance the wall thickness to span ratio is altered to: **1 : 4.67**

3.4 ST. MARGARET'S CHAPEL, EDINBURGH CASTLE

(VII Fernie: 1986, 402, 409 n.3)

Fernie demonstrates how, once the slightly skew dimensions of St. Margaret's are regularized, there exists a structure which is based on a proportional system incorporating both internal and external dimensions, and thus also the wall thickness (Figure 10). If the latter dimension was anything but two feet , the entire system would lose its proportional congruity. There is, let it be noted a certain tolerance of a few inches, and as Fernie points out, it was probably once appended to a larger building. It should also be realised that in these integrated proportions the thickness of the chancel arch has been accorded somewhat arbitrary and inconsistent treatment, sometimes being counted part of the nave, sometimes part of the sanctuary.

Coincidentally the external width of the nave is simply achieved by rotation of the diagonal of an internal square. If the internal span is taken as 10 feet and the external 14 feet, there is a root-2 relationship.

The wall thickness to span ratio is approximately **1 : 5**

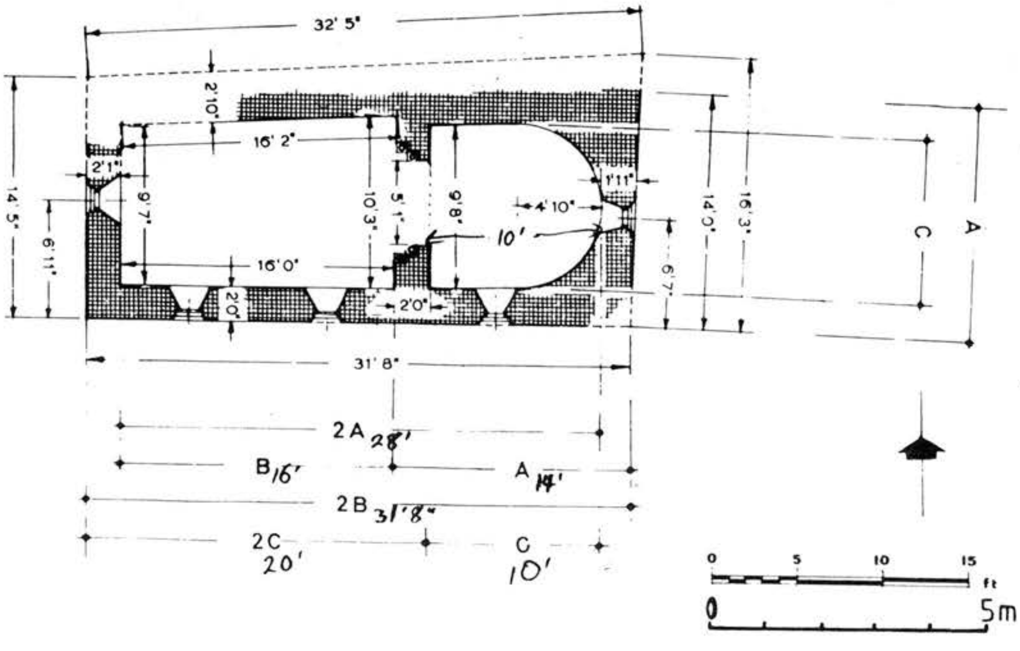


Figure 10 (Fernie)

4 VAULTED STRUCTURE SECTIONS
based on
PROPORTION
or
CONSTRUCTIVE GEOMETRY

4.1 ANDREA PALLADIO

(I Quattro Libri dell'Architettura)

Whilst saying nothing about the abutment of vaults in buildings (X Book I. Ch.XXIV), Palladio does approach the subject in his recommendations for stone bridge building (X Book III. Ch.X). Granted that some conditions attached to bridge building should perhaps differ from land-based vault construction - for instance, bridge piers must be sized with the ability to withstand floodwaters - Palladio's advice bears an uncanny relationship to that offered by others mentioned later. It should also be borne in mind that each arch of a masonry bridge was usually intended to be self-supporting during construction, rather than being reliant for abutment on the balancing thrust from the adjoining arch, which would not be built until the completion of the first.

"The pilasters (i.e. piers) ought not to be thinner than the sixth part of the arch, nor ordinarily thicker than the fourth. They must be made with large stones, which are to be joined together with cramps, and with iron or metal." (X Book III. Ch. X. 68).

Thus, a pier to span ratio of:	between	**1 : 4**
	and	**1 : 6**

4.2 SEBASTIANO SERLIO

4.2.1 *Introduction*

Whilst in his five books Serlio does not specifically set out any rules as such, he does exhibit in Book 5 Chapter 14 several folios of temple designs, mostly of central plan and domed, with thick supporting walls which are cut away here and there for altars or whole chapels. These were of course Christian churches but Serlio follows Alberti here in his nomenclature, as indeed he does in many other respects. Because some examples are of such complexity, their wall thickness is impossible to define. However, six simpler structures provide some insight to Serlio's thinking on the matter. Although he really does not give much away about the process of design employed in his actual descriptions of these temples, Serlio does provide some hints about his methods on "the most secret Art of Geometrie" (X Book 1 Fol.1)

Professor Lionel March has recently published his own interpretation of Serlio's temple designs in a work covering almost every aspect of number, measurement and proportion in western architecture up to Palladio (II 1998). March is a mathematician and the work appears to be the fruits of a lifetime's work. However, whilst many, even most aspects of his work in general may be faultless, much of his understanding of Serlio's work seems to be fundamentally flawed; but as happens in so many such cases, this provokes a depth of further examination in order to unscramble the facts that only works to the advantage of our general understanding. Being a mathematician, March is tempted to stray into overly complex arithmetical analyses and solutions in a way that is somewhat out of kilter with Mainstone's concept of "entering the mind of the designer". Serlio's design projects appear to suggest that many of the methods used by the renaissance period architect have much in common with those of the previous era. For this reason, such dependence on arithmetical solutions and explanations automatically arouse suspicion.

March also attempts interesting analyses of Serlio's and other work for theological, occult and other esoteric significance which is beyond the scope of this research and comment on these subjects is left to those more qualified in such subjects.

It is worth dwelling at some length on Serlio's designs for, although these were never built, they do give considerable insight into the thought involved in the design process around this stage in history. Before examining each temple in detail, some general remarks are appropriate by way of introduction, and concerning some principles which apply to all or most of the designs.

Firstly, these were all intended to be relatively small and/or economical to build so that they would not end up in a similar unfinished state to so many others which Serlio had seen (X Book 5 Fol. 1).

For foundations generally, Serlio recommends that "a man should from the Diameter of the thicknesse of the wall, make a perfit fouresquare, and the Diagonus of this fouresquare shall be the bredth of the foundation under the wall" (X Book 5 Fol. 1). Thus he follows in an age-old tradition of quadrature, resulting in the appearance of $1 : \sqrt{2}$ relationships.

For each project the general plan dimensions are specified by Serlio and these are quoted with the heading of each temple project, together with my own calculation of the ratio of wall thickness to overall internal roof span. Serlio's specifications are limited to *internal* diameter and wall thickness, the significance of which cannot be over-emphasized. Professor March makes what seems to be an initial error of immediately adding wall thicknesses to internal diameter, to make an overall *external* dimension in each case, and then works from that. However, most building design had, for centuries at least, begun with and been based on *internal* dimensions. Serlio had specified these, and so had almost every surviving building contract from medieval times to the seventeenth century, with a few exceptions, as we shall see in due course. In section, Serlio gives dimensions for heights to cornice and to apex of dome. Details of the chapels and/or altar niches incorporated in the wall thickness, or beyond it, are also given.

What immediately concerns us are the means by which the ground-plans are formulated and whether or not the wall thickness is determined by these same means, or by some other. Let us now examine each temple in turn to see what can be deduced in this respect.

4.2.2 *A Circular Temple Fol. 2.*

(Oddly, March does not comment on this or the next temple [Fol.3], which is also circular.)

Internal diameter: 60'

Wall thickness: "shall be the fourth part of the diameter (i.e. 15') ...that a man may easily make the chapels within it."

Wall thickness : span **1 : 4**

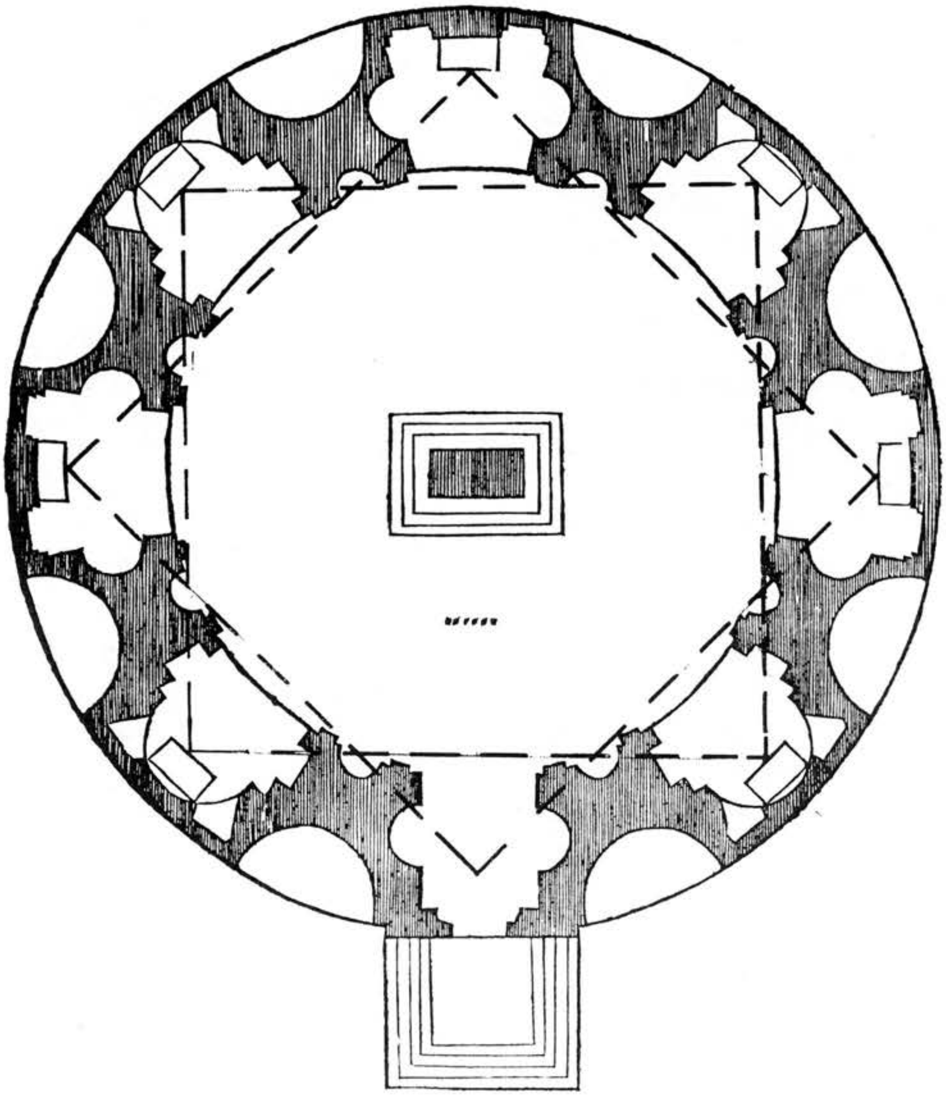


Figure 11 (Serlio. Broken lines, author)

Geometric analysis shows that the plan has an obvious octagonal as well as circular basis. Possibly coincidental is the intersection on the altar front of each chapel of the extension of the line of each alternate wall-face of the internal octagon. Other than this, there do not seem to be any significant possibilities in the geometry of the plan, certainly none that are of structural importance.

In comparison to the other temples, both wall thickness and thickness to span ratio are relatively great. For purely reasons of structural sufficiency they could certainly have been less, possibly as little as 8.57 feet , giving a ratio of 1 : 7 which is broadly the minimum found in his other work. As it is, however, the walls seem to be precisely as Serlio specified, thick enough for the chapels to be accommodated therein. Here we see a case of wall thickness being specified purely for a practical expedient, other than support of the roof, but, let it be noted, using the nearest convenient whole number ratio with the diameter.

4.2.3 *A Circular Temple Fol. 3*

Internal diameter: 48'

Wall thickness: "a seventh part of the Diameter" (i.e. 6' $10\frac{1}{3}$") with altar niches.

Wall thickness : span **1 : 7**

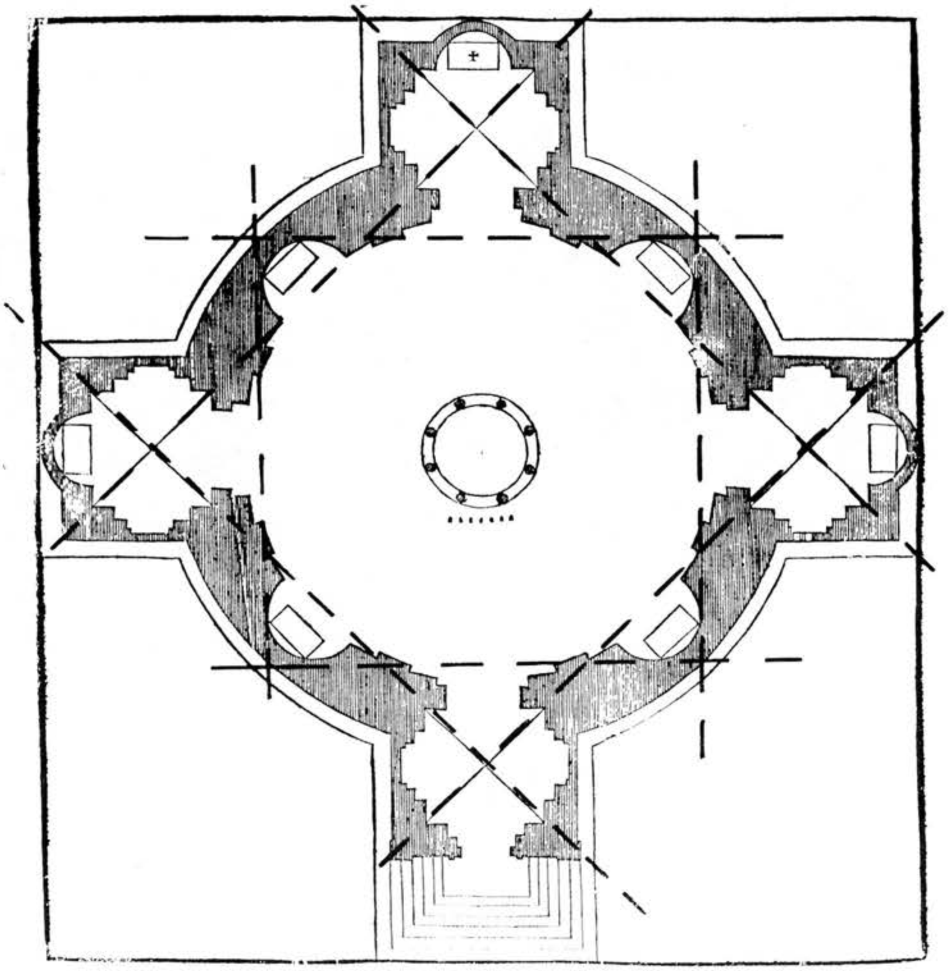


Figure 12 (Serlio. Broken lines, author)

Now there is no requirement for such thick walls to accommodate chapels as in the previous design: they have been tacked on outside, and as such they presumably also afford some buttressing function to the thrust of the dome over the main church building. The main walls, however, still have sufficient thickness to accommodate some altar niches. But how has this wall thickness of such apparent numerical obscurity been arrived at? It hardly reflects the tidy rationality of the previous example. Had the diameter been 49 feet, then the wall thickness would have been a perfect seven feet.

Again, although basically circular in plan, this temple is essentially an octagonal composition, and the intersections of the extended line of each alternate internal wall-face happens to fall on, and therefore probably mark out the external wall-face. Here is a case where the wall thickness is defined purely by a convenient accident or coincidence of geometric manipulation such as might have been used centuries earlier. This has resulted in relatively thin walls, and also a high wall thickness to span ratio. It should perhaps be noted, however, that although thinner walls than this are found (see Fol. 6. A Hexagonal Temple, below, at 5 feet), Serlio has probably used geometric manipulation to arrive at a thickness around what must have been considered the minimum limit for a temple of this size. It can only be surmised that perhaps the buttressing function of the chapel extensions may have compensated for this.

4.2.4 *An Oval Temple Fol. 4.*

Internal Diameter: 46' by 66', averaging 56'
Wall thickness: 8' with altar niches.
Wall thickness : span

Short span: **1 : 5.75**
Long span: **1 : 8.25**
Average: **1 : 7**

This might appear to be another case of structural sufficiency, possibly cutting the safety margins a little fine on the long axis.

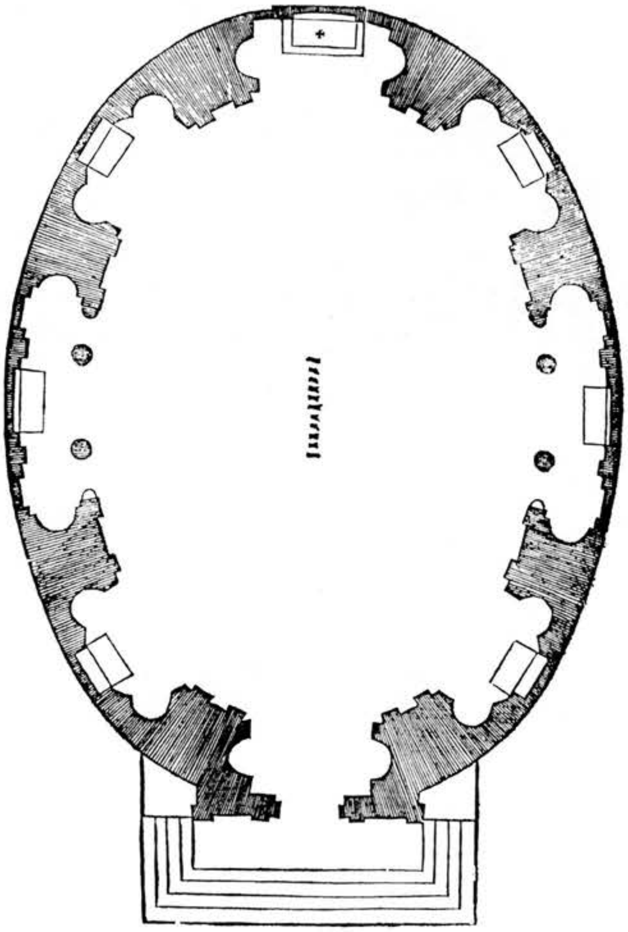


Figure 13 (Serlio)

There are several ways of constructing an oval and Serlio explained these in his first book (Fols. 10 & 11), (Figure 14). Each method automatically results in certain dimensional proportions which are fixed and cannot be adjusted without distorting the continuity of the figure's curvature. Methods one and four result in a ratio of 1 : 1.413 (very nearly 1 : √2); method two, 1 : 1.435, and method three, 1 : 1.325. Serlio's temple dimensions give it a ratio of 1 : 1.435, obviously indicating its origins in method two.

Now although Serlio only illustrates in the first method how further concentric ovals can be made in order to define the desired wall thickness, the same can be done with any of the methods, simply by extending, and then rotating the diagonals of the constituent circles. This all seems very straightforward and the simplest way of achieving the desired result, which alone seems justification enough for the reasonable assumption that Serlio would have been likely to follow it.

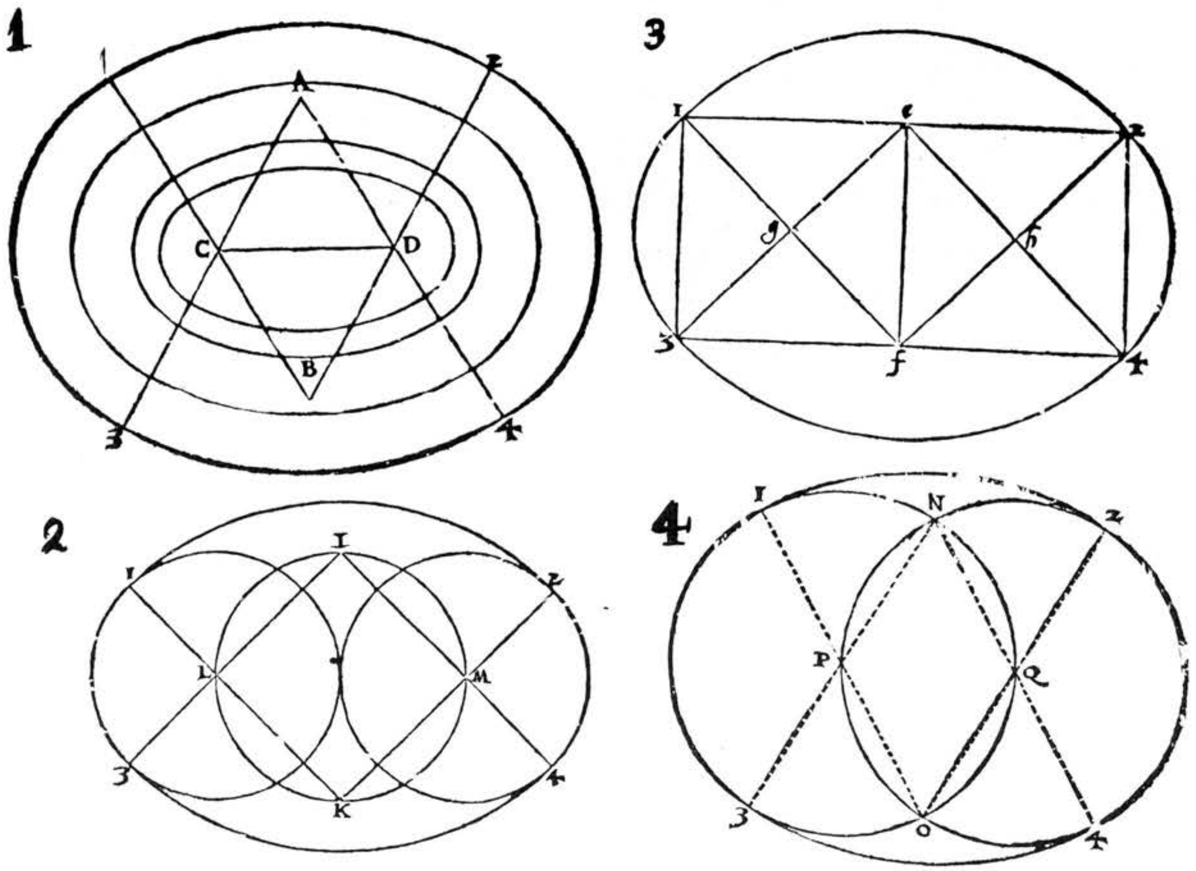
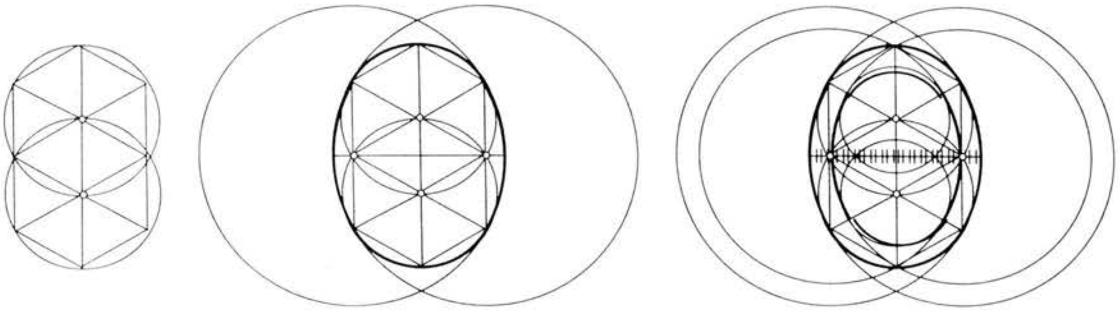


Figure 14 (Serlio Book I, Ch.1, Fols.10v. & 11r.)

Strangely, Professor March assumes Serlio has chosen one or other of the methods based on equilateral triangles: methods one and/or four (II 1998: 213), presumably the former because of the illustration of how to achieve further concentric ovals which might be used to define both interior and exterior wall planes. Unfortunately for March both these methods result in the incorrect proportions for the dimensions of Serlio's temple. They are, it must be said, very close: 65 feet instead of 66 feet long for the width of 46 feet, to be precise. In order to overcome this discrepancy, March proceeds to invoke the obscure "rule by defect", of Arabian origin, followed by lengthy calculations, together with a geometric method of oval construction to suit this particular situation, based on hexagons which is not mentioned by Serlio at all. Eventually he manages to arrive at the right answer, but along a route so tortuous as to be in danger of courting ridicule, particularly since it is illustrated by diagrams, the inaccuracy of whose processes is obvious (Figure 15). Even if Serlio had known of the arithmetical "rule by defect", he would have had no need to use it in this case. Again it seems much more logical that he would have chosen the simplest method available, probably by geometric manipulation, as had been the common tradition of his profession for centuries, rather than engage in unnecessary and over-complex arithmetic.



Geometrical construction of the ovals. Left, overlapping hexagonal armature with two circles struck each passing through the other's centre. Centre, two more circles are drawn using the diameter of the hexagons as radius. Right, the width of the oval is divided into 31 parts (62 feet) and the interior oval is formed by striking arcs through the same centres as before, but now with radii reduced by 4 parts (8 feet).

Figure 15 (March, 1998: 213)

As for the chosen wall thickness, just how has Serlio alighted on the delightfully round figure of eight feet? The principle used in his own Method 1: extending the diameter lines to the required length has already been mentioned This is, of course, possible, but it would have involved Serlio in having to arrive at a decision purely through his own intuition, judgement or calculation of some sort. The latter does not appear to have been the case in any of his other temple projects, and there does not seem any specific reason why this case should be any different. Surprisingly perhaps the result can be achieved using nothing more than constructive geometry. Assuming that he had started out by using the second method of oval construction, first inscribe hexagons in the two end circles (Figure 16). The wall thickness of eight feet is then achieved in a development of the same technique used in the previous temple project: the mid points of the sides of these hexagons are marked off and further smaller rotated hexagons are then inscribed by joining up these mid points, and extending the sides of these new figures outwards. Each such extension will intersect with the next but one at a point which is exactly eight feet from the internal wall plane. There is no need for any arithmetic at all. Everything can be accomplished with a ruler and compass.

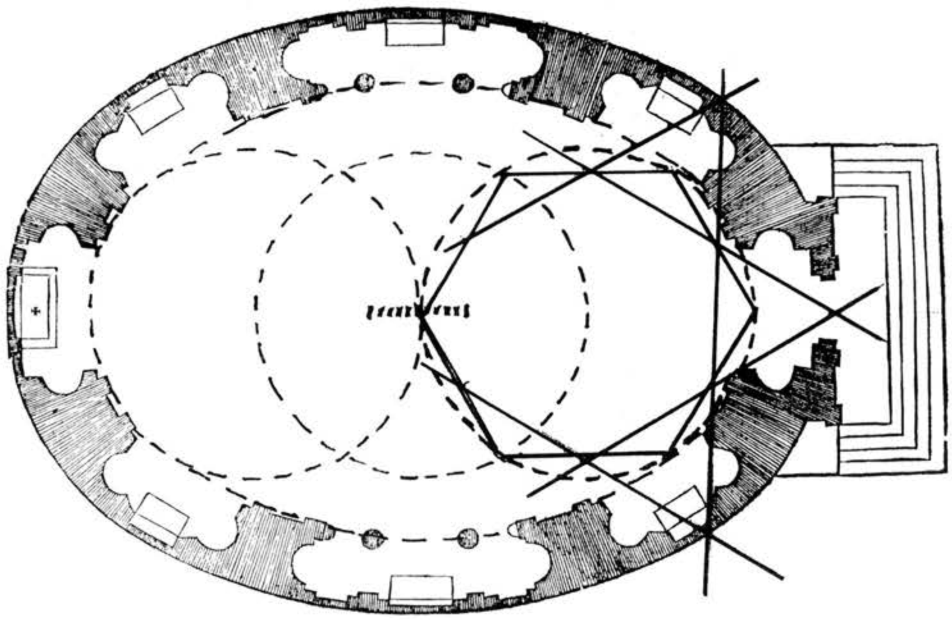


Figure 16 (Serlio. Broken lines and polygons, author)

It might be questioned, why did Serlio not continue with the octagonal basis of construction of his figure to find the wall thickness? Why change over part way through the design process to a hexagonal basis? To have continued in the manner in which he had started would have been entirely logical and appropriate to the traditional nature of design by constructive geometry. An answer presents itself as soon as the results of such a manoeuvre are examined. A wall thickness of about 5'3" would be the outcome and this would give a wall thickness to span ratio of 1 : 12.6 on the long axis; 1 : 8.8 on the shorter. Given the minimum of nearer 1 : 7 for any of the other vaulted structures, such a dimension would result in what would have been deemed an unsafe building.

It might also be questioned, why did Serlio not choose to use the intersection of lines drawn from the primary hexagons, in preference to those from the smaller secondary ones? Again, the answer could be very prosaic: this would have resulted in walls 12 feet thick, and it can only be concluded that Serlio judged this to be excessive in what was intended to be an economic building. The wall thickness to span ratios would have been 1 : 5.5 on the long axis; 1 : 3.8 on the short.

It is perhaps of significance that Serlio possibly felt constrained by tradition in this and the other design projects to opt for a solution based on constructive geometry. Simply adding an extra foot or two of masonry to the thickness of the former solution, or subtracting an appropriate amount from the latter does not seem to have been an option.

4.2.5 *A Pentagonal / Decagonal Temple Fol. 5.*

(The temple is pentagonal on the outside, but the interior plan is decagonal.)

Internal diameter: 62' It is not clear whether this dimension is intended to mean from opposite sides, or opposite corners. I agree with March that the latter is most likely (II 1998: 209).

Wall thickness: Not specified by Serlio, and because of the difference in exterior from interior forms, difficult to define. Taking approximate measurements from the published plan, the minimum appears to be in the region of ten feet.

Wall thickness : span ratio: **Approx. 1 : 4.9**

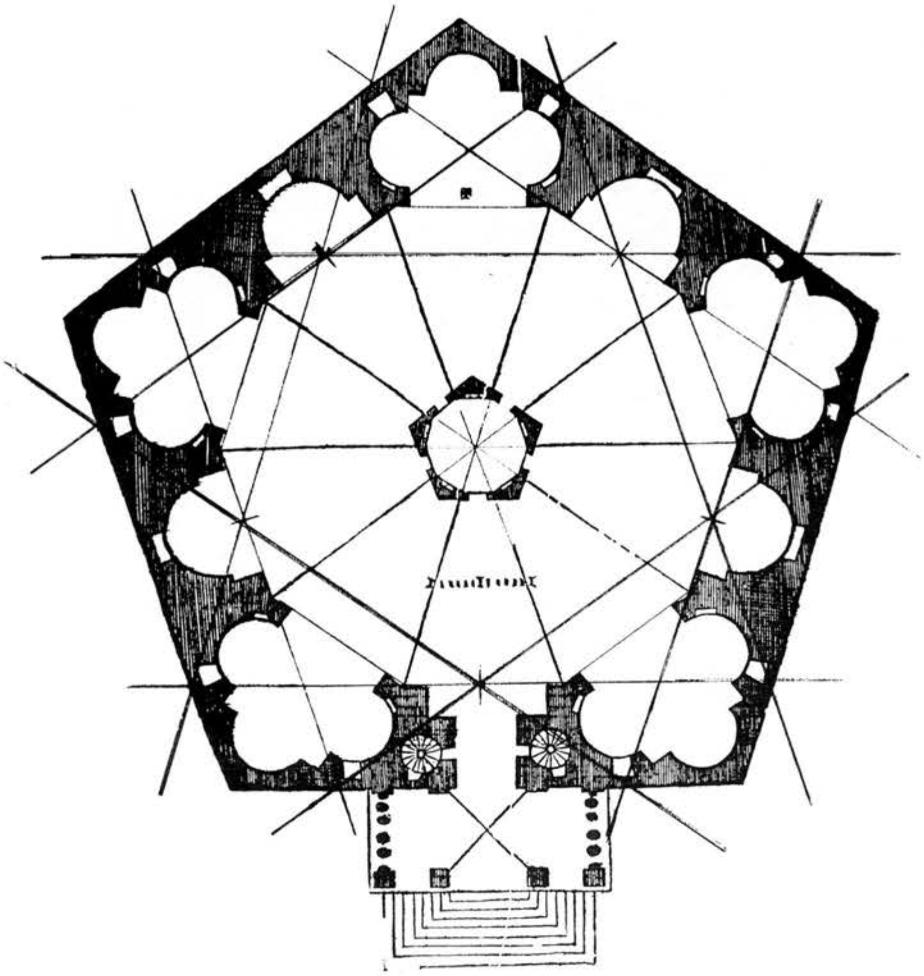


Figure 17 (Serlio. Broken lines, author)

Wall thickness definition appears again to be by simple geometric manipulation: whilst the internal figure is indeed a decagon, the dominant internal pentagon is still quite clear and can be drawn in. As with some previous examples, its sides are continued beyond each corner. Then the mid-point of each side is marked off, and connecting lines drawn in between all these mid-points, extending also outwards. Where the latter intersect with the extended sides of the internal pentagon, there will be the external wall face. Two such points will be found on each of the five sides, greatly simplifying the drawing up of the exterior plan.

4.2.6 *A Hexagonal Temple Fol. 6.*

Internal diameter: (corner to corner) 25'
Wall thickness: 5' with altar niches.
Wall thickness : span (corner to corner) **1 : 5**

For more accurate assessment of structural dimensions for the purposes of this research, as explained below:
Internal diameter: (wall to wall) 21.6'
Wall thickness : span (wall to wall) **1 : 4.3**

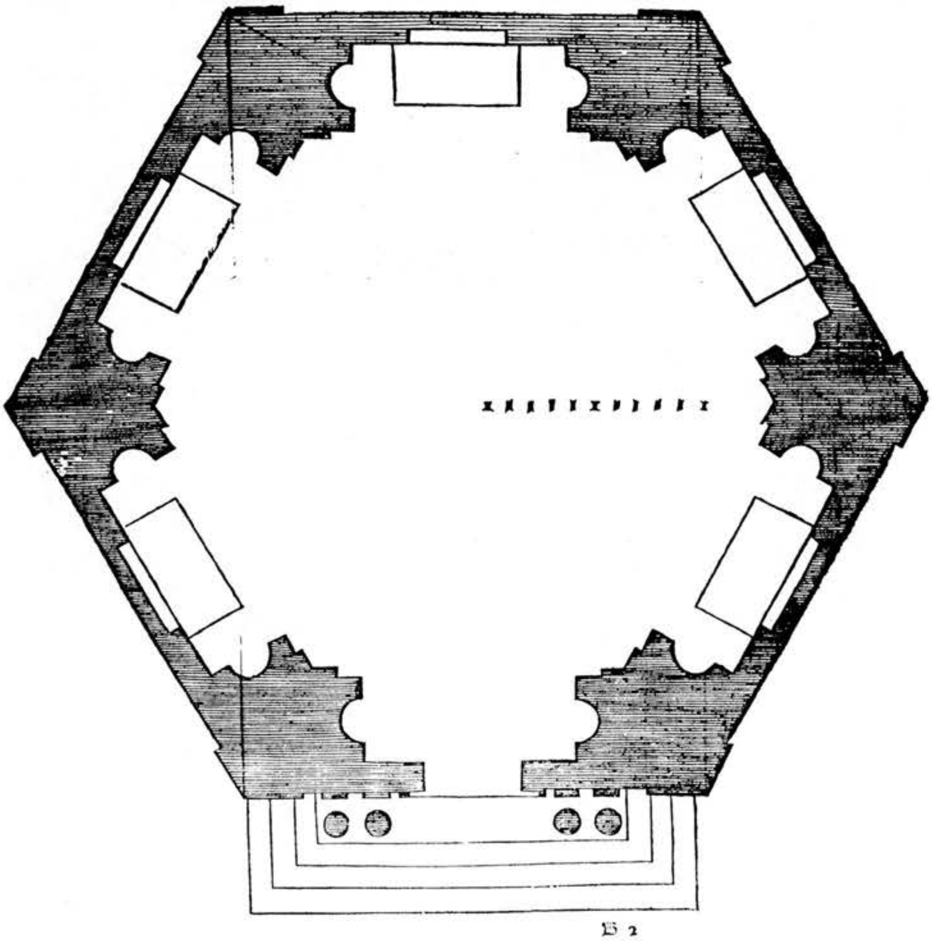


Figure 18 (Serlio)

As with the previous project, it is not immediately clear whether the diameter is intended to mean from corner to corner, or from wall to wall. Professor March states the latter, expressed as "between alternate vertices" (II 1998: 206). However, I believe that there is a strong case to be made that Serlio's diameter was actually between *opposite* vertices:

1) In his earlier instructions on geometry, Serlio describes the hexagon as "the first cornered circle" (X Book 1. Fol.11). Indeed this figure is customarily constructed in a circle. Now of course the diameter of a true circle stretches across the centre, right to the circumference on either side, that is, the maximum internal dimension. The same should apply to a hexagon, especially if it is regarded as a "cornered circle", and the maximum internal dimension will of course be through the centre, to opposite corners on the circumference.

2) If the diameter were to be from wall to wall, a problem would occur in the initial design: a hexagon can be constructed by the simple and purely graphical methods of most architects of that time either using a circle with its diameter line (which will, of course, be twice as long as each side of the hexagon); alternatively by adding together six equilateral triangles into a circular form. For both these methods the initial dimension required is of course the diameter length, corner to corner, or half of it at least. The dimension from wall to wall would not of itself directly enable the construction of a hexagon. It would bisect each constituent equilateral triangle, creating two right angled triangles, from which trigonometry would have to be employed in order to find the length of each side of the hexagon. It is seriously doubtful that any architect of that or any era would wish to go to such lengths unnecessarily.

3) Measurement of the published plan of Serlio's temple, though not highly accurate, does confirm through proportionality that the 25 foot diameter was intended from opposite corner to corner.

As to the definition of wall thickness, March theorizes on the basis of his wall to wall diameter (p.207), as shown in Figure 19. This does actually produce nearly exactly the wall thickness specified by Serlio, but I believe he has not understood the means by which the architect would have achieved this. It is more likely that Serlio would simply have rotated the chord as shown in Figure 20. Such a manipulation would be much more in character with contemporary methods of design.

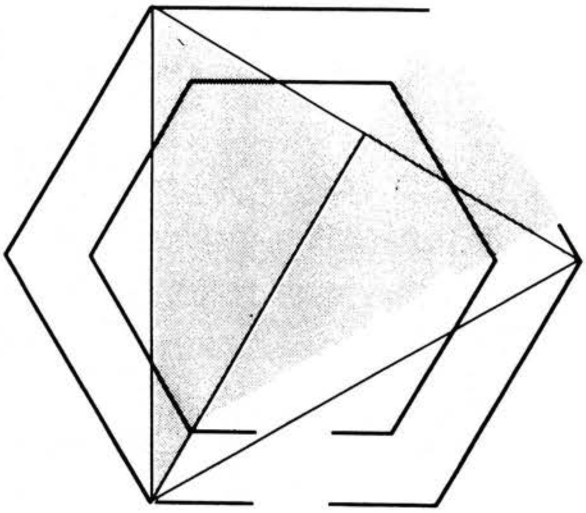


Figure 19 (March, 1998: 207)

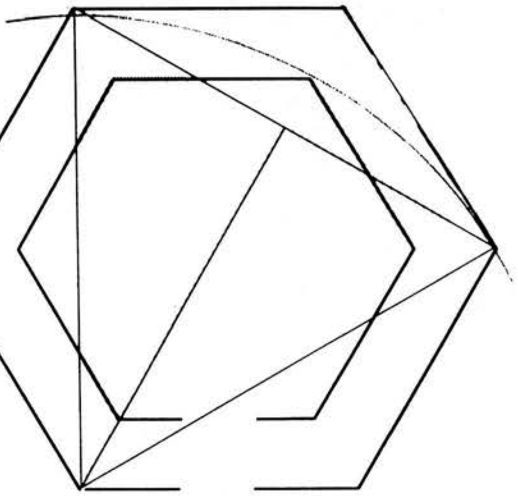


Figure 20 (March, 1998: 207)

Whilst this is quite plausible as a means of achieving the required wall thickness, there is another way which may be even more likely, since it is basically the same as used in the other temple projects: if the mid points of each side of the internal hexagon are marked off and lines drawn through them extending outwards, they will form a new smaller hexagon, inscribed and rotated inside the first, but more significantly, a hexagram outside the internal hexagon (Figure 21). If the projecting points of this figure are joined to form a new larger hexagon, we arrive at a figure a few inches larger than the external dimensions of Serlio's temple. These few inches might very possibly be accounted for by the depth of the corner pilasters which Serlio employs here. No thickness is specified for these other than "coming out a little". These conveniently allow the dimensions achieved by this method of design by constructive geometry, whilst at the same time allowing the rest of the wall thickness to be reduced to a round five feet, giving a nice tidy whole number ratio with the internal diameter of 25 feet.

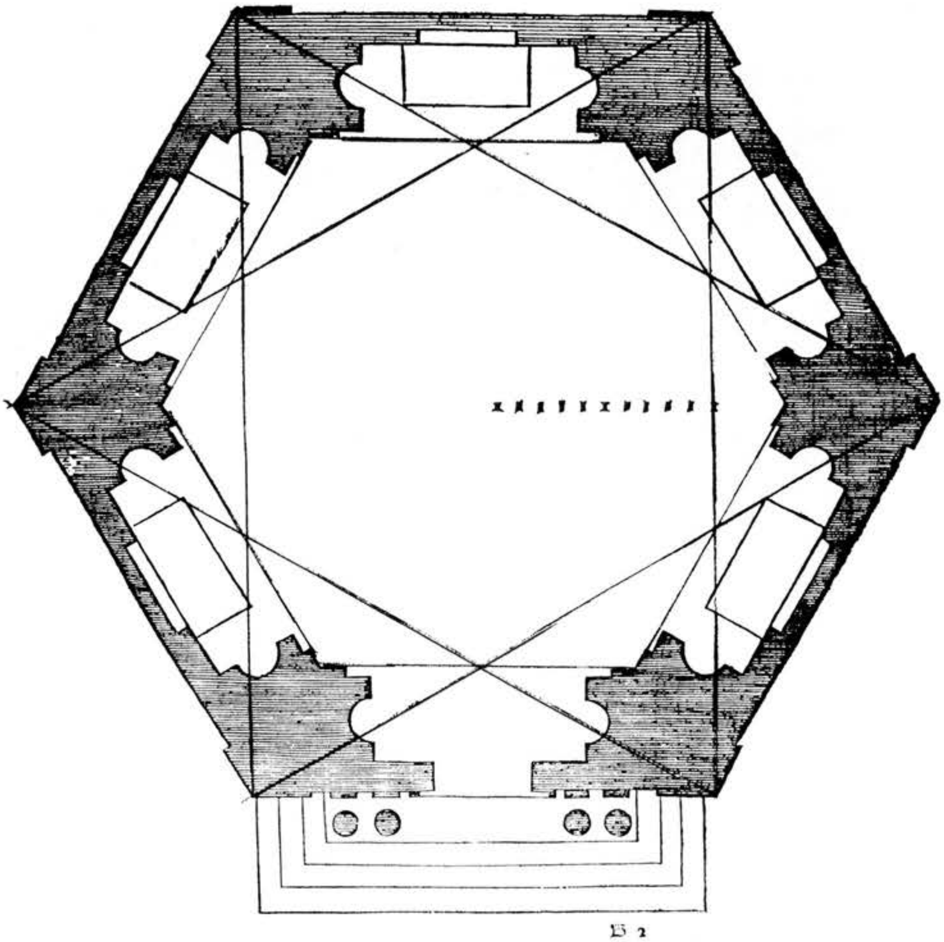


Figure 21 (Serlio. Over-drawn lines, author)

Having clarified the basis for both internal and external hexagons, a paradox arises in the basis for our calculation of the wall thickness to span ratio. The purpose of this, of course, is to ascertain the span of masonry vaulting bearing down at any given point along the wall, and it is essential that it is taken at right angles to the line of the wall. So for this purpose the shorter wall to wall 'diameter' is required. If the corner to corner diameter is 25 feet, then the wall to wall figure will be 21.6 feet. Therefore the ratio is really as low as 1 : 4.3. It is, however, tempting to think that Serlio regarded the tidier relationship of 5 : 25, or 1 : 5 of greater significance for the purposes of his published specification.

Either way, the wall thickness to span ratio is amongst the lowest, but at a mere five feet thick, the walls were probably at a standard minimum for any vaulted building.

4.2.7 *An Octagonal Temple Fol. 7.*

Internal diameter	(corner to corner):	43'	
Wall thickness:	8', with altar niches.		
Wall thickness : span	(corner to corner):		**1 : 5.4**

Internal diameter	(wall to wall):	39'9"	
Wall thickness : span	(wall to wall):		**1 : 5**

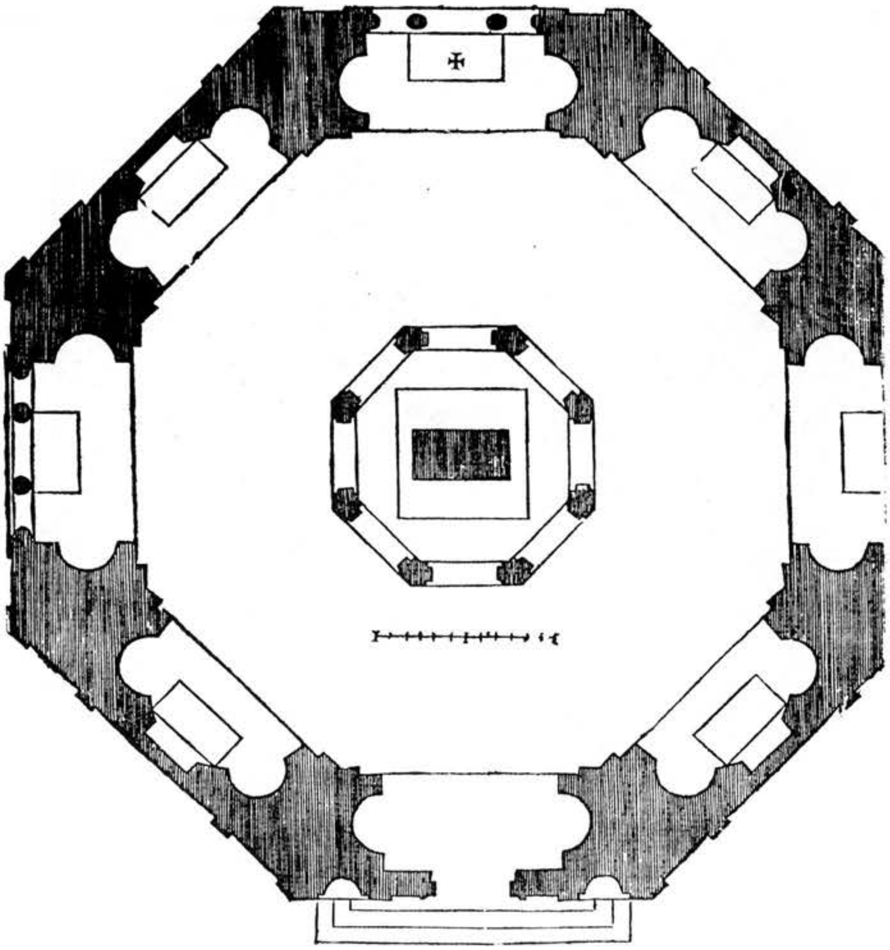


Figure 22 (Serlio)

Again, March assumes that the internal diameter is wall to wall rather than corner to corner (p. 208), and in this case, constructional logic could conceivably support this view. Construction of an octagon is in Serlio's own words "drawen out of a right foure cornerd square" (X Book 1 Fol.11), (Figure 23) and, given an initial dimension of corner to corner diameter of the finished octagon, there is no easy means of judging how large to make the initial square. The process should properly begin with a dimension for one side of the square which then becomes a wall to wall diameter.

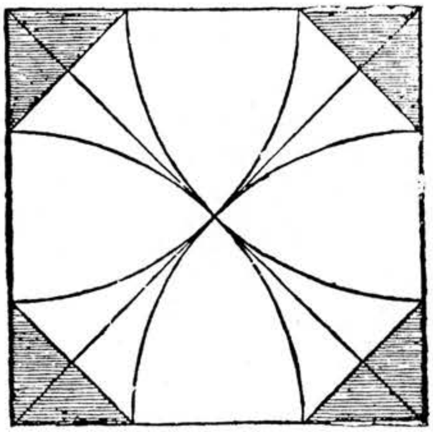


Figure 23 (Serlio Book I, Ch1, Fol. 11r.)

However, Serlio also mentions, but does not illustrate, what he considers to be a less satisfactory construction method, beginning with a circle (Figure 24). A cross is drawn therein by two diameter lines set at right angles to each other; two further diagonals are then drawn at 45° to the first, thus dividing the circle into eighths. The points on the circumference of the circle where each diagonal intersects are then joined up to form the octagon. It becomes another sort of "cornered circle" and, more significant for our purposes, the diameter which is from corner to corner, is the logical starting point, both in the architect's specification, and in the constructional process.

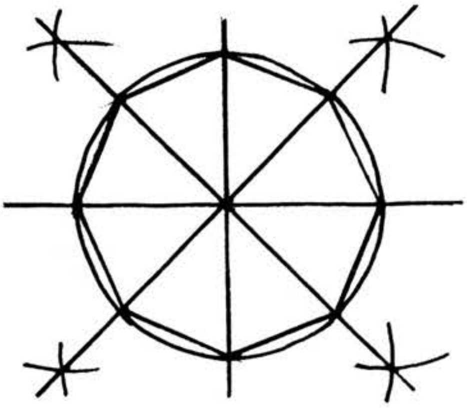


Figure 24

Now if the octagon for Serlio's temple is constructed in this way, the wall thickness can be determined in a similar operation to that employed in the previous, hexagonal temple (Figure 25). When the internal wall surfaces are drawn in they are each extended in both directions. The points at which each extended line intersects with that of the next but one side happen to be 8' 3" from the inside wall surfaces, and so these points could fall mid-way along each exterior wall plane. Serlio, however, specifies a wall thickness of eight feet exactly. As in the previous example we may have to make an assumption that the extra three inches is the depth of the pilasters which adorn this temple, but for which Serlio, again, does not specify a dimension.

For calculation of wall thickness to span ratio, the same procedure applies as for the previous temple project.

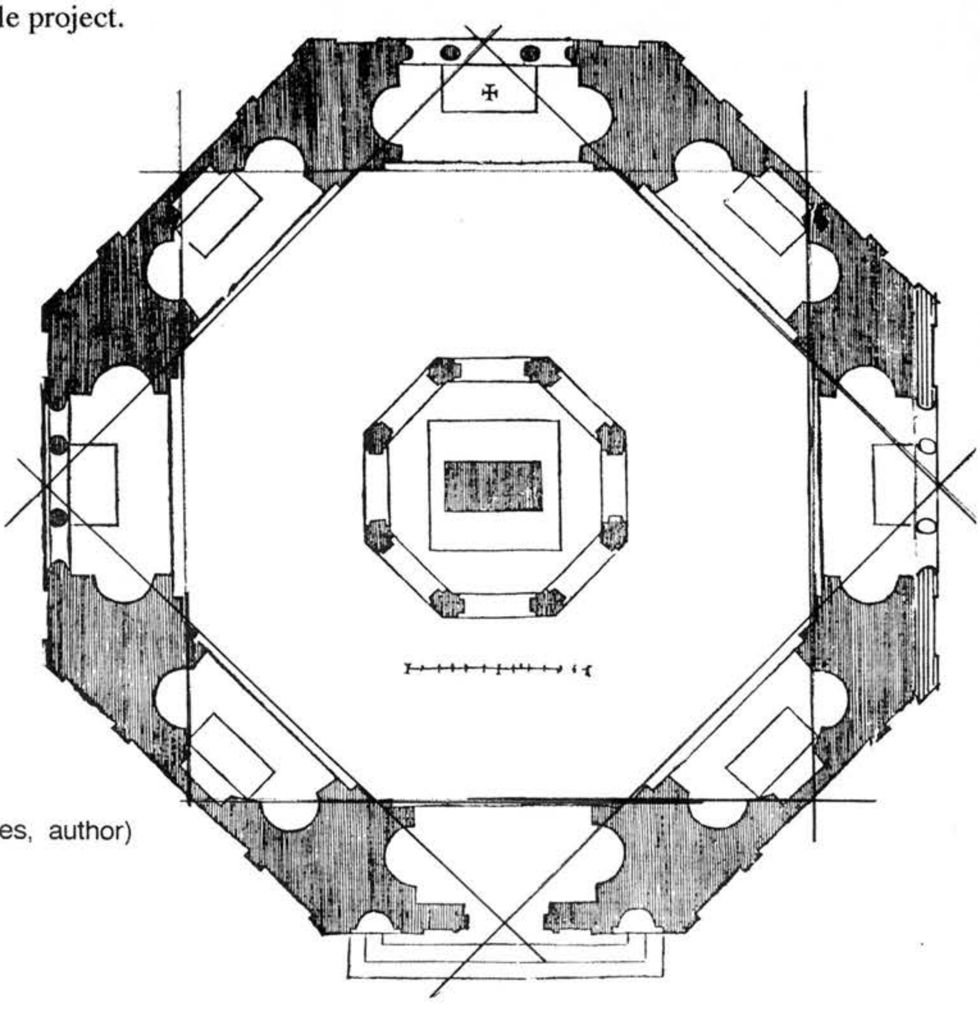


Figure 25

(Serlio. Overdrawn lines, author)

4.2.8 *Conclusion*

In conclusion, it appears beyond doubt that Serlio made extensive use of the design techniques employed by previous generations of architects: manipulation of simple geometric forms, as well as some adherence to simple whole number ratios where it suited. These projects were designed to be relatively economical and there seems to be some naive attempt at structural sufficiency, at least to the nearest size that could be obtained by the somewhat limiting expedient of constructive geometry. As such, it would perhaps be better described as structural propriety. The method clearly appealed as much to the later renaissance as it had to the medieval non-arithmetic tradition.

It might also be concluded from these projects that architects, when using constructive geometry, did not, indeed could not always be bound by one continuous 'system' or method of approach. Our exploration of the various means that Serlio might have used to design the oval temple wall thickness is particularly illustrative of the extent to which this might apply even on a relatively simple building, using an octagonal system for the overall shape of the ground-plan and changing to the hexagon for definition of wall thickness.

If any trends are apparent here in Serlio's approach to actual wall thickness and its relationship to roof span, the one that stands out above all is a preference for a ratio around 1 : 5, which compares interestingly with Palladio's prescription for bridge design. The more daring 1 : 7 ratio used in the circular temple of Folio 3 benefited from the extra abutment afforded by the side chapels. The only apparent aberration seems to have been that of the oval structure which, according to these standards, could have been given some extra support. Perhaps the noticeably thinned upper parts of the dome and the absence of any lantern were sufficient to compensate.

Serlio demonstrates also an apparent standard of architects and/or expectation by his readers that major dimensions or proportional relationships be expressed in simple whole numbers, at least over the main structure. Where in the round temple of folio 3 the wall thickness was to be a highly untidy irrational number, including fractions of an inch, this is expressed rather as an element in a relationship with the internal diameter: "one seventh". Thus in addition to any structural expediency, dimensional solutions might well have been sought specifically for their numerical rationality. Doubtless also the need to incorporate various theological or other metaphysical significances may have had a bearing on the choice of proportions used, though that is beyond the scope of this research.

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As regards Professor March's interpretations, some fundamental errors have been highlighted; there may be more, pertaining both to Serlio's work, and elsewhere in his tome. What is perhaps most distressing about these, is that for all his undoubted excellence of arithmetic ability, there is undoubtedly a lack of understanding of some of the basic design methods of the architectural and masonic crafts. The references he cites (there is no bibliography as such) reveal an almost total absence of sources on the subject.

Where March postulates mystical interpretations of numerology, and these are on the basis of such flawed understanding of the design process, it is indeed unfortunate that this work might thus have been in vain. This is particularly sad in view of the scepticism which is in no short supply in our own age for any such interpretation. It really does require the academic expertise which March brings in order to give this whole aspect some credibility.

4.3 RODRIGO GIL DE HONTAÑÓN

(II Sanabria: 1982, 281-293)

The original writings of Rodrigo Gil have not survived and his theories come to us second-hand in Simón García's *Compendio de Arquitectura y Simetría de los Templos* of 1681. Because of this, it is unclear precisely how much of the work is that of Rodrigo himself, but Sanabria and Kubler (II 1944) as well as other researchers on the subject are reasonably sure that the following can be attributed to him. Altogether Rodrigo formulated seven methods for the defining various structural dimensions.

4.3.1 *To find Buttress Projection*

(including wall thickness) for a vault: "a fourth of the span" **1 : 4**

This firstly represents a very vague generalisation by other Spanish and foreign masons encountered by Gil, and probably refers to wall thickness and buttress projection combined.

However, it is also a specific formula devised by Rodrigo himself which certainly does include both wall thickness and buttress projection, but the measurement is to be taken at *tas-de-charge* level, rather than at the ground or just above the ground table from where the former generalised convention might have been derived.

4.3.2 *To find Pier Diameter for a Hall Church*

For the diameter of cylindrical nave arcade piers in a hall church with nave and aisles of equal height:

$$\tfrac{1}{2}\sqrt{H + W + L}$$

where H is the height of the pier, and W and L are the width and length of a nave bay. As Sanabria points out, this and two other rules are the earliest surviving recorded instances of masonic rules where the square root is used arithmetically rather than by constructive geometry. This calculation is flawed, however, in that in very large churches the pier diameter becomes unnecessarily thick.

4.3.3 *To find Buttress Projection (arithmetical)*

(including wall thickness) for a Semicircular Arch and therefore a round barrel vault.

Buttress Projection $= \sqrt{H + \frac{C}{2}}$

where H is the buttress height and C is the total circumference of the intrados of the arch or vault.

The formula displays no actual understanding of structural mechanics and seems to be more an arbitrary employment of the square root, based not so much on reason and logic as on a fascination with the device as a novel mathematical tool. However, taking a church of 30' span and 45' buttress height, the span ratio works out at approximately **1 : 3.1**

4.3.4 *To find Buttress Projection (geometrical)*

(including wall thickness) for a Semicircular Arch or Vault

This is shown as a series of steps in a constructive geometric process (Figure 26), which can also be achieved arithmetically:

Buttress Projection $= 2 - \sqrt{2} \times R$

or $= 0.586 \times R$

where R is the radius of the arch

This gives a buttress depth to span ratio of: **1 : 3.414**

Rodrigo developed the process to incorporate the limit to which the arch or vault could be loaded, (stages *g* and *h*) which is of no relevance to this research.

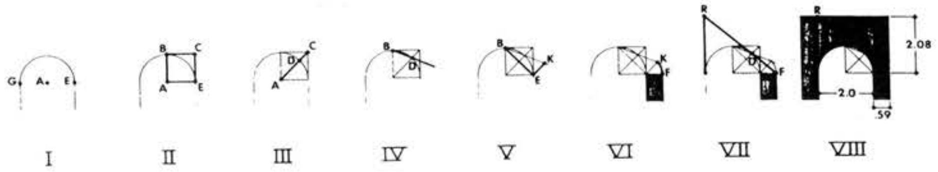

Figure 26 (Sanabria)

A problem with this process arises when an arch is not quite semicircular, as in the case of most Scottish medieval vaults: if the same method is used, as the arch becomes shallower, so the abutting wall becomes thinner, rather than more robust to absorb the increasing magnitude of lateral trust generated. A solution to this problem, can be developed from Rodrigo's process: (figure 27) find the line below the level of the springing AE from which the radius of the arch is based, WX, and add the height difference between these two horizontals, AW, to the height of the arch, BY. This enlarged rectangle WXYZ can then be used in the same way as the original square ABCE to generate an abutment in direct proportion to the shallowness of the arch.

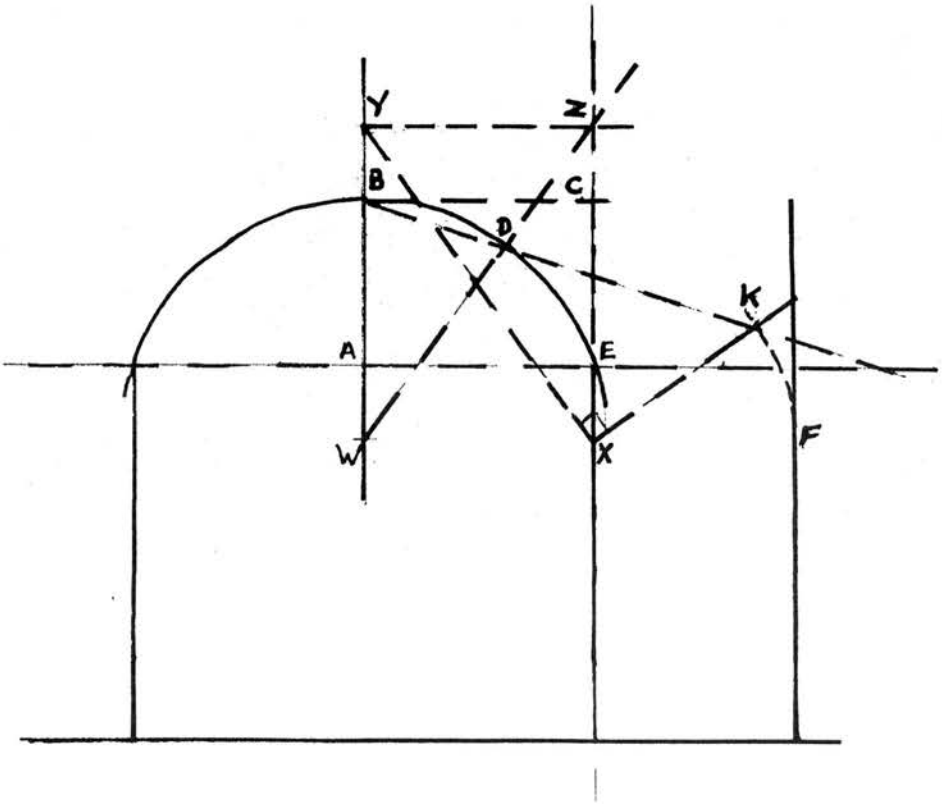

Figure 27

4.3.5 *To find Buttress Projection (geometrical - 2)*

(including wall thickness) for a Semicircular Arch or Vault.

Figure 28 shows a progression formulated by Rodrigo for defining both buttress projection and safe loading height:

a) The intrados of the arch described about E; one half of the arch-ring divided into three equal portions B,C,D;
b) Perpendiculars dropped from C and D;
c) Three lines drawn from A through B, C and D;
d) Centred on B, an arc drawn from E, through D, to intersect AC at K, and AB at F; centred on D, an arc drawn from G to intersect AD at H;
e) A line is drawn from H, through F, to intersect with a vertical drawn from E, at Q; (It seems that the architect may not have realised that AF and AH are not actually equidistant, though they are very close.)
f) Centred on K, an arc is drawn connecting H and F;
g) Centred on H, an arc is drawn connecting K and L.

Q marks the safe loading height of the vault;
L marks the required buttress projection

By calculation, Sanabria tells us that Q is situated at a point 2.894 times the arch radius above the level of the springing; the buttress projection will be either 0.615 or 0.626 of the radius; the buttress projection to span ratio: **<u>1 : 3.22</u>**

or **<u>1 : 3.25</u>**

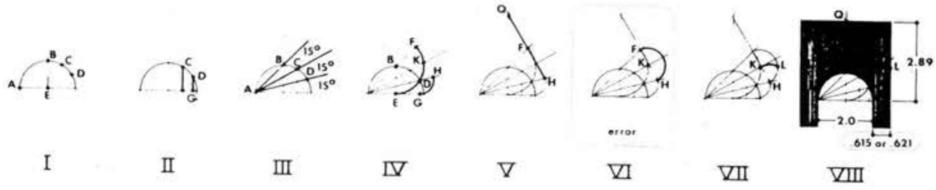

Figure 28 (Sanabria)

4.3.6 *To find Buttress Projection and Height*

for a Semicircular Arch, with given Voussoir Depth one sixth of Intrados Diameter:

a) Divide intrados diameter into three parts (figure 29); this will define the buttress projection as one third of the diameter.

b) Draw a line down from the apex of the extrados through one of the above-mentioned points (which define one third of the intrados diameter) until it intersects a line drawn down from the springing of the vault intrados; where the two meet will define the safe height for a buttress of that projection, and this will be 1.33 times the span.

In a variation of this method (figure 30), Rodrigo proposes another arched structure with a given set of proportions: the span to height (from ground to springing) ratio: 2 : 3. Voussoir thickness is fixed at one fifth of the span. Buttress projection is then found by dropping a straight line from the apex of the extrados down to the internal foot of the buttress. Where it intersects the arch diameter line defines the buttress projection.

This method produces a wall thickness to span ratio of **<u>1 : 3</u>**

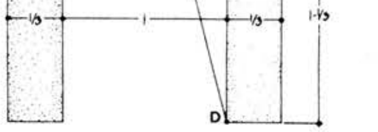

Figure 29 (Sanabria)

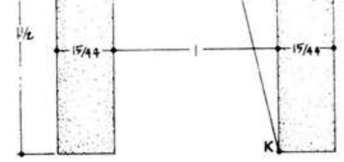

Figure 30 (Sanabria)

4.3.7 *To find Buttress Projection and Height*

Now it can be seen from these that if the span and voussoir thickness are known, then a highly versatile mechanism can be devised for fixing the buttress projection for any desired height. (Figure 31) Unfortunately the mechanism is flawed in that it is based not on theoretical or practical laws of mechanics, but on constructive geometry, but it does nonetheless apply a sliding scale of some logic to the problem.

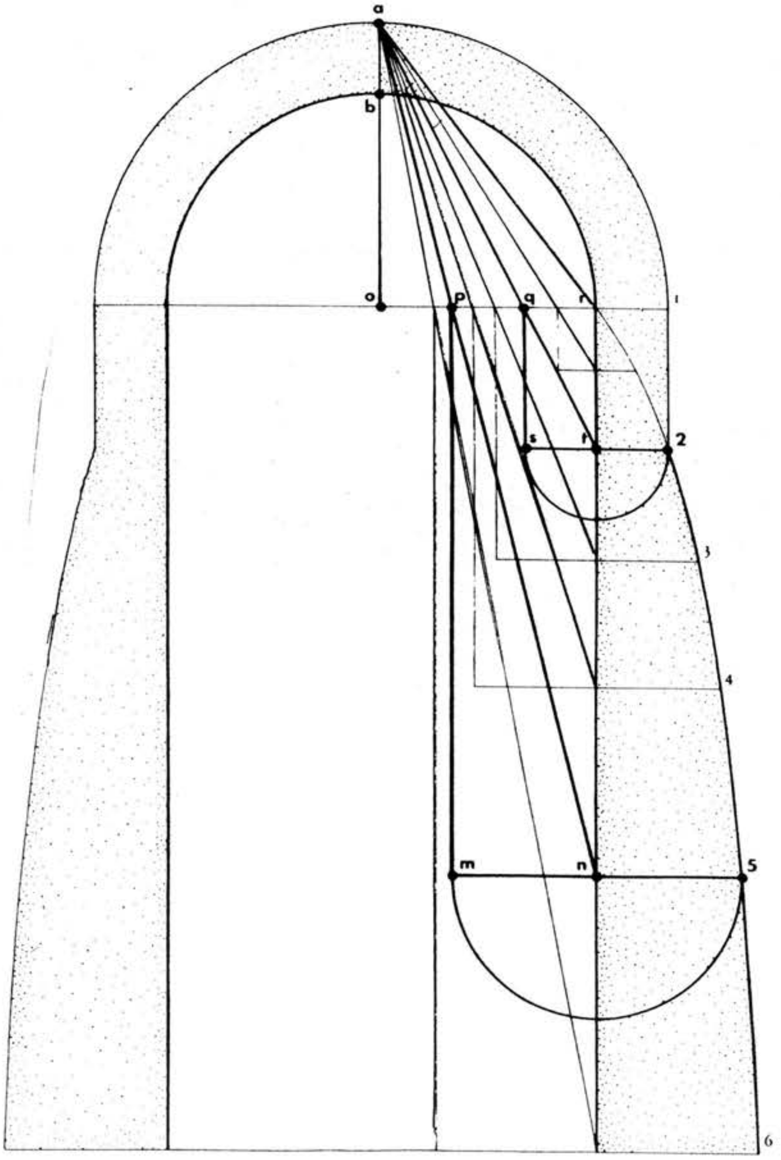

Figure 31 (Sanabria)

4.4 FRANÇOIS DÉRAND

A simple method of defining buttress projection was proposed by Dérand in 1643 in his *L'architecture des voûtes ou l'art des traits et coupe des voûtes*. The same process was published by François Blondel in his *Cours d'Architecture* of 1678 and hence is often erroneously attributed to him. The method was also published later by Rondelet (X 1847).

The method can be applied to any shape of vault and purports to take into account buttress height as well as projection. (Figure 32) First the intrados is divided by three equal chords. Then the two side chords are extended down through the springing, in a straight line totalling double its original length. Where this line ends defines the minimum projection of the buttress. Again, this system takes into account the greater lateral thrust of segmental vaults, but unlike Rodrigo's last method, appears very limited in usefulness when applied to very high buildings.

For the perfectly round arch, the wall thickness to span ratio is **1 : 4**

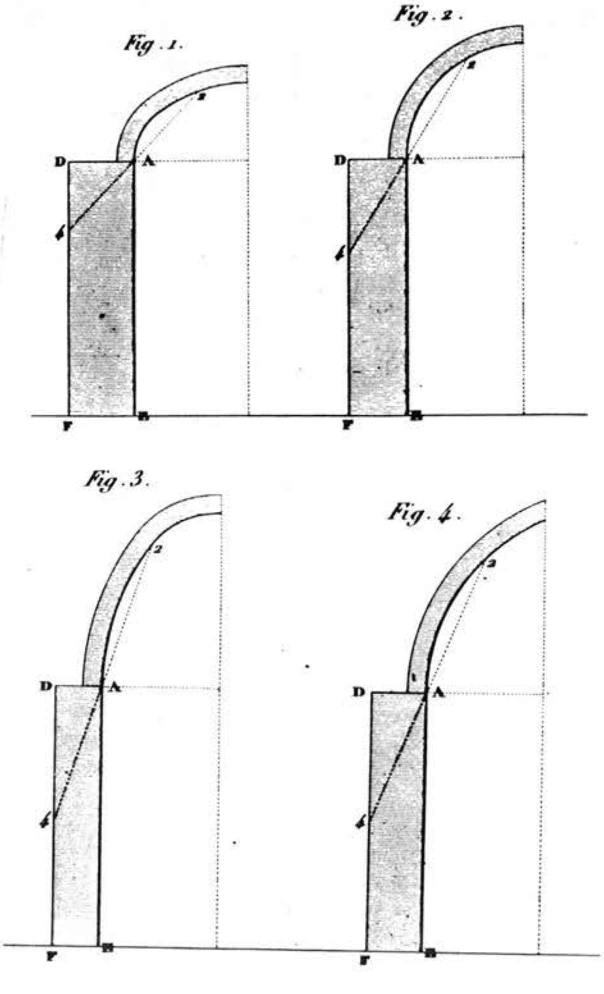

Figure 32
(Rondelet, 1847: Pl. CLXXXXIX)

4.5 H. GAUTHIER

A method published later also by Rondelet (X 1847) and has much in common with that of Dérand, but resulting in generally deeper projecting buttresses (Figure 33). First a diagonal line is drawn from the apex of the intrados C, down through the springing B and into the buttress. From B the upper portion of this line BC is then rotated both vertically to give D, and horizontally to give G. D and G are then joined by a line which intersects BC at I. From I a horizontal line is drawn intersecting BD at L, from which point it is continued to K, so that IL and LK are equal. K then marks the projection of the buttress.

For the perfectly round arch the wall thickness to span ratio is **<u>1 : 2.8</u>**

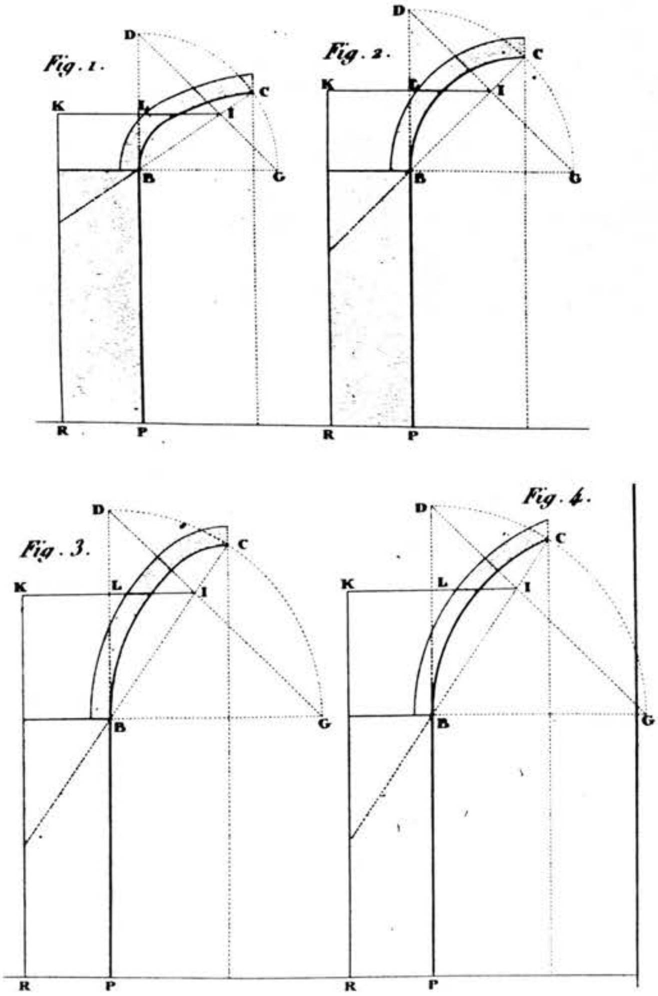

Figure 33

(Rondelet, 1847: Pl. CLXXXXIX)

4.6 JEAN RONDELET

Methods were devised by this nineteenth century theorist involving extensive calculation in the resolution of forces acting within a voussoir arch or vault. The calculations do not concern us here since, firstly, we are only using the method as an example for comparison with the achievements of architects in medieval and renaissance Scotland and, secondly, it can be assumed with relative safety that the mathematics involved would have been well beyond the wit of those architects. The method developed by Rondelet, however, can also be practised entirely by means of constructive geometry and this is shown in figure 34 below. Translation of Rondelet's geometric process is quoted direct from Gwilt (X 1889: 366):

"Let the mean curve TKG of the arch (whatever its form) be traced as in fig. 17, the secant FO perpendicularly to the curve of the arch, and through the point K, where the secant cuts the mean curve, having drawn the horizontal line IKL, and raised from the point B a vertical line meeting the horizontal IKL in the point *j* , make K*m* equal to *j*K and set the part *m*L from B to *h*, and then double the thickness of the arch from B to *n* . Let *hn* be divided into two equal parts at the point *d*, from which as a centre with a radius equal to half *hn*, describe the semi-circumference of a circle which will cut in E the horizontal line BA prolonged The part BE will indicate the thickness to be given to the piers of the arches to enable them to resist the thrust."

The resultant wall thickness to span ratio is **1 : 3.33**

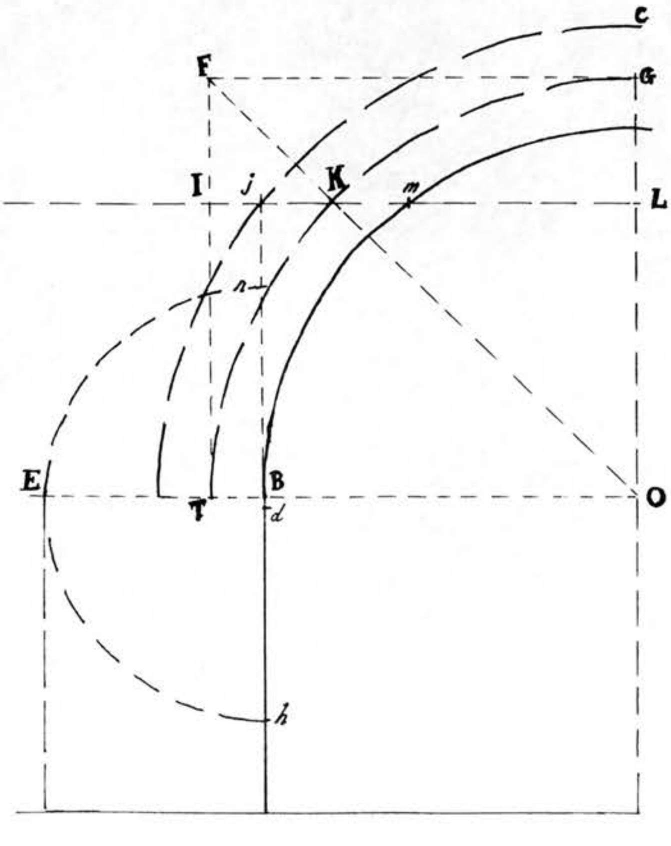

Figure 34

5 AN INTEGRATED WORKING SYSTEM: LORENZ LECHLER

Lechler's instructions to his son written in 1516 set out the means in principle for the design of a complete late medieval hall church, from dimensions of overall structure to the smaller elements such as ribs and window mullions, using both numerical ratios and the traditional technique of constructive geometry, although the latter is generally used to derive the smaller elements. They come to us in two rather confusing transcripts from the late sixteenth century which have been interpreted by Shelby and Mark (II 1979, 113-131). The following simply summarizes those elements concerned with wall thickness and its relationship to other dimensions.

WIDTH

All structural dimensions derive from the width of the choir, which is recommended to be either 20' or 30'.

HEIGHT

There are several alternatives recommended for height, which are sometimes repeated in different contexts with possible variation in meaning. In essence they can be summarized as follows :-

1½ times the width;

Twice the width;

Three times the width;

Or: "as they please, or as it must be done in that locale".

There is some ambiguity as to the point to which height is measured: "haubt" is translated by Shelby and Mark as *tas-de-charge*, later commenting that it more likely refers to the keystone, and I have to agree that the latter is more likely.

WALL THICKNESS

Related to the choir width in the ratio 1 : 10 (expressed as 2' thick for 20' span and 3' for 30' span)

Dependent on quality of building stone: subtract 3" if good hard stone used; add 3" if poor quality.

NB From the module of the wall thickness, Lechler derives other smaller elements of the building such as vault ribs and window mullions by inscription and rotation of squares within each other.

BUTTRESSES

There are two ambiguous and contradictory recommendations:

(a) For a choir 30' wide, and walls 3' thick, buttresses should be 3'2 (presumably inches) wide and twice as long i.e. 6'4". Total abutment to span ratio: **1 : 3.3**

(b) Where choir walls are 3' thick, buttresses to be 2'6" wide and 5' long. Total abutment to span ratio: **1 : 4**

Although precise formulae are lacking for the relationship of buttress size to wall thickness, there is a suggestion in (a) that the buttress width should be roughly equivalent to the wall thickness, and there is some consistency in the 1 : 2 ratio of buttress width to projection at the level immediately above the ground table.

However, actual late gothic churches inspected by Shelby and Mark are apparently more consistent with (b) above.

Slenderness ratios are obviously difficult to formulate from prescriptions as contradictory, diverse and ambiguous as these. However, let us take a choir of 20' width, with height to the keystone of the vault of 30', of which 13' is the vault itself leaving a wall height of 17'; the wall thickness is taken as 2' with a buttress width of the same, and projection of 4'.

Resultant slenderness ratio of wall thickness alone:	**1 : 8.5**
plus full buttress projection :	**1 : 2.83**
- of wall plus half the buttress projection :	**1 : 4.25**
- average of these two :	**1 : 3.54**

6 SLENDERNESS RATIO SUMMARY

FREE-STANDING WALLS (RONDELET)	1 : 8 1 : 10 1 : 12
PARTY WALLS (LONDON 1189 ACT) 3 feet	1 : 5.3
PARTY WALLS (EDINBURGH 1698 ACT) 3 to 2 feet up to c. 45 feet	1 : 18
TOWERS (ALBERTI)	1 : 20
TOWERS (STIEGLITZ)	1 : 20

7 SPAN RATIO SUMMARY

(Wall thickness including buttresses to Internal Roof Span)

ROUND VAULT (GAUTHIER theory)		1 : 2.85

ROUND VAULT (RODRIGO thickness & height theory 2)		1 : 3
ROUND VAULT (RODRIGO $\sqrt{H+\frac{C}{2}}$ theory)		1 : 3.1
ROUND VAULT (RODRIGO thickness & height theory 1)		1 : 3.22
VAULTED HALL CHURCH (LECHLER theory only)		1 : 3.3
ROUND VAULT (RONDELET theory)		1 : 3.33
ROUND VAULT (RODRIGO 2 - $\sqrt{2}$ x R theory)		1 : 3.414

ROUND VAULT (RODRIGO general recommendation)		1 : 4
VAULTED HALL CHURCH (LECHLER theory, but also local practice)		1 : 4
CIRCULAR DOMED CHURCH (SERLIO Fol.2)		1 : 4
ROUND VAULT (DÉRAND theory)		1 : 4
BRIDGES (PALLADIO General recommendations)	from	1 : 4
HEXAGONAL DOMED CHURCH (SERLIO Fol. 6)	(1 : 5)	1 : 4.3
ELY CATHEDRAL (COLDSTREAM)	(1 : 5.66)	1 : 4.67
NORWICH CATHEDRAL (FERNIE)		1 : 4.8

PENTAGONAL DOMED CHURCH (SERLIO Fol.5)		1 : 4.9

BRIDGES (PALLADIO General recommendations)	around	1 : 5
ST. MARGARETS CHAPEL, EDINBURGH CAS. (FERNIE)		1 : 5
OCTAGONAL DOMED CHURCH (SERLIO Fol.7)	(1 : 5.4)	1 : 5
OVAL DOMED CHURCH (SERLIO Fol.4)	short span	1 : 5.75

BRIDGES (PALLADIO General recommendations)	up to	1 : 6
BARREL-VAULTED CHURCH (FRANCESCO DI GIORGIO)		1 : 6.83
CIRCULAR DOMED CHURCH (SERLIO Fol.3)		1 : 7
OVAL DOMED CHURCH (SERLIO Fol.4)	long span	1 : 8.25

8 CONCLUSIONS

It quickly becomes obvious that the use of some of these models for analysis is problematic. Lechler's instructions are ambiguous and unclear, particularly concerning the height of a vaulted hall church and also the sizing of buttresses. Francesco's church is only an idealized project, as is his method of creating a module. Putting the two together was the inspiration of a later theorist, Richard Betts. Likewise Serlio's Temples are all mere paper projects and the theories of Rodrigo, Dérand and Gautier are just that: theoretical. We have little idea how much of their thinking was based on construction experience. Only Rondelet is known for a certainty to have measured existing work extensively. Nevertheless it is possible that the chronologically earlier of these may indicate to us at least characteristics of the mind of the medieval and Renaissance designer, while the later theorists give us model methods which can be used to test our own survey sample and whose results provide standards for comparison.

In any event, even in the case of odd exceptions, the figures give us a useful idea of the level of consensus amongst both builders and theorists. A closer examination of these figures is now required. Rearranging the examples and models used into order of ratio magnitude, the preferences of the majority become clearer. Several points become immediately obvious:

1. There is a marked preference for methods and systems of whatever origin for a span ratio of c.1: 4 and then for ratios up to c.1: 5 and also between c.1: 3 and c.1: 3.4.

2. The preference for the first group of around 1: 4 is backed up by Rodrigo's general recommendation as well as the general consensus among his colleagues and contemporaries.

3. The general advice of Palladio for bridges between 1: 4 and 1: 6 seems to be supported by evidence of actual built structures, although these are concentrated between 1: 4.5 and 1: 5, and also most of Serlio's temple projects.

Then there are the exceptions at both ends of the scale to be accounted for. Again it is very noticeable how amongst the ratios around 1: 3, there are no built examples; all are theoretical, and interestingly, they do not graduate up to 1: 4, all are below 1: 3.414. It is perhaps instructive that the medieval and Renaissance mason was much more economical in his use of stone then the later theorists thought they should have been.

At the other end of the scale are three apparently exceptional projects or designs. The application of Francesco's module to an ideal church has already been explained as a hypothetical interpretation by a later theorist and therefore may not need to be included. Serlio's circular temple (Fol.3) does indeed have very thin walls for its internal roof span, but as already observed this must be to some extent offset by the extra abutment provided by the four appendages of entrance portico and chapels. It is difficult, if not impossible, to envisage precisely how much buttressing effect Serlio imagined these to have. Of course it could be calculated with modern methods but these would probably not have been known by Serlio who might have been more likely to have based his judgement on other criteria. In view of the extra abutment provided by the chapels, this project should more correctly appear earlier in the list of ratio magnitudes, but it simply is not clear quite where.

Finally Serlio's oval temple project seems to defy all logic with such relatively thin walls for the long span of the oval. What was going through the architect's mind can only be guessed at, for even the ratio of the short span is exceptional in this context. Perhaps, since oval buildings were not so commonly built, Serlio simply had not thought through all the structural implications.

For the sake of interest, the average of *all* these ratios is 1: 4.57 and if all the theoretical examples below 1: 3.414 and the exceptions above 1: 5 are excluded, this figure only comes down to 1: 4.47.

APPENDIX II

MEASUREMENT IN SCOTLAND

INTRODUCTION

Any examination of the dimensional relationships within a building, whether to a set proportional programme or not, must begin with some attention to the way in which the medieval builder (whether the patron or the mason/architect) regarded the specification of size, both overall and individual dimensions, in the original conception of the structure. In what terms of measurement was a structure, and/or the space or spaces enclosed, conceived? Did these terms make a difference to the way in which a building idea was realised? Answering these questions is not straightforward. The only usable documentary sources we have are a number of surviving building contracts, and, because the Scottish examples are so rare, particularly for the medieval period, it is necessary to augment the supply with those relating to buildings in England. Fortunately Salzman has located over 120 of these, published as an appendix in his 'Building in England down to 1540', whilst most of the surviving Scottish examples have been gathered by Dunbar and published by the Scottish History Society, but these are all of seventeenth century date. Some others are published by Mylne in 'The Master Masons to the Crown of Scotland'. Yet a few more are to be found in various Burgh records, MacGibbon & Ross and elsewhere. At present very little has been recovered from the sixteenth century, an era of great importance in building history because of the transition from medieval to renaissance and more modern concepts. In the meantime, what has been published represents an adequate body of data from which to recognise some useful trends and to draw some reasonably safe conclusions.

1 MEASUREMENT AND DIMENSIONS SPECIFIED IN CONTRACTS

The variety of building types represented by the contracts recovered is wide: mainly of stone, some of timber; churches with and without aisles, cloisters, curtain-walled castles, gatehouses, classical mansions, lairds and farm houses, domestic ranges, colleges and libraries, halls, tenements and town houses, a malt-house, an oven, and free-standing walls of a multiplicity of sizes and purposes. They are listed in Appendix III with some details which are pertinent to this research.

At a most fundamental level, it is first necessary to observe which dimensions are specified in building contracts, and of equal significance, which are left out. Most frequently length and breadth are represented, as is height, but not in every case, the number of storeys sometimes being considered sufficient. What is of greatest interest in these overall dimensions is the specification that the figures given are to be either "within the walls" or "over the walls". The former *internal* dimension, however, is so commonly specified that it may reasonably be assumed that it was also intended in many cases where not mentioned, with some exceptions: obviously for instance the row of houses in Canterbury with shops below, which were to be constructed in a gap site, would have an overall *outer* length of the same 84 feet forming the length of the site. The one and only building type where external dimensions are almost invariably specified are church towers, and these shall be dealt with at greater length later.

The necessity of specifying whether dimensions given were external or internal was obviously of great importance where no plans accompanied the contract. As we have already seen, architectural drawing had become common, and indeed essential, from sometime in the thirteenth century in order to build complicated structures such as large aisled churches. The survival rate of such plans in continental Europe of the medieval period is good: over 2,200 according to Bucher (II 1968: 49), but survival in England of plans prior to 1500 is comparatively rare (IV Harvey 1972: 110). Not only this, but even reference to plans in contracts is commensurably rare for this period also. That does not necessarily imply that no plans existed, particularly for larger or more complex buildings, but rather that such plans simply did not customarily form part of the legal contract. However, for the smaller vernacular buildings to which many of the surviving medieval English contracts relate, the great volume of detailed specifications was itself to some extent adequate substitute for drawn plans, and perhaps implies their non-existence.

The increasing use of working drawings and plans from the sixteenth century is worth some explanation before proceeding to look at the contracts in more detail. The requirement for precision in measured proportional relationships in renaissance art and architecture, in the whole concept of *desegno*, and in such subjects as military engineering, all contributed to generate a culture of graphical as well as (or sometimes instead of) written description in many European centres. This was particularly significant in England from the 1530s when the survey and fortification of her coastline became necessary following Henry VIII's divorce of Catherine of Aragon and subsequent break with Rome. Such works were initially carried out mainly by foreign-born military engineers, but increasingly native master masons learned the new skills of survey, measurement and draughtsmanship to fill the need. From 1544 the mapping of parts of South East Scotland in the Rough Wooing and the construction of advanced artillery fortifications by both English and French saw the new skills exercised on Scottish territory, but not necessarily by Scots masons (IX Barber 1992: 33-56).

At another level, Henry's vast palace-building programme resulted in a plethora of more accurately drawn architectural plans. Once in place, all these skills were to be used increasingly by merchants, landowners and builders (IX Barber 1992: 36). Architectural drawing proliferated in England in the sixteenth century and we know that mason/architects regularly made sketches and plans of each others' as well as their own buildings: the will of Cornelius Brownstone bequeathed "all my plats and patterns" to John Sparrowe, his apprentice in 1562, while Robert Smythson was known to draw plans, elevations and other details that he wished to record on his travels (IV Airs 1995: 51). Of course, this was not entirely new: Villard de Honnecourt had done the same centuries earlier, but the greater availability of paper and the generally increasing culture of science, enquiry, and precision associated with the renaissance did much to promote a habit of draughtsmanship where it was appropriate and beneficial.

Working in England at this same time was a certain Leonard Digges. Having made some reputation for himself in attempts to improve the English defences of Calais and Boulogne, Digges' lasting fame resides in his popularisation of the use of mathematics and scientific measurement, surveying of land and navigation at sea. His

'Boke named Tectonicon' published first in 1556 (and followed by no less than seventeen editions up to 1656) sought to open up to a wider professional and lay readership the mathematics of measurement which had hitherto been "locked up in strange tongues" (X 1592: 1). Whether he was referring to some earlier Latin text, or to the restrictions on dissemination of professional knowledge by the mason craft is not clear, but is of little consequence to us. What is significant is that he was the first to make this knowledge more widely available (IX Barber 1992: 67). Now whether or not Digges was read in Scotland is impossible to know for certain. Again, an educated assumption must weigh in favour of at least some copies of the multiplicity of editions having crossed the border at some time.

In Scotland James V's own palace building projects in the 1530's and '40's and his use of French architects and masons to bring elements of renaissance style must be assumed to have had some impact on the way in which building design was approached. Of course this is impossible to quantify or qualify, but logic suggests that Scottish masons working alongside the French at Falkland and Stirling cannot have failed to notice the foreigners' way of working, their approach to measurement and use of measuring instruments. The concept of designing a facade which boasted the characteristics of measured symmetry, measured regularity of disposition of windows etc., and some measured proportionality of the elements and of the whole, could not have been entirely lost on the natives.

The fact that so few architectural or working drawings seem to have been produced in Scotland before the seventeenth century (VIII Knoop and Jones 1939: 24) has to be viewed against the background of these various influences: the presence of French palace builders for James V; the presence of French military engineers during the latter part of the Rough Wooing; the publication of Digges' 'Tectonicon'. Perhaps interruption in general building activity caused by the hiatus of the English invasions (VII MacKechnie 1995: 26) gave rise to a set-back in the early development of a graphical tradition. There are, after all, some references to "platts" other than in contracts, for instance the case of Alexander Clark's petition, for permission to build a land at the head of Niddry Wynd in 1575 (X Edinburgh Extracts, 1882: 36) But on the other hand, perhaps the growth of a new culture of mathematical measurement and graphic illustration, whose seeds may have been planted in the 1540's, did not find the right conditions in which to grow immediately, or perhaps the new ideas and skills did not flow freely from south of the border in sufficient volume until after the union of the crowns in 1603. It is with great difficulty that any objective judgement can be made on a subject so nebulous without more hard evidence.

Now, to return to the examination of those building contracts which have been recovered, the specification of wall-thickness seems at first sight to be remarkably random. What is immediately obvious also is the percentage of contracts where wall thickness is not mentioned at all. That of timber-framed structures is rarely specified. Wall thickness in these cases will not be of relevance so much as the size and strength of the structural timbers and that is not a subject commonly covered in the contracts either, nor is it the subject of this research. It is in masonry structures where wall-thickness will be of significance in this project and it is these which require closer examination. It quickly becomes obvious that the contracts where wall-thickness is specified before the seventeenth century in England are almost entirely for church towers, free-standing walls of various sorts, and fortified buildings. (The reasons for this will be discussed later.) There are of course exceptions, the most notable being the towers of Eton Chapel, King's College Chapel, Cambridge, and Arlingham Church of 1372. The former two documents, however, are not formal contracts but rather detailed descriptions of designs approved by Henry VI, so technical specifications are not necessarily to be expected. This leaves Arlingham Church tower as having the only published surviving contract for a church tower in Britain where wall thickness is not specified. However, the mason was contracted to build "*ad modum quo incipitur tam murorum quam aliorum membrorum in tribus annis proxime*" (IV Salzman 1997: 445) implying that the walls had been started already - the wall-thickness thus already being defined.

Apart from these three categories of structure, there are in these earlier English contracts of the fourteenth and fifteenth centuries almost no examples of other building types where wall-thickness is specified. Contracts for all other domestic structures, churches, libraries, etc. do not specify wall-thickness at this time and it is possibly safe to assume that the same may have been so in Scotland.

The sixteenth century was a time of transition but unfortunately also, a time only partially covered by Salzman's collection of contracts. Of the two English examples, we find one domestic building, the farmhouse at Holywell in Oxfordshire where wall-thickness is specified, the other, a church house at Great Sherston where it is not. It is also a period in which the use of plans drawn to scale and specifying exact measurements was becoming increasingly widespread, particularly for buildings incorporating perhaps some characteristics or features of classical origin, such as symmetry or regularity of disposition of individual elements.

Seventeenth century Scottish work sees the use of some such plans but also in some cases dimensions specified in the text of the contract, as for Gallery House, Angus, 1677 (VII Dunbar 1990: 295). Unfortunately original plans rarely survive and their existence is often only evidenced by reference in contracts. We therefore have no means of knowing whether or not plans existed for new buildings where there is no such reference. A negative assumption in such cases may seem reasonable and may turn out to be justified but, nevertheless, may not be safe. However, we can only proceed with such information as presents itself in the surviving contracts and make of it what we can, whilst keeping the latter in mind.

In some respects the story in seventeenth century Scotland is not dissimilar to that of English contracts pre 1540. Of a total of 25 contracts for masonry structures, eleven do not specify wall-thickness at all; only six do. However, seven specify what is also found earlier but appears to become increasingly common in this latter period: that walls should be of "good and sufficient thickness" or "competent thickness" or other words to similar effect. There is an implication here of the builder being obliged to guarantee the strength and quality of his workmanship, so that in the event of the building's failure within some unspecified period of time after completion, he may be called to account and sued or compelled to make good the works. Again, these expressions are certainly found in earlier documents and sometimes with the terms of a guarantee obligation, such as that imposed on the builder of Woollavington in 1586 to "at his costes and charges repaire and amend well and substanciallie all suche the decayes and defaultes ... duringe the space of one wholl yere nexte after the finishinge of the same worke" (quoted in VIII Godfrey 1924: 223).

Now as to those structures where wall-thickness is not specified, it is immediately evident that a number are small or utilitarian in nature: an oven, a doocot, a summerhouse. The Edinburgh Cowgate tenement was to have only its ground floor in masonry. The house at Abington is of only two storeys. The Fearn Abbey contract is only for the reconstruction of an aisle. Falkland Church was to be demolished and rebuilt, it seems as a simple barn-like structure (28 feet wide) with an aisle on the north side - not particularly demanding in terms of structural design. The demolition and reconstruction of Logie Church was to "conforme to ane draught drawen by ... Tobias Bachop" on which no doubt the wall-thickness appeared. The use of plans appended to the contract clearly obviated the need for such detailed specification in the contract itself, and this obviously applies to Gallery House and Panmure House, both in Angus. There were also drawings for the steeple of Heriot's Hospital.

Where wall-thickness is specified in the contract, there appears at first sight to be little in common in quite the same way that so conveniently joins the earlier group in England - church towers and fortifications of one sort or another. In the seventeenth century the design of fortifications had moved on to the earth rampart type, so their absence does not surprise. New church towers, however, were not rare in Scotland, and this was also an era of much tolbooth tower building. It is disappointing , therefore, to have no surviving contracts for this type, apart from the Edinburgh tolbooth which does not have a tower. What then, if anything, joins the five examples where wall-thickness is specified? Firstly, four of the structures are known to have been more than three storeys high: the house at Dreel, Auchenbowie, Mylnes Square and Partick Castle. Interestingly, although these tall domestic structures seem to have justified specific wall thickness, another for a similar structure, albeit less one storey, did not: The contract for a three storey house at Leys does not specify any dimensions or wall-thickness at all. Moreover, it was to be erected in a mere two months. Perhaps it is not surprising that little trace of it remains.

The specification of wall thickness where the abutment of a vault was involved also seems to have been considered essential. Partick Castle mentioned above had a vaulted basement and the wording of the contract is very mindful of this: "... of sufficient thickness of ye walls yrof as may serve for ane woltit house" (VII MacGibbon & Ross 1887-92: V 5), following which the thickness is specified as the equivalent of 37 modern inches. The builder here is concerned specifically with the relationship of wall-thickness generally with vault abutment. The same appears to be so at Cawdor where wall-thickness is specified for the rebuilding of parts where vaulting is to be installed. Conversely, it is significant that the wall-thickness of the unvaulted jamb at Partick is not specified.

2 VARIATIONS IN UNITS OF MEASUREMENT

Now whilst the specification of dimensions, wall-thickness, etc., whether written into a contract or drawn on scale plans, might appear explicit enough at first sight, it is very dependant on an understanding by both/all parties to the contract of the length of the units of measurement employed - usually feet or occasionally ells, and binary fractions thereof. To put it simply, how long is a foot and, for that matter, how long also is an ell?

Existing studies of metrology in Britain are still very incomplete. The best source covering England is undoubtedly Connor's 'The Weights and Measures of England' published in 1987, which does also give some pointers to what was happening in Scotland. Here, the only published coverage is provided in an Appendix in Pride's 'Dictionary of Scottish Building' (VII 1996 104-105), by Alan Simpson together with Connor.
Dr. Simpson is shortly to publish a full work on the subject and I am greatly indebted to him for kindly providing me with two relevant draft chapters prior to publication, upon which some of the following is based.

In essence, Scottish linear measures share much common ground with their English counterparts, in theory at least. The modern English foot of 12 inches, each inch derived from three barleycorns, or from the width of a thumb at the root of the nail of a middle-sized man (according to various documents including the Assize attributed to David I but in later text, and to the fourteenth century English *Certa Mensura*) was the basis for much official linear measurement. Richard I's Assize of Measures of 1196 laid down that "throughout the realm there should be the same yard of the same size and it should be of iron" and so the yard, and with it the foot and the inch of 30.5 millimetres was officially defined. At that time of peace and trade in goods and ideas between England and Scotland, some commonality of linear measurement units was undoubtedly achieved, but differences developed, in particular the Scottish ell, a yard and an inch, defined in David's Assize as 37 inches, became the standard unit, primarily as a measure of cloth, to begin with at least. It is generally thought that the extra inch was added on the sale of a length of cloth to ensure that if the purchaser lost anything on the cutting or tearing of the length bought, the extra inch would make allowance for that. Eventually the extra inch became added to each yard sold, rather than to each sale, and so the Scottish ell was created. (There was also an English ell, but this was 45 modern inches and had been in use in England at least before the Norman invasion). This Scottish ell came to be used for measurements also in building, land survey and, no doubt many other applications, itself giving rise to new linear units: rather than being subdivided into the inches from which it had originated, the ell in use became traditionally divided in a binary manner, into quarter, half and three-quarter ells. Each quarter ell then became divided into four quarters each known as a 'nail' being 2.3 inches long.

Now if it could be assumed that it was almost only the modern English inch, foot, yard and Scottish 37 inch ell that were the basis for linear measurement until industrialised times, this research would be greatly simplified. Certainly for goods being traded, at home and abroad, it was important that they were weighed or measured in units that were standardised and at least to some extent universally recognisable. John Reid comments in 'The Scots Gardner' that there was "no distinction betwixt a Scots and English foot" (X 1683: 38). If this were true, then this unit at least in Scotland would be standard throughout the country. For such commonality and standardisation to have existed there would have to have been one or more prerequisites: firstly, some legal edict imposed by government and also some means of communicating any such standards across the whole country. Now the Assize of David I which set out the basic measurements of inch, foot and ell described earlier, has already been mentioned, but how universal these standards ever became is impossible to assess. Even if they had become nominally ubiquitous, the degree of accuracy when a measuring rod was copied, then that copy duplicated in turn to make another, has to be questioned. The results over several generations will undoubtedly show variety. Furthermore, there will be pressure for change to suit the individual circumstances of each locality, or for particular products or materials, glass being a case in point, of which more later. With constant straying into diversity from one or other of these causes, quite apart from the less than honest merchant's ploy of deliberately using inaccurate measures, variation became inevitable and is evidenced by several further attempts by central government to legislate and to communicate fixed standards to the burghs, principally the Acts of 1425, 1587 and 1663.

Three sources of the seventeenth century provide clues as to the levels of standardisation or otherwise then prevalent in Scotland: first the 'Treatise of Weights Mets and Measures of Scotland' by Alexander Huntar published in Edinburgh in 1624. At the beginning of a section on the measurement of land, Huntar mentions that there are no "... books to informe ... according to our Scottish measures." (X 1624: 11). Hopefully Huntar had done sufficient research to assure himself that there never had been any other works of this nature. It would be interesting to know if he had by then chanced upon Digges' 'Tectonicon' which, of course did not inform specifically on Scottish measures. Even if there had been other books to inform on the subject, it is questionable whether or not they would have found particularly widespread use amongst the artisan classes.

Secondly, in the following year, at the Convention of Burghs, a new standard was set for what has commonly become known as the glazier's foot. Here, if nowhere else, is evidence that standards had not been universally adhered to. Glass manufacturers and glaziers in England had adopted a 'foot' unit of 7.92 modern inches, which reflected the limitations of window glass manufacture at that time, panes being restricted in size to that achievable by the spinning process. In Scotland the unit adopted was roughly 9 modern inches, 8.88 to be precise, being also one twenty-fifth of a 'fall', the Scots unit of land measurement roughly equivalent to an English perch or rod. This 8.88 inch foot was itself then divided into ten inch units of 0.88 modern inches each. However, because of constant abuse, which cannot be wondered at given that this glazier's foot did not have any relationship to the other nearest linear measurements such as the standard foot or the ell, the 1625 Convention of Burghs ordained that it should be henceforth defined as one quarter of an ell, that is 9.25 modern inches.

The third source is the 1663 Parliamentary Act which decreed: "...the ell is designed to be thirty seven inches, Yet many use inches by which the ell is divyded into fourty tuo inches, and of these small inches make the foot measure of a smaller proportion than it ought to be To the great preiudice of the leidges; and that the occasion of this liberty hath been Because that hitherto ther hath *no standard been appointed* for foot measures alswell as other measurs; Therfor ... from & after the first day of Junij next 1664, no workman nor other person shall make vse of any other foot measure, then such as consists of tuelve of these inches whairof the ell containes thirty seven; And that this may be the better made practicable to the leidges ... ane exact Standard foot to be made ...of yron or copper and preserved by the City of Edinburgh for all time comeing, And that all burghs shall have a measure made according to it & hung at their tolbuith doors or vpon their mercat croces befor the first of March 1664 ... And ordaines that all wrights glasiers masons and other sorts of publict workmen shall work by this foot measure allenerlie that the leidges may not be abused by varietie of measures ..." (APS 488, emphasis mine)

Now a number of noteworthy points emerge from various or all of these sources. When drafting the 1663 Act it seems to have been *perceived* that no *standard* foot had ever been officially decreed, at least not for glaziers and others in the building trades. Even the authorities did not seem to be aware of the previous legislation. Huntar believed that there had never before 1624 been any publication which communicated any standardised survey measurement system, and before the 1625 Convention of Burghs, there had been no effective regulation of the glazier's foot. Since the medieval period this had been created or evolved through customary use, particularly in the construction trades. The case for rigid standardisation and regulation of Scottish linear measure, let alone conformity to English models, looks decidedly shaky: units could be subject to abuse, to local variation, and to evolution, partly due to lack of effectively communicated regulation.

All this simply tells us of the uncertainty and variation in measurement units employed in the previous period. As if that was not enough, we must add a further factor when looking specifically at the work of masons and architects. If there were no other books or writings, as Huntar tells us, by which surveyors and builders worked, how do we know what units of measure they used, when, as a craft, they did not communicate knowledge of their trade outside the Lodges, and, even within the craft, there may have been much variation? Their knowledge was passed on from master to apprentice in an oral tradition which, incidentally, may also have been essential in the event of illiteracy. Even in some of the early European architectural treatises not all secrets are revealed: Betts comments on how Francesco di Giorgio shows how to obtain his basic module for a church design, but stops short of informing us its measure and how then to use it. (II 1993: 11). Alberti probably knew little or nothing of structural design and we are fortunate to glean anything on the subject from him. Huntar himself confesses that he has not penetrated the web of professional confidentiality which pervaded the architectural/masonic craft: "I doe not set downe the manner nor the way, how to measure the Masons nor the Sclaiters workes, because I know not the trew ground and manner thereof ..." (X 1624: 55). Again, Digges' reference to such knowledge being "locked up in strange tongues springs to mind". It is eminently noticeable how vaguely his own 'Tectonicon" and even the plethora of architectural pattern books published in and since the sixteenth century deal with the subject (IV Harvey 1972: 103). Even in the eighteenth century when Richard Neve was researching material from the architectural / building profession for his "City and Country Purchaser and Builder's Dictionary" (X 1703, 1726 & 1736) he met with a wall of reticence: although a Mr Wing informed him of some prices for masonry wall construction, Neve complained that he did not "understand what he means by all this Tattle; for he never tells us any thing of the thickness of the walls..." (X 1726: 279). In an era when the mason craft was becoming increasingly threatened, not from mere unskilled pretenders or usurpers, but from the increasingly interested public, and intellectual elite, there was a likelihood in some quarters at least of retreating into more obscure and individualistic modes of practice, rather than conforming to ever greater efforts at standardisation and regulation.

The masons' metrology cannot necessarily be compared with that of, say, the cloth merchants whose goods were to be traded, sometimes across international boundaries. Buildings were not traded in the same way, the proportional dimensions within their fabric only had to ensure that they would provide the space(s) required, and that they were structurally sound. The means by which the masons achieved these ends must have been largely up to them. Even the Schaw Statutes of 1598 do not attempt to dictate adherence to any particular standard or system. It was only stipulated that "...thay be honest, faithfull, and diligent in thair calling, and deill uprichtlie w_t the maisteris or awnaris of the workis that they sall tak vpoun hand, be it in task, meit & fie, or owlklie wage." (quoted in VIII Lyon 1873: 9). Incidentally, it is more likely that "meit & fie" refers to payment, rather than measurement. Even if there was an intended reference to the latter, still no particular standard is mentioned. Likewise the Falkland Statutes of 1616 made no reference to conventions of measurement. It is likely that any regulation on this subject may have largely passed the architect/mason by, or simply been ignored.

However, in a sense buildings were traded. The initial contract was also in many cases a specification, as we have seen, and dimensions in feet and occasionally ells were frequently mentioned. But this still does not bring us any nearer to finding the answer to the fundamental question concerning the foot, or the ell, mentioned in these contracts - precisely how long were they?

The majority of the contracts recovered reveal nothing more than their face value: they simply specify so many feet and, like ells, parts of feet were treated in a binary manner - halves, quarters and so on. Inches were rarely used unless the amount was for less than a whole foot and the item being specified was for a smaller individual element in the building such as treads of a staircase. Again, we have no clue as to how long these units actually were. Was there a common assumption that the language of contracts was of English feet, or were they of the type described in the 1663 Act: the glazier's foot of 8.88 inches apparently used by many others in the building trades? Perhaps there might have been yet other variations.

Fortunately not all the surviving contracts are so standardized in their expression of measurement. In just a few are hints that perhaps tease us as much as they inform. That of the tenement of James Belshes in Cowgait, Edinburgh specifies a length of fifty-seven "Inglisch foot", which seems straightforward enough. However, it only beggars the question: were most other contracts, because they did not specify 'English' assumed to be written in terms of some other type of foot, or was Belsches contract merely stating what was obvious and common practice?

Remembering that the 1663 Act stipulated in the building trades the use only of the foot "such as consists of twelve of these inches whairof the ell containes thirty seven ...", (that is an English foot), the calibrated scale on the plans of Holyrood Palace by Robert Mylne and William Bruce, drawn only eight years later in 1671, comes as some surprise. The plan of the first floor level of the old palace built by James V is drawn to a scale which bears the caption "Scale of 60 foot Scots which is 61 foot and 8 inches Inglish".

It is clear that Mylne and Bruce are using a Scots foot of 12.33 modern inches, and this is of course exactly one third of a Scots ell. In other words, the ell of 37 inches has at some stage been revalued or recalibrated to consist of 36 longer inches of about 1.027 modern inches. Possibly of little more significance than coincidence, this Scots foot bears a striking similarity to the so-called Rhineland foot of 12.35 modern inches. Connor has noted that English charters of the twelfth and thirteenth centuries mention "yards with inches" (IX 1987: 88) in connection with land measurement. There is obviously a parallel with the Scottish ell and Simpson suggests that the connection is to be found in the use of the Rhineland foot, which formed the basis for survey work in the German states and Low Countries until the nineteenth century. Whilst for English survey work the 36 inch yard took over from the thirteenth century, there may have been a longer connection in Scotland with whom those countries had close trading links. Whatever its origins and whatever the dictates of officialdom we have Mylne, the King's master mason, and Bruce, the court architect, using units which theoretically have no legal standing whatsoever. The questions have to be asked, are these the units employed in all building work, and indeed in building contracts? If so, for how many years, or centuries had this been customary? In what situations would this Scots foot be used in preference to the English foot, or indeed the shorter glazier's foot? A formidable range of possibilities begins to emerge, but this is only the beginning!

The contract for the High School in Edinburgh of 1578 specifies "... all ther elins to contene thre fute and ane half for the elin;" (X Edinburgh Extracts: 1882, 75). It may be noticed that 3½ feet is 42" and, coincidentally, this is nominally similar to the glaziers' and builders' ell of 42 short (8.88") inches mentioned in the 1663 Act. Now it is conceivable that the contract is saying that the ell should consist of 42 units of 0.88" each, which equals 37" - logical enough. However, as previously mentioned, the glaziers' foot consisted of *ten* such units, not twelve, and 3½ times that will be only 31". If the 3½ feet specified really are standard English feet, then we do appear to have a genuine variation on the otherwise standard Scottish ell for building purposes. Is this an isolated instance of the 3½ foot ell? Some further evidence is really needed to establish its existence beyond doubt, but it is annoyingly hard to find. There is a tantalising mention of the words "3½ foot" isolated at the lower left-hand corner of the first page of an estimate for work at Newbattle of 1693 (SRO GD 40/2/18/1.77). This all constitutes something of a conundrum!

These cases, confusing and irregular as they may be, at least indicate certain practices which probably boasted an element of standardisation within their own sphere of the building crafts. What follows takes mensuration well outside the limits of any statutory, and even possibly some craft standards, and into the realms of an infinity of personalised variation.

Perusing the literature on the origins of various units of measurement it becomes evident that many if not all ideas were drawn from nature in one form or another, and many from the human body itself or manipulations of it. The inch for example was defined in David's Assize as three average sized barley corns without tails lined up together, or as the width of an average sized man's thumb at the root of the nail, and this is echoed by other sources. David's Assize also gives the basis of the rod of land as "... 6 ells which make 18 feet of an average-sized man, neither big nor small." A German source 'Geometrei' by Jakob Kobel in 1531 (quoted by IX

Connor 1987: 44) claims that the rod was generated by sixteen men being lined up on leaving church. Simpson has also come across an undatable legal fragment defining the width of a rood of land "The rude off lande in baronyis sa conten vj elne that is to say xviiij fut off a mydlyn mane" (APS I 751 *Fragmenta ... Collecta* No. 15). Incidentally, in these and other sources, a rod, rood or perch in a burgh, as opposed to the countryside, is nearly always given as twenty of such feet.

All these and many more examples, however, represent the means by which a generalised unit of measure might be generated in a particular locality. What if the process were used in cases of individual buildings? Suppose for instance that a man wanting to build a house hired a master mason who seemed to be of average size, and it was agreed that the mason should use his own foot as a unit of measure. Or perhaps the client might insist on his own foot length being used. So long as the internal dimensions of the property were sufficient to house the patron for his purposes, and the structure was sound, it would matter little what unit of measure was used. If such units were used, would there be evidence in the building contract, or would omission of such details necessarily mean that some other more generalised standard was used?

Contrary to all expectations, there survive two contracts where this is the case: in the building of Partick Castle the contract of 1611 states that the wall-thickness of "The mayne hous being maid thrie futtis and ane half of the said georges awin fute ..." (George being George Huchesoune, a Glasgow notary who was commissioning the house) (VII MacGibbon and Ross V: 5). It goes on to specify that seven of George's feet will be the equivalent of two ells. This makes each of George's feet 10.57 modern inches (assuming that the ells specified are of 37") making him roughly a size 9, which in this day and age is fairly average. Coincidentally perhaps, the wall will therefore be one ell thick. From this contract it is difficult to know whether the ell was the dimension primarily chosen for the wall thickness because this was roughly the amount used in most other such structures, or that was 'calculated' to be appropriate for the structural design of Partick, and George's feet chanced by happy coincidence to 'fit the bill', with the possible benefit of stamping his own personality on the structural design with similar affectation to the application today of personalised number plates.

Alternatively, was such use of the natural foot actually much more common than is specified in such contracts? Was it perhaps quite normal for the master mason in charge of the job to simply use his own foot, whether or not this was specified in the contract, for ease of working so that he could simply pace out the site? It would be useful if their were a contract where it was the mason's, rather than the client's foot that was used. Fortunately there survives just one such example: the contract for Tom Bannatyne's house at Kirkton of Newtyle of 1589 specifies "... the wallis above the jestis of the cabinat to be ellevine futis hicht the sydwallis thairof sevin fute of the said John Mylneis naturall fute ..." (VII Mylne 1893: 67), Mylne being of no more distinction than master mason to King James VI. No indication is given of the equivalence of Mylne's foot in this case. The implications of this in any research into structural dimensions possibly until, even into, the eighteenth century are awesome indeed.

To summarize, there is evidence that by the late sixteenth and early seventeenth centuries at least, the following units of measure were being used in Scottish building:

UNIT	LENGTH in modern Imperial	COMMENT
Standard English foot	12"	official
Scots foot, being 1/3 of an ell of 37"	12.33"	unofficial
Scots glaziers'/builders' foot consisting ten 'inch' units of 0.88" each	8.88"	to 1625
Scots glaziers'/builders' foot being ¼ ell	9.25"	official from 1625
Natural foot, of any size, but if 'average'	c.10.5"	unofficial
Scottish ell of 37"	37"	official
Scottish ell of 42 short inch units of 0.88" each	37"	unofficial to 1663
Scottish ell of 3½ (English?) feet	42"	unofficial

It should, of course be mentioned that all this is only the information that comes down to us from building contracts. In an earlier period, the eleventh and twelfth centuries, the old Roman foot and the continental Toise may well have survived alongside the English foot and whatever else may have been customary.

One other area of question to which there may be as great a variety of answers is this: with what instruments did masons of this period measure, and with what degree of accuracy and standardisation were they calibrated? Salzman provides from documentary sources records of several alternatives (IV 1997: 340) and finds that carpenters and masons probably used the same or similar equipment:

Westminster	1354	'a long rod for the carpenters' measure'
York	1485	'metroddes'
London	1409	'2 poeles for the carpenters' measures'
Windsor	1345	'5 poles of firre for measuring the said building'
Collyweston	1503	'iij polles to take mesur of the said warkes'
Westminster	1532	'a fyrre pole whereof was made a measuryng pole for the carpenters'

York	1327	'string bought for measuring fireplaces'
Windsor	1366	'2 lines for measuring stones'
	1462	'string called *pakthrede* for making *lyne* for the masons'
Westminster	1532	'Pakthrede whereof was made rayngyng lynes for the bricklayers'

The references to 'lynes for the masons' in the 'Accounts of the Masters of Works' (Scotland) are more numerous than those relating to carpenters. Presumably they would have been used for various purposes: setting out in conjunction with pegs; guidance in achieving level courses of stone or brick; measuring both short and long structural dimensions. Of the latter, there is one more specific mention relating to work at Holyrood in 1531-32:

"ane lyne to the wrychtis for musering of the mulde cupill" (X AMW I 1957: 98)

Apart from all these references to poles and lines, one might perhaps have expected to find some references to shorter rules or perhaps ellwands. Of the latter there are none. However, of rules there is one reference that again teases rather than informs:

"Item for lynes to the maissounes and takittis to mend ther rowillis" (X AMW II 1982: 405). It requires some stretch of the imagination to envisage quite what form such "rowillis" took that they could be repaired with short nails! In 1324 William Hurley the (English) king's master carpenter was paid for an empty barrel for making rules and squares for the masons *(pro regulis et scuyris inde faciendis ad cement)*, (quoted in IV Harvey 1972: 109), and a "two-fold rule" has been noticed by Andrews on some sepulchral effigies (IV 1925: 88).

It does seem that measurement, both of whole structure, as well as of smaller elements such as doors, windows etc. could be and was done by both rods of many and various lengths and string according to what seemed most appropriate to the occasion. Harvey mentions "yard-sticks" as well as "canes of two yards - the ancestors of the modern six-foot rod" (IV 1972: 98-99), which Andrews identifies as *virga geometralis* . The same author notes similar instruments referred to as *metrods* or *metwands* (IV 1925: 65). The tomb effigy of Hugh Libergier, architect of Reims Cathedral, shows him holding a measuring rod which, if he was about an average 5'10", might possibly be a Toise (1.42m.). The long "poles of fir" mentioned above were quite possibly the length of the pole/rod/perch measurement, that is sixteen and a half feet for many purposes, particularly buildings in the country; twenty feet in burghs. A reference in the chronicle of Lambert of Ardres (quoted by IV Harvey 1972: 97) to a *geometricalibus perticis* would seem to confirm this in one instance at least. Returning to the "poles of fir", it can only be wondered with what degree of accuracy they were cut and calibrated: doubtless with best endeavours, but these records quoted by Salzman above of the manner of their acquisition hardly inspire visions of the rigid stamp of official attestation, when compared with the precision afforded to the production of the ellwands and beds which graced the tolbooths of burghs for the benefit of the clothmerchants and their fortunate customers.

The implications of all this are far reaching if not imponderable. Firstly, the accuracy and standardisation of measuring instruments for the setting out of buildings may be questionable. Then also we have in most cases absolutely no way of knowing what units of measure are being employed. If contracts could be relied upon to refer to modern English feet when they make no other specific reference, then all would be reasonably straightforward. Because this may be in doubt, the building to which each contract refers ideally requires to be measured with a modern standardised tape to ascertain the actual length of the units employed. Unfortunately only a handful of the buildings depicted in the surviving contracts have survived to be subjected to the scrutiny of the modern measuring tape. Of these the simplest and most accessible structure is the double doocot at Nether Liberton, Edinburgh, of 1680. The contract dimensions are 36' by 19'. The actual dimensions taken are as follows:-

North side	36' 4½"
South side	36' 3"
East & West sides	19' 4"

If the east and west sides had been 19' 4" and the north and south nearer 36' 7", one of two scenarios might be suspected: either the mason was using standard English feet but his measuring equipment was faulty; alternatively he was using something like the "Scots Foot" of 12.33" employed by Mylne and Bruce on the Holyrood plans. However, even allowing for diminution due to weathering, the message which the doocot seems to tell us is this: that standard English feet were used, and that about four inches were added to each dimension, probably to ensure that the mason was over- rather than undermeasuring; rather the same principle perhaps as the extra inch added to a yard of cloth to ensure that the customer is getting full value. Do we have here yet another complication to add to an already overloaded mechanism of analysis? Granted, a doocot is only a doocot, and it is unlikely that anyone would lose sleep over a few inches divergence from the building contract, especially if it was in their favour. Also, this is only *one* example, and it would be unwise to make too many generalisations on the basis of it, but it is nevertheless worth keeping in mind when collating other scraps of evidence from the past to try and form a picture of the mason's method of working. It also points to a need to examine more closely the use of the various units of measure in the simple geometric figures that form the basis of the plans, sections and elevations of masonry structures.

3 THE SQUARE AND A QUESTION OF EXACTITUDE

The fundamental significance of the square has already been mentioned. It formed the principle building block on which most spatial and structural design was founded. Its construction, using pegs and string on the ground, by any number of different methods must have been developed thousands of years ago, and the means of checking its rectilinearity by equalisation of the diagonals must surely also have been known since time immemorial. With such ease of accurate construction possible, with accuracy of paramount importance in the design of major buildings for structural stability alone, and possibly also for the intrinsic satisfaction of knowing that the finished building perfectly followed certain geometric rules and canons, reflecting to some an element of the perfection of the universe, it might be expected that measurement would reveal a building culture based on this most simple geometric figure, accurately measured.

For whatever reasons, this is strangely not the case. The accurately planned square (and its derivatives) is conspicuous by its almost consistent absence in, at least Scottish, medieval building. What is there in its place? Curious perhaps is the consistency with which is found what I will call a 'medieval near-square'. There are two variations even of this intangible figure. The ratios of their sides are generally between 1:1.04-1.05, roughly a square and a twentieth, or around 1:1.1, a square and a tenth. Such figures are to be found wherever an exact square might be expected. The bay system of an aisled church, the crossing of a church, the cloister of a monastery, the base of a church tower. In some of these cases the square and a twentieth might perhaps, in view of its diminutive scale difference, be written off as inaccurate measurement by the original builder or the later surveyor or as later movement of the building, but for the very fact of its consistency. It is almost as though the medieval builder made a virtue of it, and it was a recognised, even desirable geometric figure in its own right. Likewise the square and a tenth seems in some cases to be a most important figure. It is to be found in structures where proportional relationships are likely to be of importance such as the ground plan of the chancel of Corstorphine Collegiate Church.

The presence of near-squares has occasionally been noticed elsewhere by others, but the very oddity of the form has never excited much, if any comment at all.

In some cases the dimensions of such a figure conform to the modular system for a site generally such as in the case of Cluny III. Here Conant mentions an annexe at the east end of the abbey church, in which the "basic rectangle (exclusive of the rectangular 'aisles' attached to it) was a near-square 16 by 18 Carolingian feet" (II 1963: 3) i.e. in a ratio of 1:1.125. The pattern of the whole annexe - a near-square with rectangular aisles - "prefigures the mode of planning used in Abbot Odilo's general rebuilding of the monastery" (II Conant 1963: 3). Most historians are attracted to the explicable, to that which fits an existing and interesting pattern, involving either the manipulation of geometric forms, or an obvious proportional or other numerical relationship with adjacent structure. What are perceived as acceptable levels of inaccuracy are often swept under the historian's carpet, sometimes possibly rightly so, rather than accounted for in any more meaningful way.

The recognition of individual near-squares in measured survey work is obviously a straightforward matter. What is not so easy is the identification of such figures in longer rectangular plan or more complex buildings generally where a multiplicity of geometric figures have been added together. If these near-squares were really regarded as standardised figures in themselves, and they could be joined up with any number of other square derivatives, the variety of proportional relationships to be found in these larger multiple structures is potentially almost unlimited. Whilst instances have been found where two or three near-squares, or indeed other recognisable square derivatives have been joined, the level of complexity and uncertainty, if not ambiguity involved in attempting to divine which geometric figures or combinations of figures are at the basis of a ground plan, make it a singularly problematic task, and one in which serious academic conclusions are difficult if not impossible to achieve.

Whilst explanation of the near-square as a generic form is highly problematic, there are a number of factors which may be of use in casting light on what would otherwise seem to be an intractable subject. Firstly, let us recall Serlio's mention of "many Quadrangular proportions" (X Book I.I. Fols. 11 and 12) available to the workman other than the seven he illustrated. This implies not just near-squares but also rectangles of *many* different proportions. It has to be accepted that whilst it is very satisfying to think of medieval builders, at whatever level, engaged in designing and planning buildings using the square, in various multiples or the derivatives based on rotation or other manipulation, such as Conant illustrates: the diagon, single, dual and embracing, the hemiolion, and the auron (II 1968: 34), the real world is very different. Not only is it different, but it is often made up of many different trends and customs being carried on simultaneously. Kidson devoted his entire PhD to following the use of √2 relationships from antiquity through to the medieval period, and many others have followed in his footsteps, but little if anything is ever said about the many important structures which don't seem to conform to such convenient patterns. The tidy academic world of conformity to certain trends is not a realistic starting point for explaining such phenomena, particularly when they are products of the medieval age. It must be assumed from the beginning that there probably exists almost an infinity of variation, (Serlio certainly implies this) and that the 'misfits' are just as worthy of study, analysis and explanation as the rest. Further patient probing into this 'infinity' may bring its rewards.

In his chapter on land measurement, Alexander Huntar begins by setting out the various rectilinear figures, referring first to the square, and then to the "long square" (X 1624: 17). Is this merely a generic term for any rectangle, or is there an implication here of a wholly different attitude to geometric and other figures amongst the artisan classes of the period, an understanding which was entirely at odds with our own? Huntar's terminology is suggestive of two possible modes of thought: first, a "square" meant just that - four sides of equal length at right angles to each other, while a "long square" was simply an etymological substitute for *any* figure technically recognisable today as a rectangle. Alternatively, and more difficult to comprehend, there may have existed at that time less precise notions of what we now recognise in such definite terms, as squares and rectangles, again particularly amongst the artisan classes: perhaps a square was considered as such so long as its sides were equal, or possibly only *roughly* equal, perhaps to within the proportions of about 1: 1.05. Much more variation than this and it becomes a long square. The difference between the two may have been perceived in shades of grey rather than in black and white.

This brings us to consider the role of precision in the medieval world. In the most general terms, was there a culture of exactitude, or alternatively one of approximation? To what extent was there a perceived need to interpret instructions or even contracts to high levels of accuracy? This is a very tricky question to assess. Everyone is different and will pay greater or lesser attention to detail, according to personality, honesty, state of mind, health, time available, expense, thoroughness of application and final checking, to name but a few relevant factors. But this was an age when an inaccuracy of eight inches in the measurement of an acre crept into the English statute book in the 13th century - not a large amount, but avoidable with correct calculation and checking (IX Connor 1987: 90). Fernie has found a difference of 0.42m. between the longest and shortest bay lengths of Norwich Cathedral, though more happily most fit between 5.46 and 5.54m. In an age when knowledge and understanding of measurement and basic arithmetic were limited in commercial circles, and commonly non-existent outside, many mistakes were made, often resulting in failed businesses (IX Thomas 1987: 103-32), and failed buildings, although of course ignorance of the much more complex realm of structural engineering etc. was an issue here.

Obviously in order to ensure that relatively finely balanced structures such as large aisled churches have structural stability, a greater degree of consistency and accuracy was necessary than for a thick-walled fortress. However, that stability can still be present anywhere alongside surprising geometric and other inconsistency: Wonder still has to be expressed for instance at the slight but obvious differently sized jambs of Borthwick Castle against a background of otherwise unparalleled sophistication. This aspect of medieval building design is an integral part of the survey work at the basis of this research and will be dealt with in full later. It is sufficient for the moment to note that medieval builders generally were certainly not noted for their attention to exactitude, and that in some cases this may be a contributory factor in the appearance of near-squares.

Another possibility which cannot be ignored is a connection with the medieval and later concept of 'giving a little extra'. It has already been noted how the ell of 37" evolved at least partly because of the need to ensure that a purchaser, particularly of cloth, received full value in the event that a yard was not cut quite at right angles. Interestingly the proportional relationship of a yard to an ell is approximately 1: 1.03. Similar allowances were stipulated, often by law, in the measurement of other commodities: the concept of the "hundredweight" was applied to the sale of a wide range of goods, different values being ascribed to various groups. For instance, the *Ordinacio Facta de Modo Ponderandi per Balanciam* of 1309 specifies that "every hundred of small wares and spices such as ginger, saffron, sugar and such like which are sold by the pound contains Vxx iiii pounds" ([5x20]+4=104). Now here I have admittedly chosen a hundredweight which coincides with the ratio of 1: 1.04 commonly found in building plans - there are others, notably 112 pounds for some heavier and bulky goods in the same *Ordinacio*, and 108 pounds for some spices and wax in the *Tractatus de Ponderibus et Mensuris* attributed to 1303. Without going into too much detail in a complex subject, it is sufficient here to give Simpson &

Connor's interpretation of this document: heavy or bulky goods were weighed with a 12-pound stone on an inclined weighing beam, lighter more prized goods with a 12½-pound stone on a level beam, the ratio of the two being 1:1.04. There was a fairly consistent legal requirement to give 4 parts in 100 extra of most goods to compensate for any spillage, known as a "cloffe" allowance. It is around this ratio that most of these allowances seem to be based: the yard and ell constitute a ratio of 1: 1.03; the commonly used boll + 1 peck (1/16 of a boll) is in the ratio 1:1.06. For certain packaged commodities also the same allowance was made, not to compensate for spillage which theoretically was impossible for well packed goods, but to take account of the weight of the packaging itself, woolsacks for instance. In these cases it was known as a "tare" allowance. (IX 1996: 2015-17). How does all this relate to building plans?

In one sense it would be folly to suggest that a medieval near-square of these proportions could be the result of a policy, legally enforceable or not, to give a cloffe allowance. If rationally applied, such a principle would result in a structure being in *every* dimension one twentieth larger than the contractual specification. That is what modern rationality would expect. However, medieval culture cannot necessarily be judged or interpreted in the same terms. If geometric exactitude was not vital for its own sake, and a little extra was expected of the builder in case, for instance, the original marking out cords became accidentally knocked out of alignment, there really is no reason why it could not just be customarily given in one dimension only. This has to be considered as a possibility at least of a reason for near-squares. The builders were, after all, living in a culture where cloffe and tare allowances were the accepted norm in everyday transactions, and a building that was not quite square was perhaps regarded as in no way inferior to one that was exact.

There is another area of medieval commercial culture which requires to be mentioned in connection with this concept of a little extra, if only to exclude it from inquiry, and that is the use through medieval times right up to the first half of the seventeenth century of the "long hundred". In this system of numeration, which incidentally was employed regularly alongside the standard, involved the use of the word "hundred" or "*centum*" to denote 120 units, and likewise a "thousand" to denote 1200. It was commonly used in the trade of goods, either in number of individual items, or in units of measured length, weight or quantity. Indeed land area was sometimes measured in acres, or distance in perches, both using long hundreds. Building stone was certainly counted by this method, as well as "loads" of lime and sand. Yet often different materials might be acquired on a building site, some bought by the long hundred, others by the standard decimal system (X AMW II 50, quoted in Goodare 1993: 409). The two systems, however, were never combined in the same transaction. There was no overlap. There is therefore no reason to suppose that any combination of dimensions in a building requiring explanation is due to a theoretical use of both systems of measurement at the same time. Furthermore, the use of the long hundred and long thousand were restricted to just that: no research has so far revealed the use of a "long ten". As all buildings were measured in terms of feet, ells or in some cases, perches, there are few which could qualify to reach the minimum unit of one hundred of any of these units, except perhaps the great cathedrals and abbeys. For the building of these we unfortunately have no records of specified measurement.

To return to the real possibilities and explanations for near-squares and other such phenomena in medieval building, we have to consider that, however accurate the architect and his assistants might have been in the marking out the plan on the ground and projected elevations, later adjustments might well have been made purely for visual effect, such as in the rebuilding of Siena Cathedral, explained in section 2.3. In the light of such considerations, it may not be inconceivable the architects of at least some medieval near-squares were perhaps attempting to create the illusion of a square space by adding to it that extra 4% in which the viewer would be standing as he entered the room. Such possibilities cannot be summarily dismissed, especially in the light of the following.

4 THE ARCH AND THE VAULT

Whilst, as has been noted, the near-square seems to be much more common in surviving medieval buildings in Scotland than an exact true square, a similar situation prevails concerning the round arch and vault. Many are the examples of these which may appear superficially to be formed of a half circle in section. Those which are actually so, however, are very rare. The standard round vault in most Scottish buildings is in fact a segmental vault - in many cases only marginally so, but almost never a perfect hemicycle. Recognition of the common usage of such marginally segmental arches again comes to us from Alberti who lists arch types available to the builder. He names them the "entire" or full hemicycle, the "imperfect" whose base is less than the diameter of a full circle; and the "composite" or pointed arch which in Alberti's view is formed of two "imperfect" arches (X Book I, Ch.7: 10). The common Scottish slightly segmental vault is deemed to be "imperfect", and Alberti goes on to explain why this is so: "In all openings ... we should contrive to have the Arch never less than a half Circle, with an Addition of the seventh Part of half its Diameter: The most experienced Workmen having found that Arch to be by much the best adapted for enduring in a Manner to Perpetuity; all other Arches being thought less strong .... It is moreover imagined, that the half circle is the only Arch which has no Occasion either for Chain or any other Fortification." (X Book I, Ch.12: 18).

Alberti, although a scholar, was no engineer, and he was probably quoting second-hand information on the question of structural strength. However he was an aesthete, and it does seem likely that his recommendation of the addition of a seventh part of half the diameter of a vault or arch is made with an aesthetic end in mind: many of the arches and vaults with which he is concerned sprang from imposts, capitals or cornices which would have concealed the lowest voussoir, either partly or totally. By stilting the arch this visual loss would be restored. Now this question of visual adjustment for arcuated structure is not particularly relevant for Scottish building of that period: there are no examples that have been found in Scotland of such stilting - most vaulting was in any case of a more utilitarian nature, hardly ever being considered of intrinsic aesthetic value, although Samson does quote the isolated example of Sir Richard Maitland's eulogy of the vaults at Lethington which apparently "...pleasing are to sie, They are so great and fair." (VII 1990: 210) However, the principle of dimensional alteration to achieve visual refinement was obviously under consideration in Italy at least in the fifteenth century, and the possibility of the same in

Scotland also cannot be ruled out. Such adjustments may not have been used on arcuated structure, but they may have been tried in other dimensional manipulation, such as the near-squares discussed earlier. That, however, remains something of a vexed subject which requires much further research and analysis before more positive conclusions can be reached.

APPENDIX III

BUILDING CONTRACTS

DATE	SITE	Plans	W/O	Length	Width	Height	W/T	Matl.
1313	Lapworth -gatehouse 2 storey	-	W	40’	18’	20’ 2.5’parapet	o/s 3.5’ i/s 2.5’	S
1315	Eltham -wall	-	n/a	*“in Perches of 18’”*	n/a	12’	5’ base 4’ upper	S
1315	Lacock Abbey -Lady Chapel	-	n/s	59’	25.5’	n/s	n/s	S
1321	Hamsey -hall	-	W	60’	36’	24’ side	n/s	S
1322	Chester,							
	-round tower	-	n/s	Dia.10.5 ells	n/a	24 ells	4 ells **?**	S
	-wall	-	n/a	n/s	n/a	8 ells	4 ells **?**	S
		“ells of the king”						
1348	Stafford Castle -walls	-	n/a	*“in Perches of 24’”*	n/a	n/s	7’ base	S
1372	Arlingham	*for completion of ongoing work*						
	-church tower	-	n/a	n/s	n/s	12’ p.a. for 3 yrs.	n/s	S
1378	Carlisle Castle -tower	-	O	55’	32’	34’	6’ GF 5’ above	S
1378	Roxburgh Castle -curtain wall	-	n/a	n/s	n/a	30’	10.5’	S
1378	Bolton Castle							
	-kitchen tower	-	n/s	10 ells	8 ells	50’	2 ells	S
	-accom. tower (GF vault+3 stories)	-	n/s	12 ells	5.5 ells	40’	o/s 2 ells i/s 4’	S
	-accom. tower (GF vault +2 stories)	-	n/s	10 ells	5.5 ells	40’	o/s n/s i/s 3 or 4’	S
	-gate tower (gate+3 stories)	-	n/s	n/s	n/s	50’	n/s	S
1380	Dunstanborough Cas. -mantlet wall round keep	-	n/a	11 rods	n/a	20’	4’	S
1398	Durham Cath’l.	*rebuilding*						
	-dormitory	-	n/s	*as prev.*	*as prev.*	60’	2 ells	S
1412	Catterick Church							
	-choir	-	W	50’	22’	20’	n/s	S
	-4-arch nave	-	*“with the thickness of the west wall”*	70’	*“accordaunt of wideness betwene the pillers to the quer”*	26’	n/s	S
	-aisles	-	W	70’	11’	16’	n/s	S

Date	SITE	Plans	W/O	Length	Width	Height	W/T	Matl.
1425	Walberswick Ch.	*designed after the tower of Tunstall Church*						
	-tower	-	n/s	12'	12'	n/s	6' + 4 buttresses	S
1430	Cambridge Peterhouse Library	-	n/s	n/s	n/s	n/s	n/s	S
1433	St Mary on the Hill Chester -chapel adj. to chancel	-	W	*as chancel*	18'	*"as high as needs reasonably to be"*	n/s + 4 buttresses	S
1434	Fotheringay Church -nave & aisles	-	W	80'	*corres to exg choir*	n/s	n/s	SA
	-tower	-	W (!)	20'	20'	80'	6'	S
1436	Winchester -house	-	n/s	28'	24'	n/s	n/s	T
1442	Dunster Church -tower	-	n/s	n/s	n/s	100'	4.5' to bell 3' above + buttresses	S
1447	Eton College Chapel	*description of a design approved by Henry VI*						
	-choir	-	W	103'	32' *"within the respondes"*	80' (4sc.) *"to crest of parapet"*	n/s	S
	-vestry	-	n/s	50'	24'	20'	n/s	S
	-church (nave?)	-	W	104'	32' *"within the respondes"*	n/s	n/s	S
	-aisles	-	W	104'	15' *"within the respondes"*	n/s	n/s	S
	-cloister	-	W	n/s	15'	20'	n/s	S
	-gatehouse tower	-	(O?)	40'	24'	n/s	n/s	S
	Eton College Chapel	*description of another design approved by Henry VI*						
	-choir	-	W	150'	40'	80' (4sc.)	n/s	S
	-nave	-	W	168'	40' *"within the pillars"*	n/s	n/s	S
	-aisles	-	W	168'	20' *"fro respond to respond"*	n/s	n/s	S
	-cloister	-	n/s	200'	160'	n/s	n/s	S
1447	King's College Cambridge	*description of a design approved by Henry VI*						
	-chapel	-	W	184' (sc.)	40' (sc.)	50' (sc.)	n/s	S
	-tower	-	W (!)	24'	24'	120'	n/s	S
	-house ranges (E)	-	W(!)	230'	22'	n/s	n/s	S
	-house ranges (S)	-	W(!)	238'	22'	n/s	n/s	S
	-library	-	W	230'	24'	n/s	n/s	S
1457	Corpus Christi Cambridge -wall	- *"de standardo regio"*	n/a	4½ Rods *of 18'*	n/a	n/s	n/s	S

Date	SITE	Plans	W/O	Length	Width	Height	W/T	Matl.
1474	Milton -manor hall & chambers	-	n/s	n/s	n/s	18'	n/s + butresses	S
1478	Exeter -malthouse	-	W	20'	14'	n/s	n/s	S fdn T&M
1479	Nottingham -house	P	W	a/p	18'	n/s	n/s	T
1483	Gloucester -house	-	n/s	47'	15'	18'	n/s	T
1485	Tattershall College -almshouse	- *"by the King's yerde"*	?/W	172' *"more or less"*	19' *"within the walls"*	16'	n/s	T
1487	Helmingham Church	-	O	*"after the brede wydnesse and thicknesse of the stepyll of Framesden"*				S
1497	Canterbury -houses with shops below	-	O/W	84' *over the walls*	20' *within the walls*	n/s	n/s	T
1500	Cranbrook							
	-house	-	*"out to out"*	44'	18'	24'	n/s	T(?)
	-house	-	n/s	18'	15'	n/s	n/s	T(?)
1500/1	Edinburgh -tolbooth	*continuation of ongoing work: no specifications other than 600' of ashlar.*						
1510	London -house	-	O	40'	22'	24'	n/s	T
1511	Great Sherston -church house	-	W	60'	19'	16'	n/s	SR
E C16	Cowthally House -courtyard wall	-	(W?)	60'	24'	"*about* 5 ells"	*"thick"*	S
1516	Holywell -farmhouse	P	n/s	a/p	a/p	18'	3' GF 2.5' above	S
1532	Tower of London -4 houses	-	O	52'	18'	n/s	n/s	T
		-	O	23'	16'	n/s	n/s	T
		-	O	23'	11'	n/s	n/s	T
		-	n/s	20'	17'	n/s	n/s	T
1532	Aberdeen -blockhouse	-	n/s	36'	18'	*"as best thought expedient"*	6'	S
1532	Inverness Castle -hall/kitchen/chapel block over GF vaults	-	n/s	100'	30'	n/s	n/s	S
1542	Midcalder Church	*completion instructions*						
		-	W	24'	28'	26'	4'	SR

Date	SITE	Plans	W/O	Length	Width	Height	W/T	Matl.
1553	Kilravock Castle	P	n/s	n/s	n/s	n/s	n/s	S
		"according to the said Lordis dewyis"						
1567	Edinburgh -town walls	-	n/a	n/s	n/a	7 ells	6'	S
1569	Peebles -town walls	-	n/a	n/s	n/a	4 ells + ½ ell fdn.	3.5'	S
1578	Edinburgh -High School	-	W	110'	24'	n/s	n/s	S
		"all ther elins to contene thre fute and ane half for the elin"						
1589	Kirkton of Newtyle -house extention	-	n/s	n/s	12'	11' 7' sidewalls	n/s	S
		"natural feet of John Mylne"						
1611	Partick Castle	*contract for completion of building*						
	-main block	-	n/s	n/s	n/s	33'	3.5' *"of sufficient thickness...as may serwe for ane woltit hous"*	S
	-jamb	-	W	16'	16'	n/s	n/s	S
	-turnpike stair	-	W	*"nyne or ten futis wyde wtin ye walls"*				
		"...of the said georges awin fute"						
1616	Aberdeen -vaulted wardhouse	-	W	15 or 16'	*"breadth of the whole tolbooth"*	*"as shall be thought expedient"*	5' GF 4' above	S
1620	Falkland Church	*total demolition & rebuilding*						
		-	W	n/s	28'	*"as hie as Lord ? pleases"*	n/s	S
1637	Fearn Abbey	*partial reconstruction*						
	-aisle	-	W	7' (?)	n/s	16' (?)	n/s	S
1644	Heriot's Hospital -steeple	P	n/s	n/s	n/s	22'	n/s	S
		"conforme to the draught"						
1660	Lasswade Manse							
	- main block	-	W	54'	20'	20'	G&S	S
	-stair jamb	-	(O?)	18'	7'	n/s	n/s	S
1661	Coldingham Church -partial reconstruction	-	n/s	n/s	n/s	n/s	G&S	S
1663	Dreel, Fife -4 storey house	-	W	76'	24'	n/s	4'	S
1664	Langton, Berwicks -dyke	-	n/a	n/s	n/a	n/s	G&S	S&C
?	Whithorn quay	-	n/a	n/s	6ells	3' *above high water*	-	S
	-ramp thereon	-	n/a	n/s	n/s	1 ell	-	S
1665	Edinburgh -J Belsches tenement	-	n/s	57' *"Inglisch foot"*	17.5'	(3 storey)	n/s	GF:S above:
1666	Auchenbowie House	-	n/s	*"ane sufficient house of 19 foots in breid"*		26'	3'	S

Date	SITE	Plans	W/O	Length	Width	Height	W/T	Matl.
1666	Panmure House	P	*"according to the maner forme and dimensions...designed and set doun by the said John Mylne in draught"*					
1677	Gallery House							
	-main block	P	O	70’	38’	26’	n/s	S
	-2 jambs	P	O	18’	18’	26’	n/s	S
1677	Edinburgh -oven, Todrig’s wynd	-	W	8’ (circumf.)	n/a	n/s	n/s	S
		"in every respect in sufficiency, larges & roundness to conforme to Patrick Wallaces oven"						
1678	Galston Church							
	-loft	-	(W?)	16’	*between* 7’&8’	n/s	n/a	T
	-stair thereto	-	n/a	n/a	4’ *"at least"*	n/s	n/a	S
1679	Edinburgh Castle	-	n/a	60’	n/a	16’	4’	S
	-walls	-	n/a	n/s	n/a	12’	3’	S
1680	Netherliberton -doocot	-	O	36’	19’	26’ back 15’ front	n/s	S
1682	Abington -house by bridge	-	W	40’	18’	13’	n/s	S
1682	Cawdor Castle -dyke	-	n/a	n/s	n/s	7’3”	G&S	S
1684	Cawdor Castle	*demolition of little tower and construction of:*						
	-4 storey range	-	W	20’ rooms	18’	n/s	n/s	S
	-jamb	-	W	10-12’	*"as broad as can be got without corrupting the light of the south window of the great hall"*		n/s	S
1684	Prestonhall -summerhouse	-	W	20’	12’	17’	n/s	S
1684	Logie Church	*demolition & reconstruction*						
		P	n/s	n/s	n/s	n/s	n/s	S
		"conforme to ane draught drawen by ...Bachope"						
1686	Invermay -double house 3 storeys + garret, GF vaulted	-	n/s	48’ *"or less as the contriver...shall think fit"*	36’	n/s	n/s	S
1686	Leys, Kincardine -3 storey house	*no specifications: piece work contract stating reward for each rood of work and each foot of hewn stone*						
1688	Mylne Square -flat	-	W	40’	20’	9’ each floor	front: *"polished aislar of compitent thickness"* mid (chimney) wall: 3’ back (rubble) wall 2.5’	
1692	Kelburne-Castle	*no specifications: rebuilding of mansion to same size as previous*						
1697	Melville House	P	n/s	n/s	n/s		G&S a/g: 3’ b/g: 4’ *"or thereby"*	SA
		"according to the draught and designe made thereof"						

Date	SITE	Plans	W/O	Length	Width	Height	W/T	Matl.
1698	Craigiehall House	P	n/s	64’	46’	28’ a/g 6’ b/g	*“of sufficient masonwork”*	SA
		“according to the modell of wood and the draught signed by Sir William Bruce”						
1698	Hopetoun House							
	-main block	P	(O?)	80’	87’	38.5’ a/g 7’ b/g	G&S	SA
	-pavilions	P	(O?)	12’	12’	28’	n/s	SA
1699	Cawdor Castle	*demolition of little tower and construction of:*						
	-range	-	n/s	n/s	14,15 or 16’ *according to the old foundations*	n/s	5’ 4.5’ or more	S
1701	Craigiehall House -office wings	?	(O?)	56’	22’	14.5’	n/s	SA

Abbreviations

Headings:

W/O	measurements either “within”, or “over” the walls
W/T	wall thickness
Matl.	principal load-bearing building material

Within Table:

P	plan or draught refered to in contract
W	measurements stated as “within the walls”
(W?)	not specified but reasonably assumed to mean “within the walls”
O	measurements stated as “over the walls”
(O?)	not specified but reasonably assumed to mean “over the walls”
n/s	not specified
n/a	not applicable
a/p	as specified on the plans
sc.	measurement specified in “scores”
b/g	below ground
a/g	above ground
fdn.	foundations
GF	ground floor
G&S	“good and sufficient”
S	stone bedded in lime mortar
S&C	stone bedded in clay
SA	ashlar
SR	rubble
T	timber-framed
M	mud

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