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Stone barrel vaulting in late medieval churches in Scotland

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Abstract

This paper explores the construction characteristics and structural design of plain stone barrel vaults built to roof a new type of single-nave churches in Scotland in the 15th century, such as Dunglass Collegiate Church in 1423, Seton Collegiate Church in 1492, St. Salvator's Chapel in St. Andrews in 1450, Corstorphine in 1429 and Ladykirk in 1500. Four case studies are surveyed (Dunglass, Seton, Corstorphine, Ladykirk) and their geometry is analysed to assess their design, construction quality and structural efficiency. The analysis demonstrates a very good quality control and a consistent approach to the simplification of the pointed profile developed in cross vaults.

Introduction

Fire-proof stone vaulting in Scottish churches developed a simpler configuration of barrel vaults over single naves in the 15th century, in parallel with cross-vaulting used in the new contemporary burgh churches. These vaults are found in royal or aristocratic foundations such as Dunglass Collegiate Church in 1423, Seton Collegiate Church in 1492, St. Salvator's Chapel in St. Andrews in 1450, Corstorphine in 1429, and Ladykirk in 1500, away from the earlier large scale monasteries. Similar vaults also characterise votive or burial aisles in existing churches (Cockburnspath parish church C15, Wardlaw Vault in Dunfermline in 1617, Dirleton Aisle in 1664, Abercorn in 1727).

Cross-vaulting is usually defined by a system of ribs, which guarantees the quality of construction and creates a strongly linear architecture as they have to fully integrate with the decorative programme (concordance) and make larger openings in the envelope possible. Cross-vaults require however complex construction, especially for exposed stonework, and are not widely encountered in Scotland away from large churches. When compared, barrel vaults are simpler in design and execution, and relate to the lateral walls in a very different manner because of the single curvature and continuous support along the wall-head.

A study of the development of the technical culture of this type is presented here. The vaults have a straightforward structural scheme which will be analysed to interpret the efficiency of their design and containment of thrusts, but also to explore the masons' understanding of load paths. Their stonework is usually dressed internally but overall the structures are robust as they are roofed in flagstones and the space of the pitch is

filled with rubble. The quality of the masonry bond will also be discussed in relation to the structural design to reveal the extent to which the simplicity of the structural scheme permitted a better tectonic control.

Four case studies from the 15th century were chosen (Dunglass, Seton, Corstorphine and Ladykirk), which demonstrate a certain chronological development in bolder forms. They also represent a re-elaboration of pointed profiles and ribs, key Gothic characteristics, in the barrel vault context, and the study explores whether these were constructional devices or stylistic affiliations.

Scottish late medieval vaults

The C15 vaults studied here are elaborate and consistent designs, comparable to earlier examples such as St. Margaret's chapel in Edinburgh Castle, the C12 Dalmeny church or Sutra aisle. This new design over single-nave churches is in line with the emergence of different types of smaller and more compact, still significant, churches that deviate from previous large scale constructions such as cathedrals and abbey churches. These were founded by aristocrats as colleges of priests (Dunglass, Seton, Bothwell, Corstorphine, Crichton, Roslin, Carmelite Priory in S. Queensferry) or prestigious chapels such as St. Salvator's college chapel in St. Andrews, while royal foundations later followed the pattern too (Ladykirk). The origin of these forms seems to be more civic than religious, following techniques developed and tested in basements or banqueting halls in castles [1]. The barrel vaults built in the cloister and additions in the Augustinian Inchcolm Abbey during the 14th C are an example of robust, relatively inexpensive and durable roofing in a compound that has to provide or at least show off its ability to defend itself.

From the beginning of the 15th C, following the assertion of James I's rule, Scottish castles developed a stronger residential character combined with the need to resist the effects of artillery assault. Prominent examples that may have an influence are Bothwell, Strathclyde (imposing form with architectural qualities, refurbished in C15); Dirleton (in East Lothian, where many collegiate churches were founded), characterised by several vaulted ceilings serving various purposes (storage, kitchen, private apartments) along the face of defence and refined ashlar dressing of the elevation (Fig. 1).



Figure 1. Vaults in Dirleton Castle

If these vaults are viewed as an evolution or diversification of earlier Gothic vaults, it is worthwhile to examine how their characteristics were adapted. The cloister vaults at Inchcolm already present a smooth pointed profile,

which becomes sharper (Corstorphine 1429) and much more clearly defined later (Carmelite Priory in S. Queensferry 1441, Crichton 1449), eventually presenting an ashlar finish (Ladykirk 1500).

Ribs take a different character in this context. In the case of Bothwell (1398) or Ladykirk (1500) they divide the barrel vault into bays and are pronounced (Fig. 2A), while they spring immediately above the windows. In some cases, ribs were planned to be attached, possibly to confer some rhythm or even prestige to the design, but they would spring from corbels as surviving post holes show (Dunglass – Fig. 2B, Seton) [1].



Figure 2. A) Ladykirk; B) Dunglass

The only case of concordance is Roslin (1450) where ribs are heavy and integrated in a tripartite scheme along the shafts of the piers of the aisles, but usually the smooth barrel is continuous with the walls. They are often used however to guide difficult junctions like apses, especially in the case of Seton (Fig. 3A). Closely spaced ribs are found in the apse of Holy Rude, Stirling (the only stone-roofed part of the choir) and they are more like a flat reinforced mesh, dating before mid C16 (Fig. 3B). There is also a unique external system of ribs above the cross-vaults in the single nave of the earlier but very elaborate Lincluden Collegiate Church (1389).

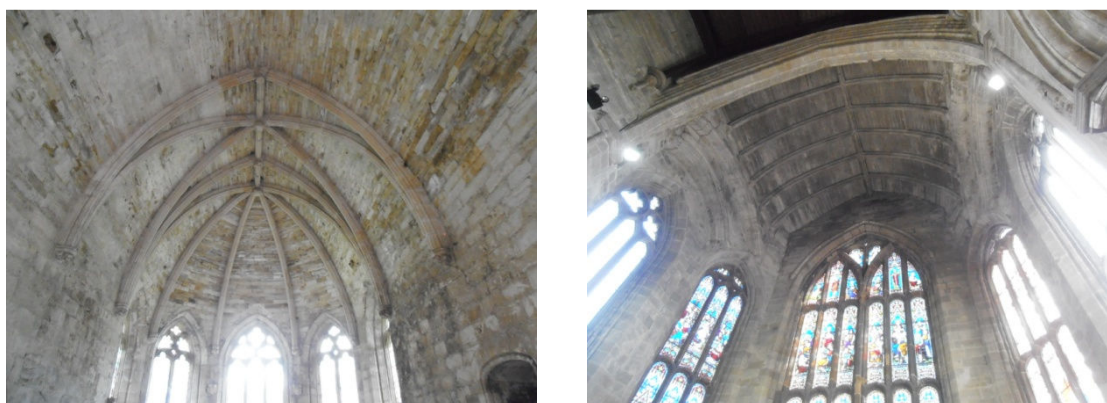


Figure 3. A) Radial ribs framing the apse of Seton; B) Orthogonal mesh roofing the apse of Holy Rude, Stirling

What characterises these vaults is that they all have exposed stonework now, although it is possible that Corstorphine or Dunglass were planned to be rendered, and in most cases the finish is ashlar: Ladykirk and Bothwell (red sandstone) or Crichton (buff sandstone).

Regarding spans and proportions, these will be examined in more detail in the four case studies. It is interesting that most span 6m to 7m while St. Salvator in St. Andrews (1450) is the biggest (ca. 9m), which had substantial amount of windows and consequently daylight, and was possibly the weakest as it was demolished in 1773. The survey of the shell itself in the case studies shows a span to rise ratio L/F between 1.4 and 2.3, but uncertainties in the springing level often indicate that the design was generated by an equilateral triangle ($L/F=1.15$).

The case studies will also evaluate the structural efficiency of the vaults' design. Pier buttresses are employed to resist thrust and their application varies: Dunglass has few and irregularly spaced; Corstorphine has a sufficient number; Ladykirk has regularly spaced, deep piers that are integral to the overall quality of the design. Empirical rules that relate span and buttress size will be tested in the discussion of the case studies [2, 3].

Focusing on the buttresses at the apses, some are perpendicular (like Dunglass, Bothwell, Crichton, Pencaitland) and others are diagonal, as in Corstorphine. Seton and Ladykirk however have buttresses normal to their polygonal apse bays, while Roslin applies flying buttresses over the aisles. The diagonal ones may indicate some stronger experience with the behaviour of the vaults and an attempt to provide a more efficient bracing. Polygonal apses also improve the stiffening of the barrel vault at its ends but the majority show straight apse ends. The polygonal ones in Seton (1492), Ladykirk (1500) or Holy Rude (Fig. 3) coincide with the latest period of this typology but are not fully integrated with the barrel vault.

Walls in medieval churches are characterised by the quest to balance daylight with structural support. The majority have a main tracery E window at the apse and very few lateral openings. Many windows appear only along the walls of St. Salvator or Bothwell but the fabric in-between does not receive the treatment of skeletal piers as traditionally occurs in the Gothic style.

Finally, an interesting aspect to be considered is the propagation of the system beyond C15, the long term safety and durability, and also its legacy. Few barrel vaults were built after 1500. The plain, ashlar vault of Dirleton Aisle is the closest direct connection but it is smaller, less deep, with a semi-circular profile spanning 4.65m and belongs to a more neoclassical context (1664) that may even have rejected pointed profiles. St Salvator's vault (the largest span) was deemed unsafe in 1772 by the neoclassical architect James Craig and, possibly because of lack of knowledge of its behaviour and construction (there was no debate or ideas recorded about a repair), was subsequently demolished [4, 5]. This may have also been precipitated by the earlier collapse of Fearn Abbey church in Ross (1742). The complete detachment from the technology of these plain structures can even characterise the reconstruction of the vaults in the nave of Corstorphine in 1903-5, where solid prefabricated concrete panels were used, strengthened with ribs.

Four case studies

The design aspects and technical culture of this typology will be explored in four representative case studies. The main tool is a measured survey using a Trimble S6 total station to perform a medium density laser-scan. The point-cloud allowed the geometry of a variety of areas within the church and each vault to be analysed and eventually key cross sections across the barrel were taken and compared (Fig. 4) - the ordinate axis starts at what is assumed to be the level of springing.

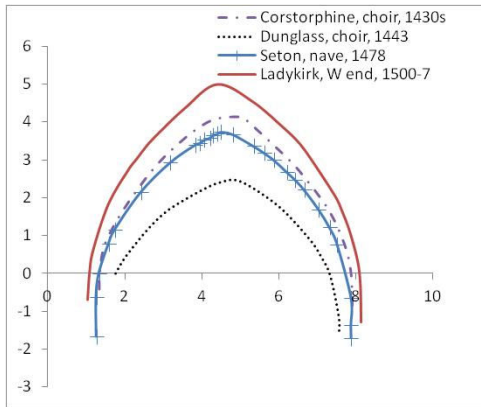


Figure 4. Comparison of representative cross sections between the four case studies

It is not always straightforward to establish the true springing of the vault. The discussion of the proportions and angles that define the vaults of each case study focuses on the clearly observed curved parts of the shell. Very often however the crown angle ϕ_1 is very close to 60° or the centre of the circular segment of the pointed vault lies at a distance from the springing that is equal to the radius R . This gives hints that the proportions of the vault were defined by an equilateral triangle which was then adjusted during construction.

Evaluation of thrust and min. thickness are based on shell solutions for masonry domes calculated by J. Heyman based on thrust line and limit-state principles [6], as in the graphs in Fig. 5 for example that relate thrust and min. thickness to the crown angle ϕ_1 . Thrusts Nf are normalised over wR , where w is self weight and R the radius of the pointed arch. To define w a uniform, reasonable thickness $t=0.4\text{m}$ is assumed in the absence of survey data - probably the real thickness varies from a max at the base (wall head) to a min. at the crown. The unit weight of stonework γ is taken as $2\text{ t/m}^3 = 20\text{ kN/m}^3$, therefore $w = \gamma t = 20 \cdot 0.4 = 8\text{ kN/m}^2$.

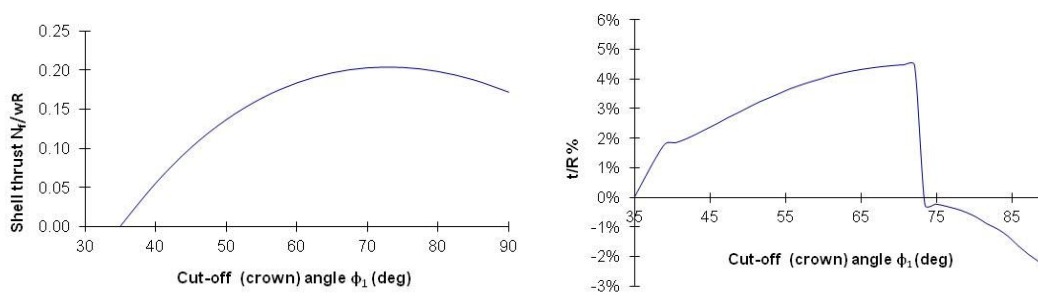


Figure 5. A) Shell thrusts Nf/wR for a pointed shell with a springing angle $\phi_0 = 35$; B) Required thickness t for a pointed shell with $\phi_0 = 35$

A) St. John's Collegiate Church, Corstorphine, Edinburgh

The church built before 1158 became a collegiate one possibly in 1429 by Sir John Forrester [7]. The building was transformed to the new form of worship, allowing space for the parish, and this included the absorption of earlier Gothic features and the erection of the barrel vaults, which may have been completed by 1436. The E choir (Fig. 6) and the adjacent sacristy are the only original roofs that survived, and the vaults of the nave and aisle were re-made in precast concrete ribbed panels during the restoration in 1903-5 by George Henderson [8].



Figure 6. Corstorphine Collegiate Church, vault at E choir

The survey of the E choir demonstrates the very good quality of the construction of the vault as there are almost no differences in various sections drawn along the bay. The span from the springing is measured as $L=6.55\text{m}$ (21.5ft) and the rise $F=3.97\text{m}$ (13ft), resulting in $L/F = 1.65$. The corresponding circle has a radius $R = 5.3\text{m}$ (ca. 17ft) and there are minor deviations around the spandrel, supporting the observation of good quality control of construction. The springing angle $\varphi_0 = 9^\circ$ and at the crown $\varphi_1 = 63^\circ$, therefore the normalised thrust of a representative tranche [6] is $N_f = 0.6471 \cdot wR = 0.6471 \cdot 8 \cdot 5.3 = 27.4\text{kN/m}$. The minimum thickness seems to be very small and hinges may form close to the crown, so the form appears to be almost a catenary and develops mainly axial compressive forces. These large thrusts are contained by widely projecting buttresses and rather thick walls.

The proportions of this vault give a hint that an equilateral triangle of sides equal to R defines the profile, which then was adjusted to the thickness of the walls or extended with stiling.

The walls of the choir have a rubble finish currently and at the springing of the vault the masonry is made of oblong thin blocks laid regularly, which makes the construction of the vault feasible without specialist skills or experience. There was no apparent intention of an architectural finish to the stonework and the surfaces were possibly unified by lime-wash, to match the quality of the tombs and tracery in the window.

It is very interesting how a more sophisticated, pre-existing vault like that of the S transept was treated in this remodelling. This vault was absorbed into the remodelled church in 1429 and at the N end the ribs were truncated without apparent concern for integration into the new design. Their design does not appear as a dominant structural scheme to work around as it shows a structurally slightly arbitrary pattern of a semi-quadrupartite arrangement of ribs rising from a springing point at the centre of the bays [1].

B) St. Mary's Collegiate Church, Dungleigh, E. Lothian

The church may date from after a college of priests was founded in 1443 [9]. The plan is quite articulated and all the spaces are vaulted, creating a continuous stone surface between the walls and the vaults, which are not at present divided by any permanent decoration or cornices (cf. Bothwell). There are two main barrel vaults at the E choir and W nave (taller, but narrower), and three minor ones over the two transepts and a burial vault at the S

side. Stylistic analysis of the arches where these vaults meet the nave and traces of foundations of walls show these vaults were added later [9].

The E window is smoothly pointed (Fig. 2A) and the profile of the barrel vault is similarly gentle, especially when compared to the other cases (Fig. 4). The vault of the nave was surveyed and spans $L = 5.5\text{m}$ at the springing (or 18 ft), while the walls at footprint divert slightly to a span of 6.1m (20ft). The rise of the vault (from the springing) $F = 2.43\text{m}$ (8ft), producing $L/F = 2.25$. The radius R that generates the pointed profile was evaluated as 6m (20ft) and the centre lies about 10ft below springing.

The springing angle φ_0 was measured as 37° and crown φ_1 is 69° . The normalised thrust is evaluated from Fig. 5A as $Nf = 0.202 \cdot wR$ (for $\varphi_0 = 35^\circ$, $\varphi_1 = 70^\circ$), or $0.202 \cdot 8 \cdot 6 = 9.7\text{kN/m}$. Regarding the min. thickness to withstand self-weight, Fig. 5A shows it $0.045R$ or 0.27m and if below, a hinge can form at a 46° from springing. These calculations show the design of the choir has a comfortable safety margin. Flagstone roofing covers all bays which indicates each vault successfully carries a substantial load.

If the circle segment that corresponds to these proportions is superimposed, there is a vertical deviation at the crown but it is small, almost 8cm, i.e. the quality of construction is of efficient level to maintain the original form as planned.

The vault of the nave has a shorter span and its overall height is taller than the choir. The proportions therefore are not too different, but the pier buttresses are only normal to the walls of the choir and are shallow, so either the masons became confident of the stability of the design of such a vault after the choir was built or they relied on the later addition of the S burial vault to abut the nave. It would be interesting to survey the nave vault as well to verify any differences in the design or deformation.

The quality of the stonework bond is variable and improves to a firmer ashlar in the later transepts and nave. In the choir, the blocks of the wall are rectangular up to a height of 4.5m where they become thin and oblong for a further meter until the springing and continue as such along the barrel vault. A visual inspection shows different proportions and springing points at each bay. There are no ribs or intentions for them, and the sockets on the barrel were made when the church became a stable and decks were added.

C) St. Mary and Holy Cross Collegiate Church, Seton

The development of the church is well documented in the history of the founders, the Seton family, written by G. Maitland around 1560 [9]. Today the (original) W nave is missing but there remain the very simply and uniformly designed vaults over the choir and the two transepts. This documentation is summarised in [9]: the choir (apparently the ribbed apse) and the sacristy were built by the third Lord Seton (before his death in 1478) but the plain W part of the choir was added by the fourth Lord, who also founded a college in 1492, while the choir was roofed later with a flagstone roof by the fifth Lord (+1513). The transepts were added later, first the N one (1541) and then the S (1545).

Sections along the W choir taken from the survey are very similar, showing high construction quality control. Minor sinking or deviations from a circle were measured. A similar profile however was more difficult to obtain

for the apse, probably due to the presence of the ribs. The irregular profile (Fig. 7A) and the layout of the blocks (Fig. 7B) show the ribs were built first as a geometric guide and the oblong blocks of the shell were then attached.

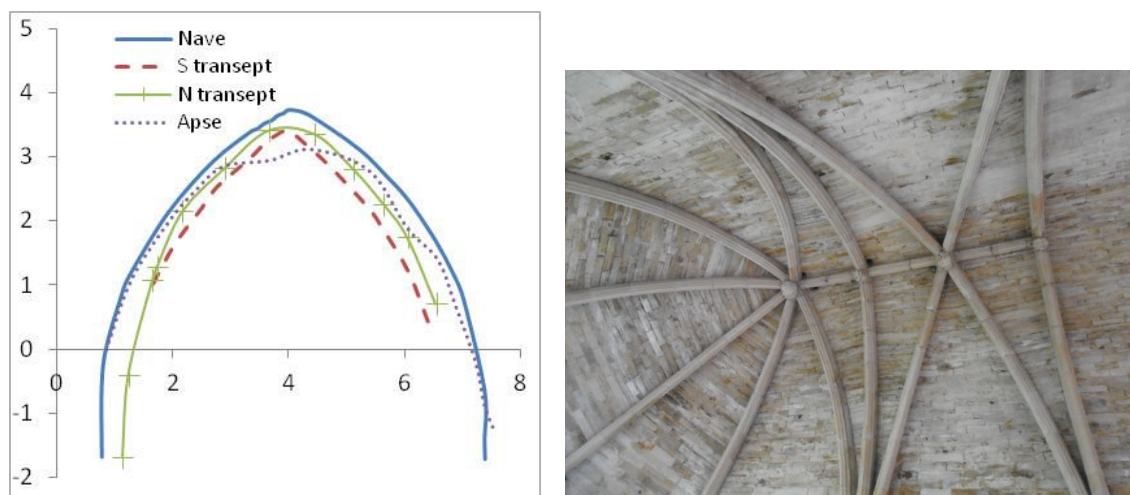


Figure 7. A) Profiles of the barrel vaults in Seton Collegiate Church B) The apse

Focusing on the choir, the generating radius $R=4.85\text{m}$ (ca. 16ft), the span $L = 6.46\text{ m}$ (ca 21 ft) and rise $F=3.75\text{m}$, so $L/F=1.7$. The springing angle φ_0 was measured as 9.5° and cut-off (crown) φ_1 is 68° . The normalised thrust is calculated as $Nf=0.647wR$ (for $\varphi_0=10^\circ$, $\varphi_1 = 65^\circ$) $=0.647 \cdot 8 \cdot 4.85 = 25.1\text{kN/m}$. The calculation of the thickness [6] shows a similar phenomenon as in the right-hand section of Fig. 4, i.e. there is no min. thickness as the profile of the vault may correspond to a catenary, hence no bending develops.

All divisions are braced with substantial pier buttresses, built contemporarily with the fabric and vault, and at some point would have been highlighted with a pinnacle. Several geometric rules existed around the time to calculate the depth of the buttress, as the later manuscript of Rodrigo Gil de Hontañón indicates (1544-54) but there is no evidence recorded of such rules in Scotland. Since they are all empirical in nature, one that is quite intuitive is considered here, the rule of Martinez de Aranda [2], which evaluates the buttress depth as ca. 1.5m. This matches well the real depth of the buttress 5ft or 1.52m.

The bays of the choir vary 16-18 ft in spacing and apart from a regular division of the area they do not seem to be in any proportion with the profile of the vault. There are several large openings, each with a tracery, invariably on each division and the survey shows some minor deformations in their vicinity. The (later) S transept shows a minor distortion of the vault towards its S end and the N transept shows a small irregular deformation at the N window.

Study of the stonework shows a visual and tectonic continuity as the rectangular ashlar of the wall changes quite smoothly around the springing to the exposed oblong blocks of the vault. The plain and almost continuous aspect of the stonework (affected slightly today by humidity and salts around the spandrels of the vault) provides a uniform, subtle and peaceful treatment of the interior, which may not have been altered significantly by the furnishings of the period.

When compared with the choir, the transept's vaults are smaller (Fig. 7A), which shows the masons were not capable of (or interested in) copying the vaults of the choir. Even the construction quality between them varies, with the N transept being slightly more irregularly built, although they followed the same materiality principles.

D) Ladykirk Parish Church (or Kirk of Steill), Scottish Borders

This is a brand new design that had no constraints from pre-existing structures. It is considered as a votive church founded by James IV and was built between 1500 and 1507, the year when the master-mason Nicholas Jackson (who had worked in Linlithgow Palace) was at work on the roof [10]. The church has a unique pattern combining a three-sided E end apse (instituted earlier in St. Salvator's from 1450) with two transverse ones, each roofed with a domical ribbed vault which is a variation of the strongly pointed vault of the nave.

The nave vault is the highest and most imposing of the four case studies and is prominently pointed (Fig. 4). The section is constant throughout the nave, indicating high control during construction, which is also manifested in the ashlar finish of the shell. The vault profile matches fully the corresponding circle of a radius $R = 7.3\text{m}$ (24 ft). $L/F = 7.2/4.99 = 1.44$, the springing angle φ_0 was measured as 18° and cut-off (crown) φ_1 is 62° . The normalised thrust is evaluated as $Nf = 0.374wR$ (for $\varphi_0 = 20^\circ$, $\varphi_1 = 60^\circ$) $= 0.374 \cdot 8 \cdot 7.3 = 21.8$ kN/m. Thickness is evaluated $t = 0.04R = 0.29\text{m}$, and there is an apparently large safety margin.

To test the efficiency of the profile, it was compared with a catenary that corresponds to the proportions of the vault, calculated using a readily available spreadsheet [11]. There is a visible deviation from this profile so some bending develops, which is absorbed by the thickness of the shell.

The vault carries a substantial load from the flagstone roof and the infill or diaphragm walls that form the pitch. The thrusts are contained by deep buttresses, topped with a pinnacle, which shows some awareness of their function. These piers and the corresponding bays are widely and regularly spaced every $S = 13\text{ft}$. The divisions are marked with ribs, springing from corbels at a height of ca. $22\text{ft} = 6.6\text{m}$, which is not far off the radius.

To complete the structural scheme, the transeptal apses abut the barrel nave at mid-height and their edge is finished with a solid arch. There is no full assimilation of the visual aspects of this function [1], which is in contrast with earlier achievements of Gothic as have been manifested in the cross-vaulted churches of the period (St. Giles, Trinity College).

Discussion

Gothic masons' structural design (*scientia*) was firmly based on geometry as the form guarantees a safe state of equilibrium [2]. This initial study from the survey and the structural analysis of the forms reveals some things about the designers' choices and their relation to the construction process. The profiles in the four case studies are consistently pointed and there appears to be an underlying scheme of equilateral triangle that defines the overall dimensions of the vault itself. The comparison of the profiles show a slow increase of the sizes (Fig. 4) and Ladykirk shows a confident and safe design of the pointed shell (6.5m span), with a low normalised thrust $0.374wR$, something that may have failed earlier in the larger span of St. Salvator (9 m).

The construction is solid and of good quality, and not many defects or deviations from a circular profile are observed (Fig. 7). This shows the structural form is not too sensitive to the construction process (whether bottom to top or end to end).

The impression of the structures, even within the context of large stone roofing of the time, is one of uniformity, maturity and simplicity, as can be compared with Trinity College, Haddington or St. Giles. In a way is a return to more archaic, Romanesque forms (see for example Tranni Cathedral, Puglia), but with a tectonic impression of a continuous surface of stone adjusted here for the absence of aisles and lateral walls. In conclusion, the simple form of single curvature vaults shows Scottish masons were capable of achieving high quality of construction and control of the forces (both the load path and the containment of the thrusts). Among them only St Salvator (and possibly Fearn) failed but the effectiveness of the scheme was undermined by the rigidity of the space it created, which curiously enough was more suitable for the different spaces created after the Reformation later in C16.

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References

- [1] R. Fawcett, *The architecture of the Scottish medieval church 1100-1560*, London: Yale University Press, 2011.
- [2] S. Huerta, "Geometry and equilibrium: The gothic theory of structural design". The Structural Engineer, vol 84(2), pp. 23-28.
- [3] S. L. Sanabria, "The mechanisation of design in the 16th century: The structural formulae of Rodrigo Gil de Hontañón", J. Soc. Architectural Historians, 41, 1982, pp 281-293
- [4] R. G. Cant, *The college of St. Salvator*, Edinburgh: Oliver and Boyd, 1950.
- [5] D. Theodossopoulos, "Limitations in the understanding of the performance of complex structures and vaults as manifested in the fatal repairs of the Holyrood Abbey church roof in 1760". Forthcoming publication, 2014
- [6] J. Heyman, *The Stone skeleton. Structural engineering of masonry architecture*. Cambridge: Cambridge University Press, 1995
- [7] C. McWilliam, D. Walker & J. Gifford. *The Buildings of Scotland: Edinburgh*, London: Penguin, 1984
- [8] Fergusson, Dickson, James and Traquair, "The Church of Corstorphine and its recent restoration" The Scottish Ecclesiological Society, vol.1 (3), 1905-1906, pp. 286-298
- [9] C. McWilliam *The Buildings of Scotland: Lothian* London: Penguin, 1978
- [10] K. Cruft, J. Dunbar and R. Fawcett *The Buildings of Scotland: Borders* London: Penguin, 2005
- [11] Catenary function (2009): <http://newtonexcelbach.wordpress.com/2009/06/25/a-catenary-function/> posted 25 June 2009