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AN INVESTIGATION INTO THE STRENGTH PROPERTIES OF RECLAIMED TIMBER JOISTS

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Abstract

This research was designed to investigate the mechanical properties of timbers reclaimed from demolition, with the aim of generating a visual grade and model expression to grade these materials for structural reuse. The use of timber, reclaimed from demolition, for new construction or refurbishment has both environmental and economic benefits.

The research developed an appropriate, alternate visual grading method which takes account of the unique problems associated with timber reclaimed from demolition. The research also investigated the loading capacity of timbers where previous structural loading may have affected the strength, and how grading without prior knowledge of the timber species can be utilised. Complimentary research suggested that the number of timber growth rings in a specimen has a direct effect on the mechanical properties, and that this can serve as a predictor of elastic modulus, especially when considered in conjunction with the density of the specimen.

This thesis presents the findings of the research, which involved developing an alternate visual grading methodology, appropriate to the inherent ‘in service’ damage sustained by timber, and quantifying the mechanical properties of reclaimed timber joists and comparing these with small clear tests. The visual grade accounted for the lack of species data available, by becoming independent of timber species. The research analysis considered density, specimen age and tree ring frequency as the variables in generating the model expression. In the final instance the analysis rejected the age of the specimen as a variable; this was found to be an anomalous and inaccurate figure, which could only be estimated and added very little to the accuracy of the model expression. The model expression uses tree ring frequency and specimen density to estimate the modulus of elasticity of the specimen and thus its strength grade.

The contribution to knowledge in this research is through the introduction of an alternate, novel method of investigation and an expression to estimate the modulus of elasticity; the method is aimed specifically towards operatives at the demolition site using simple measuring equipment.

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Special thanks must also go to my employer NBS/RIBA Enterprises whose financial assistance enabled me to carry out this research.

In loving memory of my mother and father, Dorothy and Ronnie Stewart.

DECLARATION

I declare that the work contained in this thesis has not been submitted for any other award and that it is all my own work. I also confirm that this work fully acknowledges opinions, ideas and contributions from the work of others.

Name: Michael John Smith

Signature: ______________________________

Date: ______________________________

1 Introduction

The UK is one of the world's major users of timber and timber products; however, it is also one of the most wasteful. Reclaimed timber elements are often discarded, reprocessed for lesser use or consigned to waste streams, even though they could be used again. Structural timber use in modern construction is increasingly dependent on concerns about global climate change, depletion of fossil energy reserves, and increasing biodiversity loss. Responsible management of forests and woodlands help to support biodiversity conservation, though in its report, UK construction industry overview, CorporateWatch (2004) stated ‘there are no currently reliable statistics for the amount of wood waste generated in the UK’. The report did, however, calculate that wood waste in the construction industry contained more than:

- 2.5 million tonnes a year from construction sites, and
- 2.1 million tonnes a year from demolition

The consignment of used timber to waste and non structural use is placing immense pressure on the world's forests, and is a major cause of their destruction and deterioration. Currently, much of the timber reclaimed from demolition is simply shredded for use as pulp, reprocessed for strand-board, land-filled or destroyed; only a small amount of this is reused for building applications. Reclaimed timber could very easily be used in new buildings, renovations or alterations, and current building regulations and practice means that demand for good quality timber for construction is high. A great many UK companies, both large and small, are in business reclaiming and selling building materials of all kinds. However, this industry only constitutes a drop in the ocean when compared to the overall total mass of timber waste in the UK. At the time of writing, the turnover of the reclamation industry, as a whole, is around £450 million per year; however, no official figures exist for timber reclamation alone.

1.1 Motivation

There were several reasons for carrying out this research. Virgin, new timber is produced, often from sustainable sources, at extremely competitive prices; however, reclaimed timber has the edge environmentally. Care for the environment, maintaining biodiversity, cost implications in using reclaimed timber and an attempt to steer future legislation and best practice, are the drivers behind this research project. The level of knowledge relating to the amounts, types and location of demolition reclaimed construction materials is, at best, an informed guess. Until the proposals of increasing legislation and growing public concern over the environment and the loss of biodiversity, there was little opportunity, or need, to benchmark demolition waste streams.

Existing and new legislation relating to construction waste and materials reuse, and a more general move towards cost saving in construction, have highlighted the issue of reclamation and reuse of demolition materials without further processing to a wider audience. These issues, and a probable future of increasing legislation relating to construction waste coupled with innovations in technology, aswell as reducing the effects of waste on the environment, has been the guiding motivation for this research.

1.2 Current status of reclaimed timber in construction

Reclaimed timber is not specifically included within the scope of many current timber standards; however, with minor additional application rules they could be extended to include reclaimed timber. Unfortunately, at the present time, there exists a dearth of tools and techniques suited to the deconstruction of timber structures and buildings. BS 6187 Code of practice for demolition (BSI, 2000), recommends that timber structures should either be demolished by deliberate collapse methods or deconstructed. This second option presented by the standard suffers due to the quantity of, and difficulty in removing, connectors in timber structures and the time taken in precise deconstruction; making this option far more costly.

Many timber components reclaimed from deconstruction or demolition are tainted, for direct construction purposes, with nails and screws that must be removed or made safe for handling, before even considering reuse. This can be an extremely time consuming process, only proving to be viable for high value, large section timber joists. Many lower value components such as small section beams and joists will need to be free of nails and screws if they are to be reused, in any capacity. Nailed and screwed connections are used to attain explicit values for material shear and pullout (the tendency of opposing structural forces to draw nails out of timber connections).

While there exists a wide knowledge base on these criteria, there is currently, little research establishing basic rules for the performance of nails in reused timber joists. For these reasons, timber reclaimed through demolition operations is often sent to waste streams; no operator wishes to be burdened with the costs involved in the reclamation process.

1.2.1 What is strength grading and how is it carried out?

In its simplest form strength grading, formerly known as stress grading, is a method of accurately estimating the limit state of a piece of plain sawn timber. Construction professionals often encounter, with equal measure, the terms 'strength graded' and 'dry graded', which are often used interchangeably in texts on the subject. Strength grading of timber has been conducted for many decades, but it is only relatively recently that moisture content requirements have been introduced into the standards, hence the use of the phrases 'dry grading’ and ‘dry graded'.

Strength grading may be carried out by either visual or mechanical methods; visually, by individually licensed operatives, and mechanically, by companies operating individually licensed strength grading machines. Each separately licensed grade mark contains a unique identifying number, of the grader or grading machine, ensuring total traceability throughout the process.

Visual strength grading is undertaken by specially trained individuals licensed by independent third party certification companies including, BM TRADA Certification, BRE QA and BSI QA. Visual strength graders examine each piece of timber and assess it for the presence of naturally occurring growth characteristics which affect strength. Visual strength grading produces two grades - GS (General Structural) and SS (Special Structural). Machine, or mechanical, strength grading also requires the assessment of every piece of timber. Strength grading machines measure the stiffness of timber; there is a direct correlation between the stiffness of a piece of timber and its other strength properties. Strength grading machines are licensed by independent third party certification companies. BS EN 14081 Strength graded structural timber with rectangular cross section (BSI, 2011) governs the process issues and machine testing for the mechanical strength grading of softwoods.

1.2.2 Why use strength graded structural timber?

Timber, used structurally in a building, is a safety critical construction element, and the use of strength graded timber is a requirement of the UK Building Regulations - Approved Document A (DCLG, 2010). Dry graded timber is seen as a material which is 'fit for purpose' in structural engineering terms. It is stronger, and being dry, it is dimensionally stable, further reducing the risk of shrinkage or distortion which can occur if the timber is subject to changes in moisture content. It is also lighter because of this reduced moisture content, and as a result is easier to handle, machines better and gives a smoother finish, thereby also providing an improved surface appearance.

1.2.3 Need for a change of the rules for reclaimed timber

When timber is reclaimed from demolition it will usually have been subject to a stable, dry atmosphere for several decades, so usually appears in the dry condition, where the measured moisture content is equal to, or less than 12%. This offers the potential for immediate dry grading, prior to structural reuse. However, sustainable reclamation of timber from demolition can only occur where it is feasible and economic to carry the reclamation operations out. In recent years certain industry and regulatory drivers have increased the potential scope for the reclamation of timber for direct reuse in construction:

- Increased cost of sending timber to landfill (Landfill tax)
- Better tools and techniques available for deconstruction
- Regulations concerning site waste management
- Development of more effective routes to market
- Increased client demand for reuse in construction, renovation and DIY.

Standards or best practice guidance for the regrading of reclaimed timber joists would be the obvious next step in this developmental path. This research seeks to add to the existing body of evidence in favour of the direct reuse of timber components from demolition in further construction operations.

1.3 Research framework

This research thesis is organised into several discussion areas; an Introduction and background, a Literature search and review, Project methodology, Results, Analysis and discussion, and Conclusions and suggestions for further work.

The research introduction and background investigates the status of reclaimed timber from demolition in today's construction industry, the motivation for this research project and a general background to reclaimed timber use in the UK.

The Literature review details a large scale view of the use of reclaimed materials, both in the UK and global construction industry. The review then considers a more narrowly focussed investigation of reclaimed and recycled timber; fielding the argument that there is ample scope already to reuse timber directly in new construction. At this point the review investigates why there is little direct use of reclaimed timber in new construction; considering whether the lack of an industry compliant regrading protocol contributes to this. It further suggests that, from recent complimentary research, there is scope for the introduction of a method of regrading that is quick, inexpensive, and that can be carried out directly, at the site of building demolition/timber recovery.

The Project methodology diverges into two parts: Firstly, how an industry test regimen could be administered by a certified testing company, and the resultant regraded timbers delivered to the construction sales market. Secondly, how the test methods utilised to carry out this research project could be laboratory duplicated, including the visual and machine tests involved. This section also discusses and clarifies the visual grading, machine grading simulation, small clear testing, density tests, age calculation and tree ring frequency testing, in enough detail to enable the tests to be reproduced by other researchers.

The Results presents the test results for this research; Modulus of Elasticity (MOE), Modulus of Rupture (MOR), density, dating of samples and tree ring frequency. While this section contains some discussion, it only relates directly to the results obtained.

The Research Analysis section of this document presents a discussion based on the results obtained from the research. It also discusses the methods of generation of model calculations produced from the sets of results obtained. The calculated models relate to the theory that tree ring frequency and measured density of the timber yield a model calculation, able to act as a predictor of the modulus of elasticity of similar timbers recovered from demolition. The assumed age of a reclaimed timber sample is also considered as a partial indicator quality and remaining strength.

The research conclusions, suggestions and closing remarks are a discussion relating to how the results of this research can be further used, recommendations arrived at from inferences in the previous sections; and how these results and recommendations may inform the basis of further research work in this field.

1.4 Background to the research

The original intention of this research project was to investigate the possible direct reuse of many different types of building materials; from bricks, timber and slates, to complete units such as air conditioning and heating units. However, it was discovered in the formative period of the research that this was going to be a very large task. Even narrowing the investigation to only consider timber reclaimed from demolition still involved considering an extensive list of variables. The other reason for concentrating on timber reclamation is that it is probably the most wasteful of the post demolition processes, with much of the timber reclaimed going to landfill.

While there can be, in some cases, little difference in material qualities between virgin and reclaimed timber, there are currently no recognised grading rules or best practice guidelines for the stress grading of reused timber, either by machine or visually. Since the majority of timber reclaimed from demolition of buildings will require some reprocessing before it is reused structurally, it will be necessary to carry out some form of regrading operation on the timber prior to reuse.

Establishment of a ‘rule of thumb’ or a basis for grading best practice for reclaimed timber is the first step in establishing an altered form of the existing guidance. The formation of a rule of thumb for grading reclaimed timber, and a basic form of best practice for doing this, is the goal that this research project aspires to contribute to.

1.5 Contribution of the study to new knowledge

This research will contribute a best practice methodology for grading reclaimed timber from demolition, while it is still at the demolition site; speeding the grading process and allowing direct reuse of the reclaimed timber in new build structures or refurbishment of existing buildings.

The research will also generate a model expression, based on tree ring frequency and calculated density, which can be used to give an accurate estimate of the modulus of elasticity and thus, a reliable strength grade of timber joists recovered from demolition.

2 Literature review

2.1 Introduction

The Bruntland report, Our common future, (WCED, 1987) described sustainable development as ‘meeting the needs of the present without compromising the ability of future generations to meet their own needs’. Simply put, this means that globally we should take care of the resources available to us now, to safeguard their availability in the future. This applies to all resources, not just foodstuffs and resources, such as oil, coal, timber, aggregates etc. All resources need to be conserved to allow their sustained use.

Sustainability in terms of construction often refers to a culture of reduction in the use of non replaceable materials, reuse of materials, and recycling. This culture can be increasingly attained in the modern world through using the latest technology, novel building methods, new and recycled materials and extensive thermal and energy management techniques. However, this attainment should also include directly reusing materials from demolition, as they are often an appropriate substitution for certain building products when coupled with new building methods and increased insulation values. Timber reuse in new construction is a case in point.

Sustainability is also described in financial terms by Dickson (2002) who cites the timber market as differentiating between the ‘capital’ of the forests, and the ‘income’ which can be used to meet our present needs. Therefore, there is a requirement in global terms for construction to be more sustainable.

Deconstruction and dismantling of buildings instead of demolishing them increases the amount of components that can be reused, reducing the share of demolition waste deposited in landfills. Schultmann et al (2001) illustrated that in Germany and France several research projects have shown environment-friendly dismantling and recycling strategies can even be advantageous from an economic point of view. The research presents sophisticated methodologies for the deconstruction and recycling of buildings, based on a review and a comparison of different research projects addressing the relevant problems and solutions concerning how deconstruction work is planned. The objective of the Schultmann study was to produce guidelines that would serve as a basis for forthcoming standards for the deconstruction and recycling of buildings and for the direct reuse of components.

In a more detailed evaluation, Chini, Acquaye and Rinker (2001) considered the mechanical properties of timber salvaged from two residential buildings in Florida, USA; comparing these to virgin timber tested under the same conditions. The research here proved that the salvaged timber was on average 50% denser than similar newly acquired virgin timber; furthermore, it was also strong enough to merit its structural reuse in building construction. Results of the visual grading in this research found that more than half of the reclaimed timbers (57%) had damage due to use and deconstruction, which resulted in a reduction of the grades reported.

2.2 Timber reuse in the UK

According to reported figures from CorporateWatch (2004) the UK construction sector accounts for around 10% of the British economy, employs around 1.5 million people, and is a major source of waste and emissions. Waste materials; noise, vehicle emissions and other contaminants are released into the atmosphere, ground and water on a daily basis. Furthermore, the report states that energy produced from non-renewable sources and consumed in buildings accounts for approximately 50% of UK CO_2 emissions, while the production of building materials accounts for a further 10%. The construction industry also generates one third of all the waste in Britain. It has been further estimated by the UK construction industry itself that 20% of new building materials on the average building site are simply thrown away at the end of the project (DCLG, 2007).

There exists a need to cut the energy output and materials wastage of the construction industry and in recent years there has been a shift to a culture of three zeros – ‘zero carbon, zero water and zero waste’, sometimes phrased as design-for-disassembly (DFD). This practice aims to build zero carbon buildings that have little or no net effect on the environment; which have low water consumption, in both construction and during habitation; and which offer zero waste products, again during construction and habitation. In construction this idea is often put into practice using a ‘reduce, reuse, recycle’ philosophy. Much of the work in this area of constructions currently being spearheaded in the UK by BRE Research and the Waste Action Resources Programme (WRAP, 2004); determining the methodologies, tools and products that need to be put in place to optimise materials recovery from existing buildings and from future construction. Complementary work by Hobbs and Hurley (2001) examined the waste arisings in the construction and demolition (C&D) industries, the legislative, strategic, fiscal and policy issues relating to deconstruction and how they can work effectively within the C&D and recycling industries. This study built on previous work by BRE in designating definitions for the various aspects of deconstruction and reuse in the UK:

- Disassembly - taking apart components without damaging, but not necessarily to reuse them.

- Demolition - a process of intentional destruction.
- Deconstruction – Disassembly which considers reusing the components.
- Refurbishment - Improving building performance through partial or complete replacement and/or upgrade
- Retrofit - Change of use or purpose occurring post construction and occupation
- Adaptable Building - A multi-use building which allows for change in its use

In the UK some local authorities are incorporating demolition of selected properties into their overall strategy for reuse. The work of Bowes and Golton (2001) investigated the demolition of flats in Oldham, North West England, examining the issues behind the obsolescence of the building, the local authority's decision to demolish, and assessment of the physical demolition process: the methods employed; the debris trails produced; and the level of reclamation and recycling on the project. The research also examined the attempts made to 'close the loop' by finding new uses for the project's debris within the local authority area.

Timber reuse in construction can fulfil this philosophy, and in part already does. The introduction of limit state working, exemplified by Eurocode 5 (BSI, 2008), in modern buildings means that modern buildings use a far smaller volume of timber than they did in previous eras. Eurocode 5 in common with the other Eurocodes provides no data on strength and stiffness properties for structural materials. It merely states the rules appropriate to the determination of these values to achieve compatibility with the safety format of the design rules of the Code. Used timber sourced from demolition and new timber sourced from waste from building sites is recycled into many composite construction forms, from medium density fibreboard (MDF) to oriented strand board (OSB). However, reuse of timber recovered from demolition is one facet of timber reprocessing that does not enjoy the same success; even though it is easy to achieve.

As a construction resource timber consumes about 50% of the energy needed to produce similar volumes of concrete and about 1% of the energy needed to produce a similar volume of steel. This, coupled with the fact that trees can improve land quality and soil fertility and are also a prime sink for carbon emissions, signals that timber has the potential to be a totally sustainable resource. This sustainability can be improved by increasing their carbon sink characteristic through usage and re-usage as reclaimed construction elements in long life products such as timber frame buildings. Timber frame construction, therefore, has a major environmental advantage over its competitors in the UK market and this is expected to be a contributing factor to its continuing growth.

Hairstans, Kermani and Lawson (2004) considered that sustainability issues, the application of the Eurocodes and consumer awareness will result in the increased usage of timber as a structural material in the UK. An extremely versatile material with a wide range of physical and mechanical properties, timber is a renewable and reusable resource with an exceptional strength-to-weight ratio. There is also now increased global pressure on the construction industry to use timber as a structural component due to its sustainability; with particular attention paid, in the UK, to the domestic dwelling construction market.

The use of timber as a structural material has become far more widespread; and now, following the implementation of Eurocode 5 and the improvements in engineered wood products, there exists an unique opportunity for the construction industry to produce timber frame houses in the UK constructed entirely from products from sustainably managed sources or from recycled and/or reclaimed materials.

2.3 UK demolition waste

The demolition industry has undergone a major transformation in the last few decades from a labour intensive, low skill, low technology, and poorly regulated activity, to a highly mechanised, skilled process. This has been brought about by the increased complexity of building design, financial pressures from clients, health and safety issues, regulatory requirements and significant advances in demolition plant design. The demolition industry today employs fewer, but more highly skilled, operators using very expensive and specialised equipment. Traditionally, much of the demolition contractors' income was from the sale of salvaged and recycled materials. However, this has changed and income today is mostly generated from the contract fee; demolishing as quickly and as safely as possible. Nevertheless, substantial amounts of materials and components are still reclaimed, though these appear to be mostly down-cycled and not reused to their full potential

Limited studies have identified that demolition waste is mostly composed of concrete, with smaller amounts of ceramics, furniture, timber, metal, plastic, electrical goods and miscellaneous materials. In six case studies carried out for the Building Research Establishment (Hobbs and Hurley, 2001) there is an overall variation between the types of wastes being generated and the reuse or recycling potential for the key demolition products.

Table 2.1. Variable percentages quantity of materials (by weight) reclaimed from six case studies featured in the UK Country Report on Deconstruction (Hurley and Hobbs 2001)

	Multi-storey housing	**Prefab housing**	**Factory**	**Multi-storey offices**	**Factory 2**	**Hospital**
Ceramic	2.3		9.3	1	16	67
Metal	3.1	0.4	2.8	1.5	2	1
Furniture	2.3			59.9	1	
Plastic	0.6	1.1		1.7		1
Concrete	86.6	85.2	86.5	34.1	78	12
Timber	3.5	7.7	1.4	1.8	2	19
Miscellaneous	1.4	5.6			1	
Total	100	100	100	100	100	100

While the variation in materials will be determined by the construction type, the reuse potential will consider how the materials were bound together as well as their quality and condition. Table 2.1, illustrates the relative values (by weight) of reusable products sourced from demolition during six case studies. In all of the six studies, concrete waste was proven to be the most ubiquitous form; however, the studies also show that a not inconsiderable amount of timber waste was also recovered from the sites.

There are eight factors which affect the choice of demolition method, and in the BRE six building study there were substantial opportunities to reuse as well as recycle. The research illustrates that any single building, as part of its demolition, will be subject to a unique combination of the following 8 factors:

1) Structural form of the building
2) Scale of construction - A large building may make a complex method more economic
3) Location of the building - Access can affect the choice of demolition equipment
4) Permitted levels of nuisance
5) Scope of the demolition - Some methods are not suitable for partial demolition.
6) Use of the building - A contaminated structure will be treated differently to an ordinary residence
7) Safety
8) Time period - Clients often want to see a rapid return on their investment, precluding full reclamation

However, as part of the recommendations of the BRE study, Hobbs and Hurley (2001) suggest that four further factors should be added to the list; though, these are again concerned with issues unrelated to the physical attributes of the building:

1) The proposed fate of the building materials and components - Once the structure is demolished this will probably affect the choice to some extent. For example, explosives will reduce a building to small pieces taking little or no account of the separation of materials.

2) The culture of the demolition firm carrying out the work – This will, to a certain degree, condition the choice of method for dealing with a particular problem.
3) Monetary cost - If a method would place a heavy burden on the contractor, without presenting any other advantages it is unlikely to be chosen
4) Site Waste Management Plan (SWMP) – now a legal requirement. The legislation determines that for all construction projects with an estimated cost greater than £300,000 excluding VAT, the SWMP must record details of the construction project, estimates of the types and quantities of waste that will be produced, and confirmation of the actual waste types generated and how they have been managed, including waste generated by demolition.

There will usually be several methods of tackling any given demolition project, each of which will have its own various merits. There may be no right or wrong method, just alternative options based on assessment of the relevant factors.

2.4 Definition of reclaimed materials

Reclaimed materials are considered to be those that have been used before either in buildings, temporary works or other uses and are re-used as construction materials without reprocessing. Reclaimed materials may be adapted and cut to size, cleaned up and refinished; however, they are fundamentally being re-used in their original form.

Table 2.2. Examples of the differences between reclaimed and recycled materials (CorporateWatch, 2004)

Reclaimed	**Recycled**
Directly re-used timber sections or floorboards	Panel products with chipped recycled timber
Building bricks cleaned up and re-used	Crushed concrete or bricks for hardcore
Steel sections shot-blasted and re-fabricated	Steel with a proportion of recycled content
Re-used, complete glass panels or windows	Crushed glass recycled as sand or cement replacement

Timber recovered from old buildings, through demolition, is generally considered to be of superior quality to modern joinery timber. However, this is not because the timber is inherently better; it is because older timber is more likely to contain a higher proportion of heartwood than, less durable, sapwood (CIRIA, 1999).

Generally, in reusing construction materials, there are certain issues that must be considered. These are especially important when considering the reuse applications of reclaimed timber:

- Identify materials that are easily available at the right quality and quantity.
- Reclaimed materials are usually obtained from different sources to new building products. Set up relationships with new suppliers in the salvage trade.
- Early design information helps in the sourcing of reclaimed materials. Lead times for ordering will need to be longer.
- Identify demolition projects near to the construction project. Reclaimed materials can then be selected and extracted as required.

- Material specifications need to be flexible enough to allow for the variations in reclaimed material sizes. Specifications should outline the essential performance properties required, without over defining the details.
- Agree on a sample of the reclaimed material which can be used to show clearly the quality that is expected in order to meet the design requirements.

Generally, salvaging direct from demolition is often cheap or free, while older antique or reclaimed materials, in large quantities, may be much more costly.

2.5 Reclaimed timber reuse

While government and the public support the introduction of new and novel forms of materials and reuse strategies, it has in the past proven difficult to introduce new technologies and processes into the construction sector in the UK. There are various reasons for this:

- Prescriptive building regulations.
- The low impact of innovation on costs.
- An inherent conservativeness on behalf of the industry.
- Suspicion of new technologies due to past experiences.

Reclaimed or recycled construction elements are one such innovation. An appraisal of the amount of timber waste produced at regional, national or even worldwide levels is important as this availability will outline both the market possibilities for timber reuse and the necessary structure involved in processing.

The World Business for Sustainable Development emphasises that there are several barriers to reuse and recycling, other than the technical difficulties. They include economic, geographic and regulatory (or environmental), legal, business, social, time and informational barriers. While there are clear benefits in materials reuse (the figure below for reclaimed against new timber studwork shows a definite benefit in ecopoints and lessening of detrimental effects on the environment) John and Zordan (2001) illustrate that the environmental benefit of any form of recycling will only be utilised if the product succeeds on the market. They consider that whatever the reuse process, it must include technical, environmental and marketing aspects.

Already mentioned, research from the Waste Resources Action Programme (WRAP, 2004), considers the availability of timber waste from demolition to be intermittent, at best; frequently only happening when the economy is good and new buildings are in progress. This effect introduces the necessity of suppliers of reclaimed timber having stockpiles in order to sustain the uninterrupted reuse of the product, or of having a special arrangement with business, which makes reuse a viable option.

The geographical localisation of timbers is also relevant. Transportation distance is a key aspect on the cost of reuse. Transportation also affects the environmental balance of the reused product. Having large amounts of timber and several sources of supply improves chances for the reuse product to succeed on the market.

The total cost of managing a waste material is a good way to calculate the interest for its reuse and is a strong argument when asking for financial support. If the waste does not have a significant cost or is not the object of social or regulatory pressure, there is probably little interest in reuse from the industry's point of view. Consequently a detailed study of the legal and social status of the waste is very important. Any study into reuse of waste materials would have to consider:

- Production process - a study of the production process involved in reuse, including variability, normally gives significant information about characteristics, including the possible presence of contaminants. Even a small variation on processing parameters or composition can result in significant changes in the overall reuse characteristics
- Waste composition and presentation - most industries have little information about their own waste except that which is legally required by environmental and other government agencies; therefore, most of the time the information available will be useful only as a starting point for a deeper study
- Selection of possible application - selecting the best potential uses for reuse. As a rule the best application is one that will use the material's true characteristics and properties to enhance the performance of the new use and minimise environmental and health risks

Waste applications should not be made on a preconceived basis. Tukker and Gielen (1994) present a methodological scheme to evaluate the environmental benefits of different waste use options, including life cycle evaluations of these options. One alternative approach that simplifies the work is to consider some processing rules to be observed:

a) Minimise the need for industrial transformation of the waste
b) Minimise the transportation impact of the waste to the processing plant and the final product to its consumers

c) Processing must minimise the leaching or volatilisation of dangerous chemical compounds by avoiding contact of the new product with the users or any deterioration agent, such running water
d) The new product must be reusable/recyclable
e) The new product must present a competitive advantage in comparison to the established market and improve the waste value

Timber is naturally renewable with a low environmental impact, so it would seem that the most environmentally friendly option, and the ultimate target for the construction industry, is the reuse of timber building components without modification. Since the deconstruction process can cause damage to timber elements, the suitability of timber for reuse will often depend, not only on the condition of the timber, but on its robustness to withstand damage during removal from the demolition site. This suggests that larger section timber will be more suited to reuse and, in practice, this is often the norm.

This investigation into the strength qualities of reclaimed timber joists aims to pave the way for the development of a methodology, utilising both quantative and qualitative procedures, which can be used as a basis for testing reclaimed construction timbers with a view to their unmodified reuse as construction elements.

Despite interest at the research level by bodies such as BRE, Construction Industry Research and Information Association (CIRIA), Timber Trade Federation (TTF) and the Timber Research and Development Association (TRADA), much of the reclaimed and antique materials available from demolition are bought by private customers, rather than by professional builders or architects. Constraints on the use of reclaimed timber include comprehensive building regulations, which require certain manufacturing or performance standards; often difficult to prove for reclaimed timber.

One of the other main reasons that reclaimed timber is not often directly reused for construction is that of expense. Grading of virgin timber is part of the sawmill production process and is factored into the basic price. This makes the grading of newly cut and processed timber a cheap, efficient and speedy process.

Contamination with toxic chemicals, which may have been perfectly acceptable for use as timber treatments in the past, is another potential issue. However, by far the largest constraint to supply and demand for building materials is availability at a set point in time of reclaimed timber of the right size, type and specification to fit a project design or pre-agreed site schedule. Anecdotal evidence suggests that only when builders and architects are forced by regulation, will the widespread use of reclaimed timber become commonplace.

Interest at the building industry body level includes contributions by; CIRIA (1999), who produced a handbook on the use of reclaimed and recycled construction materials – the Reclaimed and recycled construction materials handbook; and TRADA, who inaugurated the Timber Dwelling Project, which involves best practice demonstration sites featuring the use of recycled materials and the re-use or recycling of waste created, on these sites, during the construction process. Other sources which are involved in the timber aspect of building materials include the BRE, which has set up an internet Materials Information Exchange service, where suppliers and users of reclaimed materials can post information on availability and suitability for reuse. BRE is hoping to establish itself as a specific industry trade body in this area.

The main, in depth, academic studies relating to the strength of reclaimed timber are American, and latterly northern European in origin; for example, Plume (1996) considered that manufacturers should reuse heavy timber for post and frame buildings because it is typically dry and stable; however, assignment of a strength grade is a significant obstacle. Similarly, several researchers have investigated the properties of timber that has been in-service for a considerable period of time; Lanius et al. (1981) used in-situ stress wave techniques to non-destructively determine the elastic modulus of floor joists; it is important to note that they stated this method should be used in conjunction with a visual inspection. Fridley et al. (1996) evaluated the wood strength of roof trusses after 85 years of service life by cutting small clear specimens from several truss members to determine strength properties. A comparison of these values to historical research values showed no difference in clear wood material strength. However, it should be noted that both studies did not evaluate the strength properties of standard size members with natural faults.

To fully understand how this research project will progress toward producing a best practice method of testing reclaimed timber it is necessary to understand the process by which new timber is graded. After reviewing the current timber processing industry method of grading virgin timber, this project will then investigate how and if this method can be developed to deal with the idiosyncrasies of reclaimed timber joists.

It is a requirement of the structural timber design code, BS 5268-2 (BSI, 2002), that all timber used in the UK for structural purposes should be strength graded, either visually or by machine, to an accepted standard. The UK standards cited are BS 4978 (BSI, 2007) and BS EN 519 (BSI, 2000a) for softwoods. For softwood timbers graded outside the UK, compliance with the standards or rules listed in BS 5268-2, clause 1.5 is acceptable. However, the introduction of Eurocode 5 has changed how timber is specified for construction.

The strength of timber is affected by its moisture content; with strength increasing relative to moisture content. For example, the bending and compression stresses for timber graded as ‘wet’ (Service class 3) are, respectively, 80% and 60% of those for timber graded as ‘dry’ (Service class 1). Because of this, it is essential that timber used for structural purposes is strength graded at a moisture content appropriate to the exposure conditions of the timber in service. For example, timber to be used in building construction is always graded to Service class 1 or 2. The three service classes are defined in the standard (BSI, 2000a) as:

- Service class 1: Characterised by a moisture content in the materials corresponding to a temperature of 20ºC and the relative humidity of the surrounding air only exceeding 65% for a few weeks per year. In such moisture conditions most timber will attain an average moisture content not exceeding 12%.
- Service class 2: Characterised by a moisture content in materials corresponding to a temperature of 20ºC and the relative humidity of the surrounding air only exceeding 85% for a few weeks per year. In such moisture conditions most timber will attain an average moisture content not exceeding 20%.

- Service class 3: Characterised by higher moisture contents than service class 2.

A moisture content of 20% is therefore used as the dividing point for grading timber for use in wet or dry conditions.

Structural softwood timbers can be graded either visually or by machine. Visual strength grading takes into account timber growth characteristics such as rate of growth, slope of grain, distortion, knots, resin pockets, etc. Machine strength grading exploits the relationship between strength and stiffness of the timber product. Each piece is graded, in accordance with BS EN 519 (BSI, 2000a), directly to a strength class, as specified in BS EN 338 (BSI, 2009), and is marked accordingly.

2.6 Traditional and modern information for strength grading

Current standards for the grading and use of sawn timber in construction focus predominantly on new timber stock:

- Eurocode 5 - Design of timber structures (BSI, 2008)
- BS EN 336 - Structural timber – sizes – permitted deviations (BSI, 2003)
- BS EN 519 - Machine stress grading of timber (BSI, 2000a)
- BS EN 14081 - Strength graded structural timber with rectangular cross section (BSI, 2011)

The majority of reclaimed timber intended for reuse structurally can be partially assessed by BS EN 14081 (BSI, 2011) and BS 4978 Visual strength grading of softwood (BSI, 2007), which is still current. However, this does not account for service anomalies and damage in the timber, such as:

- Through nails, screws and fastenings
- Through notching, holes and cut outs
- Through splits and cracks (or checks) through drying out in service

As part of the reclaimed timber regrading process these anomalies need to be thoroughly investigated. Work by Rammer (1999), Cooper et al. (1996) and Nakajima and Murakami (2008) illustrate that reclaimed timber can still be of useful structural use, even in light of considerable 'in service' damage. There are currently no plans to make provisions in UK standards for regrading timber with this kind of damage; however, there are existing solutions, including plugging (as long as the material used is of greater strength/stiffness than the parent wood) and/or machining out damaged areas; though these methods affect the size and quality of the finished product.

Regrading timber from demolition will involve utilising existing legislation and standards, modifying visual grading techniques, and extending current methods of grading of timber for construction. This information can be combined to use a quantative method, enabling robust tests to be carried out on reclaimed timber elements and conclusions to be drawn from the results.

There are several issues surrounding the grading of reclaimed timber that are evident, but that will not be addressed by this research, these are:

- Long term effects of 'in place' structural load forces – while loads will have an effect on the reclaimed timber there is not a sure way of identifying this, other than removing the timber joist from the intact building, thus giving a more complete history of its use
- Possible identification of the timber species from visual characteristics of the wood structure – species identification is, at best, 95% accurate even with the most complete specimens.

However, long term loading in timber is an issue that has been investigated in some detail by previous commentators, and is known to cause strength reduction on a logarithmic scale, resulting in a reduction of around 40-45% after 100 years of use, evidenced in Construction materials: their nature and behaviour (Domone and Illston, 1993). Friedley et al. (1995) also provides an in depth study of the history of 'duration of loading' research. Species identification, however, has already been shown by Ravenshorst and Van-de-Kuilen (2006) not to be a significant factor in the strength grading of individual timber joists. This has also been made evident in the introduction of Eurocode 5 (BSI, 2008), where timber can be specified by its physical limitations or by species; however, species specification is considered mainly for aesthetic or durability characteristics.

2.7 Expected safety margins for reclaimed timber

Wood is a heterogeneous material whose properties depend greatly on its species, biological diversity and growth conditions. Timber strength properties are affected by many parameters, including temperature, creep, knots, number of growth rings, density and grain angle. In reclaimed timber there are also the effects of age and surrounding humidity to take account of. All of these factors can affect the safety margins for use/reuse.

There are several methods of alleviating load stress and safety margins, including using a percentage-based ‘size penalty' on reclaimed timber when compared to new timber. This would relate to established tables, currently in use, to determine the dimensions of structural timbers needed for a given span or distance. This research will also investigate the effects on the regrading process of:

- The age of the reclaimed timber – using small clear tests this research will investigate the effects that the age of a timber element may have on its strength grading
- Heartwood versus sapwood in the longevity and strength of timber elements

Much of this work will be new and, as such, there is little authorative work to draw upon at present. However, ongoing industry testing and academic research pertaining to reclaimed timber elements and structures will supply a constantly growing set of data to help in formulating theories.

2.8 Timber strength grading using visual and simple methods

Several pieces of research have analysed the behaviour of wood under stress to determine its strength. In these analyses, the influences of physical parameters, such as moisture content and density, on the modulus of elasticity were considered. The most significant of these is the work of Dinwoodie (2000), which offers a history of timber stress grading, highlighting how this has changed from visual, to a mix of visual and machine grading, to its standing now of purely machine grading. The work also highlights how small clear tests were originally used in conjunction with visual grading of timber joists, and the relationship in results between small clear tests and stress testing of full sized timbers.

Knots in the timber structure are associated with distortion of the grain and since even slight deviations in grain angle reduce the strength of timber appreciably it follows that knots will have a marked influence on strength (Mitsuhashi et al. 2008). The significance of knots, in relation to the overall strength of the timber joist, will depend on their size and distribution both along the length and in cross-section. Knots in clusters are more important than knots of a similar size which are evenly distributed, and knots on the top or bottom edge of a joist are more significant than those in the centre; furthermore, large knots are much more critical than small knots.

Research by Mitsuhashi et al. (2008) also introduced a new method of describing this parameter, the area reduction factor (ARF), which considers the effect of knots on the tension strength of timber. ARF considers both the projected area of knots and the effect of the slope of grains around the knots. ARF was determined as the minimum value obtained when a knot measurement window of 100 mm was slid along the plank.

Dinwoodie’s (2000) work illustrates that density is a function of cell wall thickness and therefore dependent on the relative proportions of cell components and the level of cell wall development. However, variation in density can occur within the same species and even within a single tree. In general, as density increases so the various strength properties increase, and thus, density remains the best traditional predictor of timber strength; high correlations between strength and density are common observations in timber strength studies. Dinwoodie (2000) states that: ‘In most of the timbers used commercially the range of the relationship between density and strength can safely be assumed to be linear’.

Accepted literature contains many analyses of moisture content significantly affecting the elastic constants of timber. There are also several studies; Gerhards (1982), and Lenth and Sargent (2004), that show an increase in temperature and humidity results in a decrease in the elastic constants of timber.

Since timber density is influenced by the rate of growth of the tree, it should follow that variations in tree ring width and frequency will affect changes in the density of the timber, and hence, it’s strength. In softwoods, increasing rate of growth results in a lower frequency of growth rings and an increased percentage of low-density early wood; consequently both density and strength appear to decrease as ring width increases.

Exceptionally, it is also found that in certain cases very narrow rings can also have very low density, though this is only characteristic of softwoods from very northern latitudes where latewood development is restricted by the short summer period. Latewood is more dense than wood that is formed early in the season, but the mechanics of tree growth mean that latewood is only formed during the later part of the summer season; hence the greater the proportion of latewood, the greater the density and strength.

The frequency of growth rings can also affect timber strength; this is especially prevalent when considered in conjunction with timber density. This fact is not commonly presented in the literature; however, it can significantly interfere with the values of the modulus of elasticity and rupture. In their study of the parameters that influence redwood crush, Cramer, Hermanson and McMurtry (1996) noted that the number of growth rings per inch may predict the crush behaviour more efficiently than the density alone. This validated earlier findings regarding the changes in elastic modulus and strength within an annual ring as, for example Bodig and Jayne (1982) discussed, suggesting a variation in the tensile strength of wood within the location of the growth rings.

2.8.1 Small clear samples

Basic stress is that level of loading which can be permanently sustained with safety by an ideal structural component. In the derivation of basic stresses from the tests on the small clear samples consideration was given to both the variability in the strength figures for clear timber and the need to ensure that the imposed load was a safe one for that particular set of conditions.

Timber has been described as a variable material and a measure of this variability was shown in how the frequency distribution of a set of test results approximates closely to a normal distribution curve which can be used to calculate the value below which a certain percentage of the results will not fall.

The apparent strength of timber is influenced by rate of loading, specimen size and shape, and duration of loading. So, rather than apply a series of factors, a single factor derived mainly from experience has been used. Dinwoodie (2000) states that: ‘Generally a value of 2.25 was used for most properties, excepting compression parallel to the grain where it was 1.4. These factors are in effect a safety factor for pieces of minimum strength, and also cover the possibility of slight overloading’.

In the static small clear bend test a specimen is supported and a load-deflection diagram plotted. Three strength properties are usually determined from this test. The first and most important is the modulus of rupture (MOR), which is a measure of the ultimate bending strength of timber for that size of sample and that rate of loading. This is actually the stress in the extreme fibres of the specimen at the point of failure. The second strength parameter is work to maximum load, which is a measure of the energy expended in failure and is determined from the area under the load-deflection curve up to the point of maximum load. The third parameter, total work, is the area under the load-deflection curve, and is taken to complete failure.

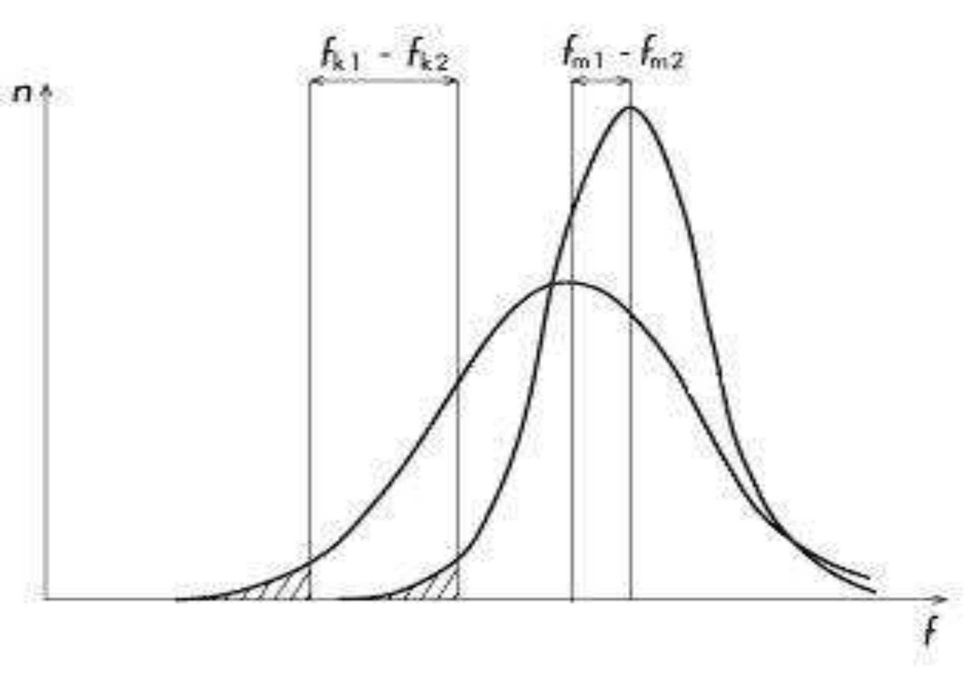
Before the rise of machine grading the basic stress, therefore, for each property was obtained primarily from the results of the standard tests on small clear specimens by dividing the statistical minimum by the appropriate safety factor (2.25 or 1.4). Most structural timbers have some defects so it was necessary to apply a factor known as the strength ratio to the basic stress in order to obtain safe operating conditions for these joists.

2.9 Aims of this research

Timber production has undergone major change in the last 150 years, from visual grading, using exclusively mature heartwood where possible and over specifying of timber joists for use in construction; to cutting timber with a greater proportion of juvenile wood, kiln drying, and limit state calculations and specifications for timber to work nearer to its mechanical limits when utilised in construction.

This change in the methods of timber processing and specification for construction, may have already affected the potential for recovery for much of the timber used in modern building projects. However, older timber joists still have enormous potential for reclamation and reuse, ostensibly because they started life with a higher specification and generally higher strength; often greater than would have been needed for their original constructional use. Even though this strength may have reduced through ‘duration of loading’ and general material decay over time, these timbers remain a valuable and viable reclamation source.

Figure 2.1. Diagram of theoretical distributions, generally illustrating the higher relative strength and smaller spread of characteristics in older timber joists than corresponding modern components (where fk = 5th %tile and fm = mean strength)



The main aim of this research was to investigate the potential for the recovery and direct reuse of timber structural joists and other elements and to show that, through calculation and visual observation, the existing timber grades can be applied to timber reclaimed from demolition. Utilising the timber density, age of the timber and a count of the average tree ring frequency, in conjunction with an alternative visual grading method, this research project aims to build a model calculation to predict an expected strength grade of timber joists recovered from demolition operations.

2.10 Objectives of this research

The research proposes to modify the existing visual grading process for timber to allow an ‘on site’ contractor or demolitions operative to carry out specified tests on reclaimed timber from demolition processes. To do this it is necessary to:

- Establish the timber condition by modified visual grading
- Produce a grading system that is independent of timber species
- Set up a testing model for large timber joists, sourced directly from demolition, and normalised to the test area
- Set up a testing model for small clear timber tests of samples cut from the large joists recovered from demolition
- Calculate the density of the reclaimed timber joists
- Calculate, or count, the tree ring frequency of the reclaimed timber samples
- Establish the cross sectional area and length of the timber joist - giving an indication of whether the joist can undergo further machining
- Analyse the results of all of the tests and formulate a model, to grade further timber joists separately recovered from demolition
- Test the model using a sample of reclaimed timber not used in the development of the model itself

The final result of this research will be a regrading best practice, which can be utilised to enhance the viability and eligibility of reclaimed timber joists for direct use as structural elements in construction projects. This methodology will be targeted at use where operatives can carry out the regrading operation ‘at the demolition site’, adding to the reuse potential of timber elements reclaimed from demolition.

While legislation such as the Site Waste Management Plans Regulations (HMSO, 2008) request the reuse of materials recovered from on site demolition, on new buildings. This research is being carried out in consideration of current regulatory calls to reuse waste materials, from demolition operations from all sites, whether large or small; and is expectant that these regulatory calls will be extended to direct reuse of reclaimed materials during the coming years.

3 Methodology and testing

The wide range of properties available from timber provides an almost unlimited choice for both structural and decorative applications. However, to produce a uniform test for reclaimed timber it is necessary to use characteristics common to all types of timber, and then formulate a methodology specifically targeted at reclaimed timber.

Similarly the methodology will differ as to whether the practitioner is a professional in the demolition or timber trade, or a researcher attempting to duplicate this work. However, before focussing on the tools and specific methods that could be utilised to carry out this research, an investigation of traditional and modern methods of timber strength testing must be explored.

Strength grading allows efficient use to be made of structural timber. Both visual grading and machine grading are used and both are equally valid. Visual grading assesses the size, frequency and positions of defects in the timber, such as knots, wane and sloping grain, and compares them to grading rules contained in BS EN 14081 (BSI, 2011). Machine grading measures the resistance of the timber to flexing, which gives a measure of the strength of the joist or member. Machine grading is carried out to the requirements of BS EN 519 (BSI, 2000a).

3.1 Traditional methods of grading

The traditional method of timber strength grading, formerly known as stress grading, is by visual inspection by individually licensed operatives. Every grade mark contains a unique identifying number of the grader, so total traceability of each piece of graded timber is ensured, thus ensuring timber quality and customer confidence

3.1.1 Visual grading

Before the advent of BS 5268 (BSI, 2008), or its originator CP 112 (BSI, 1952), the only testing regime for timber was by visual grading. This generally led to an over specification of timber joists, used in many older buildings, for the load to be carried. Timber for reuse in structures must be graded, visually or mechanically, just as new timber is graded. The graded timber is then assumed to have characteristic values of strength, stiffness and density. BS EN 14081 (BSI, 2011) specifies a method of strength grading softwood visually for structural use, specifying two visual strength grades - General Structural (GS) and Special Structural (SS). However, the standard gives only the minimum requirements for visual strength grading, so the following characteristics should be taken into account when carrying out this operation:

- limitations for strength reducing characteristics: knots, slope of grain, density or rate of growth
- limitations for geometric characteristics: wane, distortion (bow, spring, twist)
- limitations for biological characteristics: fungal and insect damage
- other characteristics, such as mechanical damage.

In order to determine these characteristics, all four faces of each piece of timber must be examined; however, simple economics do not allow for a through examination (in sawmills a piece of timber is machine graded in two to four seconds). Considering these negative points, TRADA (1995) states that there are advantages in visual strength grading of timber and that these are:

- it is simple, easily understood and does not require great technical skill
- it does not require expensive equipment
- it is an effective method, if correctly applied.

The first phase of this research was to produce an alternative method of visual grading that would still satisfy BS EN 14081 (BSI, 2011); this would serve to weed out inferior reclaimed timbers from those which would undergo further machine testing. To facilitate this, the existing visual grading process had to be investigated, and additions made to take into consideration any extra physical damage through ‘service life wear and tear’ that older timbers often demonstrate. Visual examination of new timbers under the standard investigates characteristics such as;

- Knots
- Slope of grain
- Wane
- Fissures
- Resin/bark pockets
- Distortion
- Rate of growth

The alternative test proposed by this research also considers;

- Damage - caused by insects, fungus, machinery or fittings
- Chemical treatments
- Density
- Condition – wet/dry
- Recovered size – cross sectional area and length

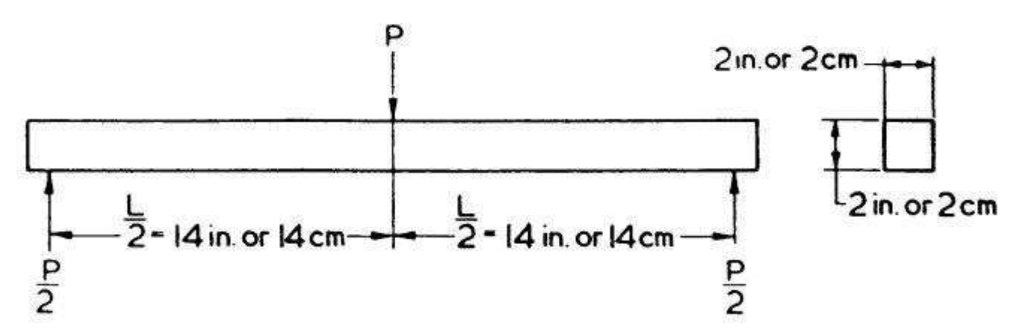
Visually strength graded timber, whether new or reclaimed, must have a minimum cross-sectional area of 2000 mm^2 and a minimum thickness of 20 mm. However, If regrading is carried out before processing, provided that the processing reduction from the target size is not greater than 3mm for dimensions less than or equal to 100 mm, or not greater than 5 mm for dimensions greater than 100 mm, the visual grade will not change and it will still conform to BS EN 14081 (BSI, 2011).

3.1.2 Static bending or ‘small clear’ tests

The static bending test utilised in this study is carried out by the central loading method, as detailed in BS 373 (BSI, 1957). The dimensions of the central loading test pieces were 2 cm by 2 cm by 30 cm, detailed in the 2 cm standard test.

The specimens should be air dried to constant mass at 12% moisture content, prior to being tested. In the central loading method the distance between the points of support of the test piece are 28 cm, and the load applied to the central point of the test piece, illustrated in Figure 3.1.

Figure 3.1. Central loading for 2cm standard test piece. After BS 373 (BSI, 1957)



The loading head must move as near as possible at a constant speed of 0.11 mm/s, and contour of the head, which is in contact with the joist, must have a radiused form with a 30 mm radius. The deflection of the test piece, at mid length, is measured with reference to the outer supported points, until the test piece breaks completely, or is fractured and unable to hold 60% of the greatest load placed upon it during the test.

Immediately after each mechanical test has been completed, a determination of the absolute moisture content of the test piece must be made. A section should be removed from the test piece; this must be a transverse section from near the point of fracture. The specimen must be weighed and then dried in an oven at a temperature of 103 ± 2 °C until the weight is constant; this may take several hours, dependent upon the moisture content of the test piece. The loss in weight, expressed as a percentage of the final oven-dry weight, is noted down as the moisture content of the test piece.

3.1.3 Indication of strength within the joist

While three-point loading tests, on a complete recovered timber joist, offer an overall strength grade, small clear test results can offer strength grading of a certain area of the cross section of the joist. Utilising this method to illustrate the weak areas of reclaimed timber joists was considered early during the research period, when the idea of machining out damaged areas was investigated with regard to the viability of recovering heavily damaged timber joists.

The small clear tests offer a method of directly observing the modulus of rupture; hence, being able to calculate the expected, actual strength of the timber joist. However, a problem with this method is that it because of the different stresses sustained during the working life of the timber dissimilar results in the small clear tests occur when these are taken from different areas of the cross section or along the length of the timber joist. This being expected, taking the lowest result from small clear results for a single timber should yield a least possible result for the modulus of rupture in the joist. This is considered further in the research analysis (Section 5).

3.2 Modern methods of grading

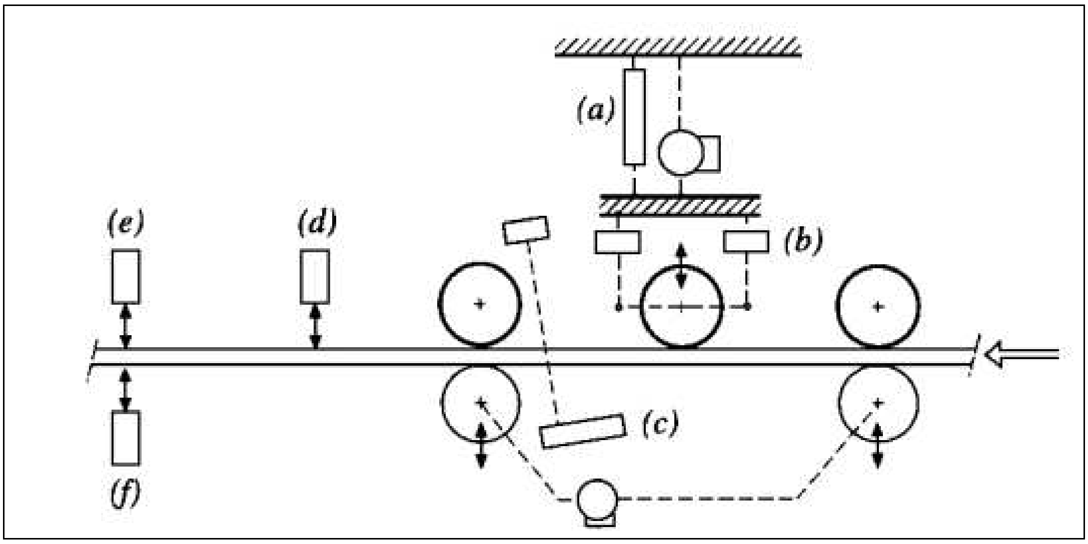
All structural members, assemblies or frameworks utilised in the construction of a building, should be capable of sustaining, the whole dead, imposed, wind and other types of loading referred to in Eurocode 5 (BSI, 2008). These requirements should be satisfied either by calculation, or by load testing of the individual timber members through machine grading.

3.2.1 Machine grading

Machine strength grading of timber has been used commercially for around 40 years, but still remains a specialised subject. Timber enters a grading machine at one end and leaves the other having been given a strength class; with no obvious means of how this is achieved.

After kiln drying, the timber is passed through a highly automated grading line where a combination of measurements is taken which closely relate to strength. From this, the machine determines the Strength Class of the piece of timber.

Figure 3.2. Scheme of an European strength grading machine with multiple sensing devices for measuring deformation (a), load (b), radiation absorption (c), bow (d), thickness (e) and moisture content (f), after TRADA (1995)



The disadvantages of visual strength grading can be overcome by machine strength grading. Most of the grading machines currently in use determine average bending modulus of elasticity over short lengths (Fewell, 1982). Timber is fed continuously through the grading machine, which bends each piece as a plank (about its weaker axis) between two supports and either measures the applied load required to give a fixed deflection or measures the deflection under a particular load. From these values a local modulus of elasticity is calculated, taking into account the cross-sectional dimensions and natural bow of the piece of timber.

Numerous investigations have dealt with the determination of modulus of elasticity by methods other than bending, such as vibration, microwaves and ultrasound. Recent research has shown that predictive accuracy of machine grading can be further improved by technical modifications of the machine and by a combination of several grading parameters. For example, the combination of modulus of elasticity (MOE) and knots has a better correlation with strength than MOE by itself (TRADA, 1995). The incorporation of density into the grading process can also contribute to the grading results.

One important difference between visual and machine grading is that with visual grading, it is possible to check at any time the correctness of the grade assignment, even when the timber is in use. For this reason there has to be frequent and regular control of the reliability of machine grading and, to accomplish this, two distinct control methods have been developed; the output controlled system, and the machine controlled system. BS EN 519 (2000a) outlines the requirements for the machine strength grading operations under both output controlled systems and machine controlled systems.

Naturally, the higher efficiency of machine strength grading comes at a high cost; grading machines currently available vary greatly in performance and price.

3.3 Issues specific to reclaimed timber

This section investigates the specific issues which are attached to grading reclaimed timbers; focussing on; the timber drying out, duration of loading, moisture content, density, resin pockets, distortion, slope of the grain, growth patterns, knots, species recognition, ring frequency calculation, timber specimen age and other forms of strength grading.

3.3.1 Drying

The rate at which wood dries depends upon a number of factors, the most important of which are the temperature, the dimensions of the wood, and the relative humidity of the surrounding atmosphere. Simpson and Tschernitz (1979) developed a simple model of wood drying as a function of these three variables. Although the analysis was originally carried out for red oak specimens, the procedure may be applied to any species of wood by adjusting the constant parameters of the model.

3.3.2 Duration of loading

The grade stresses and the joint strengths associated with the application of Eurocode 5 (BSI, 2008) are applicable to long-term loading. A modification factor, by which timbers strength should be multiplied for various durations of loading, is given in the relevant standards. Loss of strength due to duration of load over time is a proven issue; timber under load undergoes a logarithmic loss of strength over time, as proven by research by Wood (1951) on the Madison curve. Duration of loading is discussed further in section 3.3.12 with regard to the affects of timber age on its strength.

3.3.3 Moisture content

Moisture content of the cells of the timber of living trees and freshly felled logs is often very high and liquid water can constitute over 50% of the timber weight; thus, water content has a significant influence on material properties. Timber continually exchanges moisture with its surroundings, although the rate of exchange is strongly affected by the degree to which it is sealed and the immediate surrounding atmosphere. Timber contains moisture in two forms:

1. Free water - The bulk of water in cell lumens, held by capillary forces.
2. Bound or hygroscopic water - Bound to the wood via hydrogen bonds.

3. Vapour - Water in cell lumens in the form of water vapour is normally negligible at normal temperature and humidity.

Since timber moisture content influences distortion, fissures and wood dimensions, the timber grade limits have to be related to a reference moisture content, which is set at 20% (TRADA, 1995). The moisture content of wood is usually calculated by the formula from research by Siau (1984):

$$\text{moisture content} = \frac{m_g - m_{od}}{m_{od}} \qquad (1)$$

Where

m_g is the green mass of the wood,

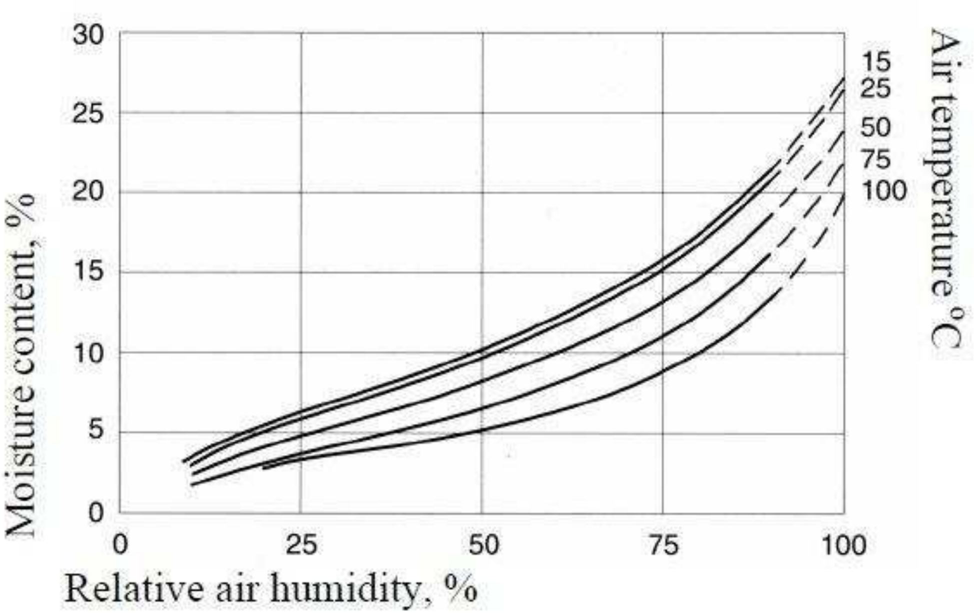
m_{od} is its oven-dry mass (the attainment of constant mass generally after drying in an oven set at 103 +/- 2 °C for 24 hours as mentioned by Walker et al. (1993).

The equation can also be expressed as a fraction of the mass of the water and the mass of the oven-dry wood rather than a percentage. For example, 0.59 kg/kg (oven dry basis) expresses the same moisture content as 59% (oven dry basis).

Accepted literature contains many analyses of moisture content significantly affecting the mechanical characteristics of timber. For example, Gerhards (1982), and Lenth and Sargent (2004), both illustrate that increasing temperature and humidity results in a decrease in the elastic constants of timber. The moisture content of timber is commonly determined in accordance with BS EN 336 (BSI, 2003) and given a ‘Dry’ or ‘Wet’ grading:

- Dry graded timber - has an average moisture content of 20 % or less, with no reading exceeding 24 % moisture content.
- Wet graded timber - because thick timber is difficult to dry, the provisions of the relevant standard do not apply to timber that has a target thickness of 100 mm or more, where a timber moisture content higher than 20 % would be prevalent (corresponding to service class 3).

Figure 3.3. Graph of the influence of moisture content for small clear specimens. After Larsen (2001)



Timber releases or absorbs moisture in response to changes in relative humidity in its immediate surroundings or working environment until the moisture content of the timber has stabilised at an equilibrium moisture content (EMC). Moisture changes below the fibre saturation point (just below 30%) influence the strength and stiffness and result in dimensional changes (shrinking/swelling). For timber in equilibrium with its surroundings the moisture content depends approximately on the relative humidity (RH) and temperature of the surrounding atmosphere.

Table 3.1. Influence of moisture content for small clear specimens. For structural timber the influence is only about 50 % of the values shown. After Larsen (2001)

	Strength loss(%) for a unit increase in the moisture percentage	**Strength increase (%) when drying from fibre saturation point to 12%**
Tension parallel to grain	3	50
Tension perpendicular to grain	2	35
Compression parallel and perpendicular to grain	5	65
Bending	4	60
Shear	3	50
Stiffness	1.5	25

The usual method of minimising the likelihood of any adverse effects in timber construction is to ensure that the timber joist, when first installed, is at a moisture content approximately mid-way between the extremes of the equilibrium moisture content it is likely to attain in service. Internal flooring, for example, would probably need to be installed with its moisture content at around 12%. Kiln dried virgin timber is usually processed at a moisture content of between 10% and 15%.

3.3.4 Density

In general, as timber density increases so its various mechanical properties also increase. Density remains the best general predictor of timber strength, since there exists a high correlation between strength and density in many timber studies. While this is not a universal truth, it is a common result.

Density of timber at a specific moisture content is the amount (mass) of wood substance in a given volume. Density is influenced by the concentration of wood cell wall relative to the amount of void space in and between the cells. The density of timber cell walls (fibres, tracheids, vessels or rays) are relatively constant in all timber species, so the main factors affecting density are the size of the cells, the amount of void spaces, and the proportions and distribution of the various cell types.

Table 3.2. Timbers in common use for housebuilding prior to 1955 (TRADA, 1954)

Common Name	**Botanical name**	**Density (kg/m^3)**	**Mean MOE (N/mm^2)**
Cedar, western red	Thuja plicata	390	8500
Cedar, yellow	Chamaecyparis nootkatensis	420	8800
Douglas fir	Pseudotsuga taxifolia	530	8800
Fir, balsam	Abies balsamea	415	
Hemlock, western	Tsuga heterophylla	480	8800
Larch, European	Larix occidentalis	550	9000
Pine, Corsican	Pinus nigra var maritima	510	
Pine, pitch	Pinus rigida	710	11000
Pine, ponderosa	Pinus ponderosa	430	
Pine, Scots (Redwood, European)	Pinus sylvestris	510	9000
Spruce, Canadian	Picea glauca	450	6800
Spruce, European (Whitewood, European)	Picea abies Abies alba	430-470	6800
Spruce, Sitka	Picea sitchensis	450	6800

Table 3.2 illustrates some common softwood types which were used in construction prior to 1955 and how their average strength (MOE) is affected by their density, at

standard temperature and pressure (STP). For reference and comparison, the average density of the most popular modern softwoods used for general construction is usually less than 400 kg/m^3 (Holzabsatzfonds, 2007).

In general terms, density is a reliable indicator of strength, as well as being a good indicator of several other properties. However, density is greatly influenced by the amount of moisture contained in the timber at the time of measurement.

3.3.5 Resin and bark pockets

Resin pockets and bark pockets are assessed as fissures or knots according to their shape. If a bark pocket is assessed as a knot it shall be taken into account when assessing the knot area ratio.

3.3.6 Distortion

The methods of assessing distortion are illustrated in BS EN 14081 (BSI, 2011). Bow, spring and twist are assessed over a 2 m length, anywhere on the timber surface. As distortion is influenced by moisture content precise limits to cover all conditions and applications cannot be given, only those acceptable at 20 % moisture content.

3.3.7 Slope of grain

Slope of grain is assessed as the inclination of the wood fibres (grain) to the longitudinal axis of the piece, usually expressed as the number of units of length over which the deviation occurs. It is measured over a distance sufficiently great to determine the general slope, disregarding local deviations. Where the slope of the grain is excessive, strength of the piece can be approximated using Hankinson's formula and by assuming that the MOE of wood perpendicular to grain is about 1/50 the value of MOE parallel to grain. The general form of Hankinson's formula is:

$$\frac{\Theta_0\,\Theta_{90}}{\Theta_0 \sin^n a + \Theta_{90} \cos^n a} \tag{2}$$

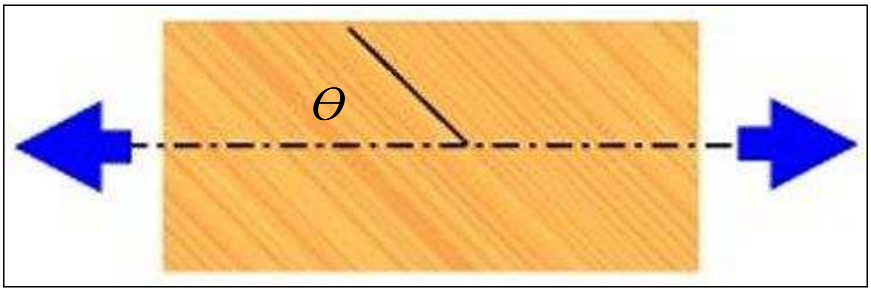
Where

Θ_0 = MOE parallel to grain

Θ_{90} = MOE perpendicular to grain

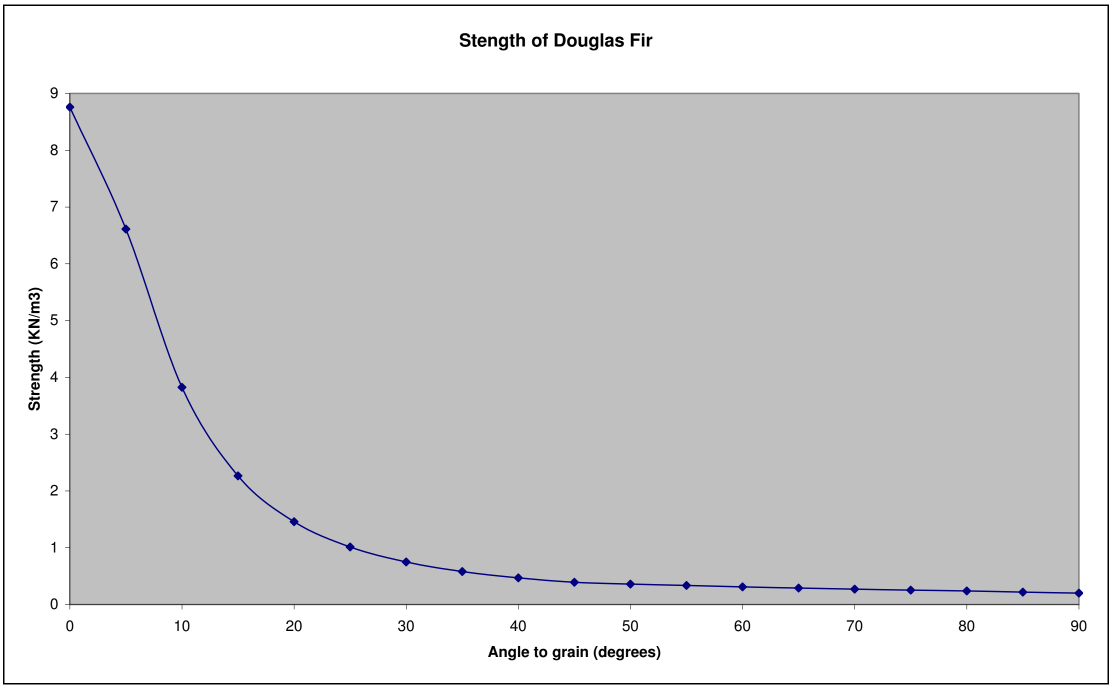
a = angle of slope of grain to the longitudinal axis and where the exponent n can take values between 1.5 and 2.

Figure 3.4. Illustration of the form of Hankinsons formula



Even though the original relation was based on studies of spruce, Hankinson's formula has been found to be remarkably accurate for many other types of wood (Clauston, 1995). However, for the purposes of testing reclaimed timber, the slope of grain was largely ignored. Visual grading and slope of grain testing is likely to have already been carried out when the timber joist was installed during construction. It is worth noting, though, that the slope of the grain can have a disastrous effect on the strength of a timber joist, and as an example, the strength of a Douglas fir joist is illustrated in the following graph (Figure 3.5).

Figure 3.5. Strength graph of Douglas fir. After Breyer, Fridley and Cobeen (1999)

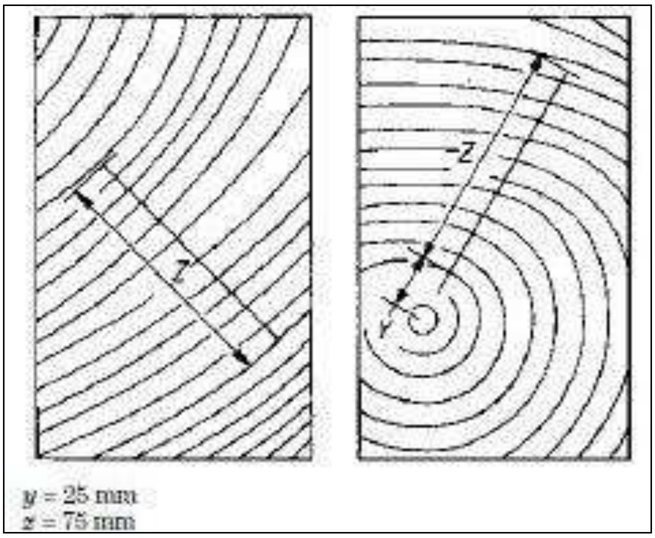


Where:
Joist parallel tensile strength = 8.76 kN/m^3
Joist perpendicular tensile strength = 0.2 kN/m^3

3.3.8 Rate of growth

To assess the rate of growth, measurement is made on one end of the piece and expressed as the average ring width, in millimetres.

Figure 3.6. Rate of growth measurements. After BS 4978 (BSI, 1996)



The measurement are taken along a straight line 75 mm long, normal to the growth rings, which; when the pith is absent, passes through the centre of the end of the piece, and when the pith is present, commences 25 mm from the pith. If a line 75 mm long is unobtainable, the measurement on the longest possible line normal to the growth rings and passing through the centre of the piece is taken. This measurement is expressed in Figure 3.6 above.

3.3.9 Knots

Knots in sawn timber vary greatly in shape. They may vary with sawing patterns and timber dimensions and are often difficult to determine and classify. Timber strength is mainly reduced by grain deviations around knots, rather than by the knots themselves. This becomes more evident when investigating a joist failure; these anomalies often start from extreme fibre deviations in the vicinity of knots. Wood structure may be even more affected when several knots are situated close together in a piece of timber.

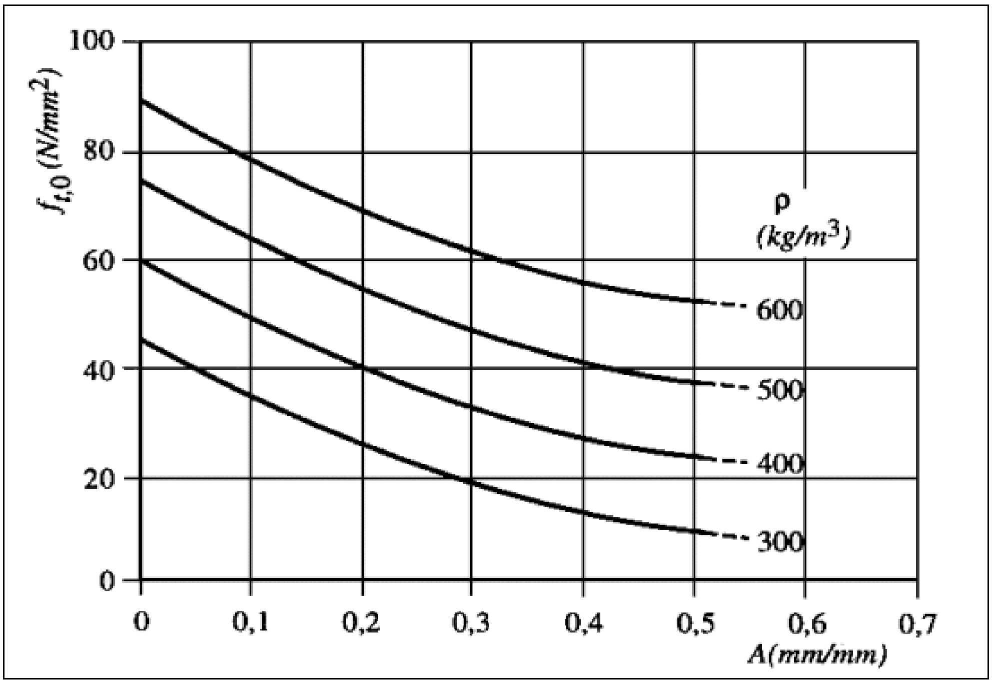
Knots are assessed by their total knot area ratio (TKAR) and their margin knot area ratio (MKAR). If any part of a knot or the grain disturbances for which they are responsible overlap along the length of the piece, the knots are considered as part of the same cross-section; however, in making this assessment, knots or knot holes of 5 mm diameter or less are ignored, as outlined below:

- **total knot area ratio** (TKAR) - Ratio of the sum of the total projected cross-sectional areas of all knots intersected by any cross-section to the total cross-sectional area of the piece.
- **margin knot area ratio** (MKAR) - Ratio of the sum of the projected cross-sectional areas of all knots or portions of knots in a margin intersected at any cross-section, to the cross-sectional area of margin.

Thus, knot ratio is usually calculated from the sum of knots within a defined section along the length of a piece of timber rather than simply from the biggest knot. Edge knots and knots in tensile zones have a greater effect on strength than centre knots or knots in compression zones. Therefore, the position of knots within cross-sections of timber is often also taken into account in grading rules.

As has been previously mentioned, the significance of knots will depend on their size and distribution within the cross section and profile of the joist.

Figure 3.7. Effect of knot ratio A and density on tensile strength f_t,0 of structural timber. After Glos (1983).



In accounting for the weakening effect of knots, the assumption can be made that the knot is effectively a hole through the piece, reducing the cross section. For a joist containing an edge knot, the bending strength ratio can be visualised as the ratio of the bending moment that can be resisted by a joist with a reduced cross section, to that of a joist with a full cross section (Mitsuhashi et al. 2008).

The ratio is illustrated on the following page and is represented by the formula:

$$SR = 1 - (k/h)^2 \quad (3)$$

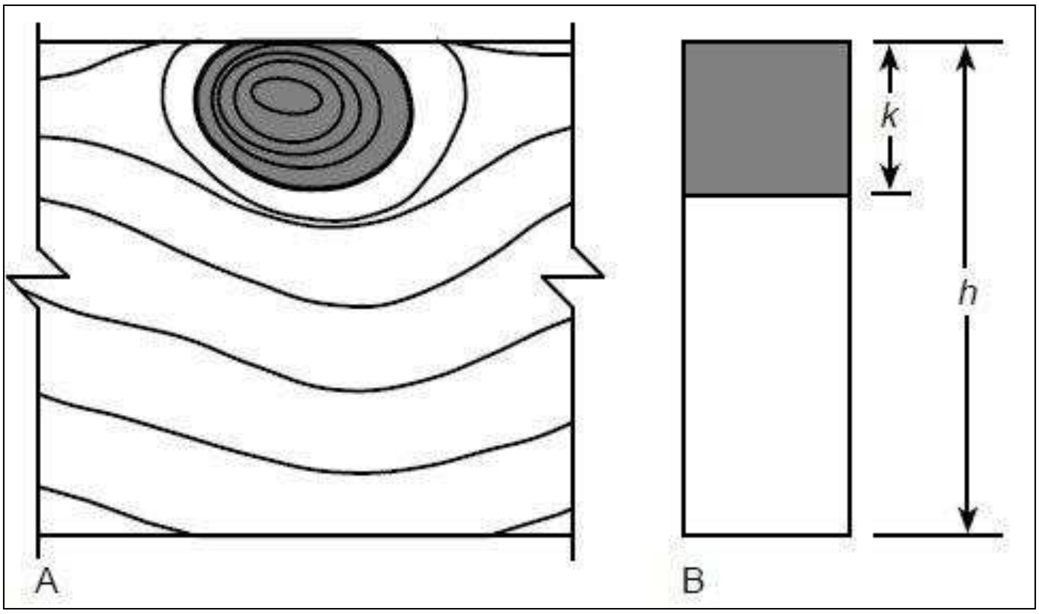
Where

SR = strength ratio,

k = knot size, and

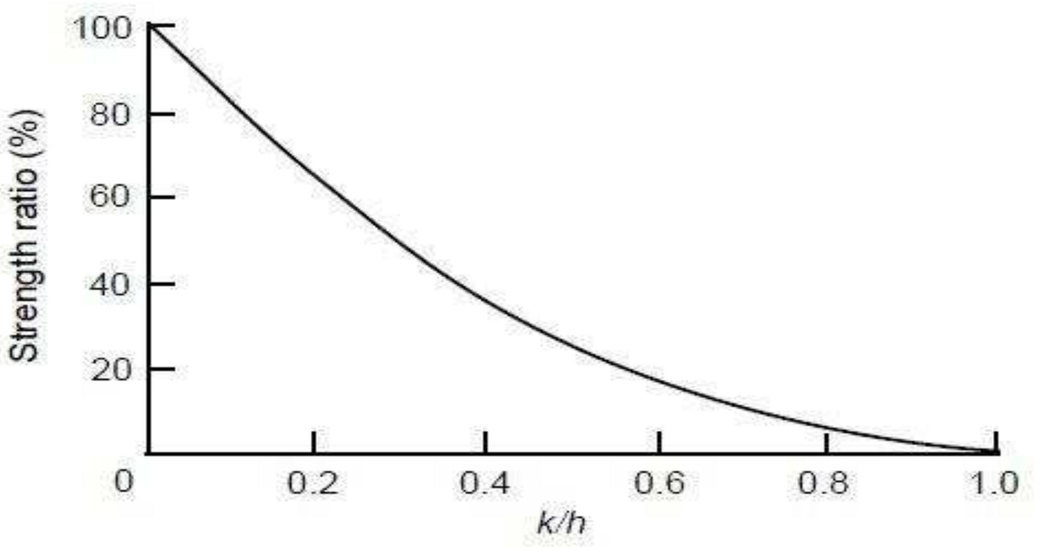
h = width of face containing the knot.

Figure 3.8. Effect of edge knot: (A) edge knot in timber joist and (B) assumed loss of cross section (shaded area). Mitsuhashi et al. (2008)



This is the basic expression for the effect of a knot at the edge of the vertical face of a joist that is deflected vertically. The following figure illustrates how strength ratio changes with knot size according to the formula above.

Figure 3.9. Relationship between bending strength ratio and size of edge knot expressed as fraction of face width. k is knot size; h, width of face containing the knot (AF & PA, 1997).



3.3.10 Timber species identification

One major difference in timber obtained directly from sawmills and from reclamation is the assurance of species uniformity. Sawmill timber will typically originate from a single species stream; as identified by the bark, needles, and geographic origin of the tree. Reclaimed timber, however, will be very likely sourced from a building that contained a mixture of species, and that could be a result of the original building material supply chain or remodelling and repair (or both). Unless a grade stamp exists, species uniformity cannot be guaranteed. Also, visual identification to confirm species presents a potential problem as the timber will often be dirty or discoloured.

In construction, many factors are involved in the choice of species, but from the purely structural view it is the strength grade which is of prime importance. To provide an alternative method of specification for the designer, coupled with greater flexibility of supply, BS 5268-2 (BSI, 2002) gives a series of strength classes which for design use can be considered as being independent of species. However, for some applications it may be necessary to specify particular species (or exclude them) from within a strength class to take account of particular characteristics, e.g. natural durability of the timber or amenability to preservatives, glues and fasteners.

Timber species recognition can be easily carried out by a trained technician, using no more that a microscope, the timber species is identified from recognition of the cell structure. While this does not give an absolute result, it does give a 95% chance of correct identification of the species. The aim in species identification is to establish a correlation between microscopic examination and; timber colour, grain, density and rate of growth, in order to produce an estimation of the timber species from these other characteristics. Thus, negating the need to use more expensive methods of identification.

Identification of species has been called attempting the impossible, as the only sure path to identifying the species is through identification of the leaves and fruit of the tree. Any other attempt at identification must state that ‘the features observed, accord well with species X, but can only be confirmed by comparison with authenticated specimens’. Therefore, in a general identification it would be reasonable to exhaust the easy macro clues first, before seeking more costly advice. Some of the macro-clues, when present, which will help in species identification are:

- A knowledge of the history of the piece/element can be helpful
- Size - Larger sections of softwood more likely to be Canadian, unless early Victorian
- Saw marks - Hand sawn pieces will be earlier than circular sawn or band sawn
- Colour - As seen, as freshly cut, as polished. Should be viewed under daylight conditions
- Ease of cutting - hardness and smoothness enable estimation of density
- Smell - Use a drill to generate some friction (pines have a distinct smell)
- Knot arrangement
- Shippers marks - can give the name of the manufacturer and hence country of origin, strength grade and even the species
- Rate of growth (absence of growth rings is an identifying feature)
- Density - Consulting density charts can be helpful in identification

Because of the difficulty involved in correct timber species identification, it was decided early in the research programme, that while the identification of various timber species from the reclaimed specimens was useful for the research analysis, especially for pinpointing anomalous results in the strength grading tests, it would ultimately not prove to be viable as part of a methodology or process that could be carried out with any ease.

Furthermore, the introduction of Eurocode 5 (BSI, 2008), offers the designer the choice of timber specification by grade strength or by species. This means that identification of timber species procured through reclamation, is no longer necessary. Eurocode 5 states; ‘A timber population may be assigned to a strength class if its characteristic values of bending strength and density equal or exceed the values for that strength class given (in the standard), and its characteristic mean modulus of elasticity in bending equals or exceeds 95% of the value for that strength class given’ (BSI, 2008 p. 8).

In this research there has risen a need for strength grading of 'unknown' species. The dataset developed will be used to develop a species independent model. Because the proposed method of visual assessment looks at characteristics other than timber species, it is proposed that this will represent a best practice in species independent softwood grading, similar to that proposed in the work of Ravenshorst and Van-de-Kuilen (2006). For these reasons, species identification is not pursued as part of the methodology in this present work.

3.3.11 Tree ring frequency calculation

In temperate regions of the world, each year the girth of a tree trunk increases by one growth ring as each sheath of secondary xylem is added. At the beginning of the growing season earlywood or spring growth, in the form of large thin walled cells are produced by the cambium. At some point during the growing seasons (late summer/autumn) the type of cells produced by the cambium changes and latewood growth occurs resulting in cells with thick walls. Cell production by the cambium stops abruptly with the onset of winter. This is followed by the onset of new growth the following spring and the formation, once again, of earlywood cells. This pattern occurs for all softwoods, other than tropical softwoods.

In softwoods, the variation in colour that occurs throughout a growth ring can be related to changes in thickness of the cell walls. The variations in cell wall thickness between earlywood and latewood cells account for differing properties between these regions.

Without magnification, growth rings appear as alternating bands of light and dark material. Using a microscope the difference between the size of the earlywood cells and the latewood cells is fairly obvious. Since density is influenced by the rate of growth of timber it follows that variations in ring width and frequency will change the density of the timber and hence the strength.

The frequency of growth rings per inch also affects timber strength; this is especially prevalent when considered in conjunction with timber density; large annual growth rings mean a low density and thus a lower strength (Larsen, 2001). This fact is not commonly presented in the literature; however, it can significantly interfere with the values of the modulus of elasticity and rupture. In their study of the parameters that influence redwood crush, Cramer et al. (1996) noted that the number of growth rings per inch may predict the crush behaviour more efficiently than the density alone. This validated earlier findings regarding the changes in elastic modulus and strength within an annual ring as, for example Bodig and Jayne (1982) showed, suggesting a variation in the tensile strength of wood within the location of the growth rings.

Other recent research by Mascia et al. (2009) illustrates that the frequency of the occurrence of growth rings can also considerably affect the strength of timbers.

3.3.12 Age of the reclaimed timber

This is not easy to ascertain and can only be determined with any accuracy by knowing the location of the site from where the specimen was removed. From this information, local searches may reveal the age of the site, or buildings upon it, and thus, by extrapolation, the probable age of the timbers used in the building. Alternatively, if there are any date markings on the building, such as dedications or cornerstones, these may give an exact date of the first use of building materials on the site. However, it should be borne in mind that before that advent of kiln drying, timber joists would have been air seasoned for several years prior to their first use, and so any date can only yield a near approximation of the actual timber age.

Dendrochronology and Radio Carbon (RC) dating are probably more obvious methods for dating timber joists from reclamation; however, both of these methods are extremely expensive, and even for a research project, add prohibitive costs to the overall budget. Furthermore, as the methodology is constructed as a simple to use process, in practice Dendrochronology and RC dating will make the 'on site' nature and benefit of the tests too complex.

There is some debate about how time affects the characteristics of timber joists; it is assumed that they become more stiff, dry, and generally less strong, as they age. The loss of strength is a proven issue; timber undergoes a logarithmic loss of strength over time, as proven by research by Wood (1951) on the Madison curve. Subsequent studies, such as Pearson (1972) found good agreement despite differences of species, dimensions and moisture content. The best exponential relationship to fit the results below SL = 100% was shown to be

$$SL = 90.4 - 6.5 \log_{10} t_f \qquad (4)$$

Where

t_f = time to failure in hours.

SL = actual stress level over predicted short-term strength

Based on this methodology, Madsen (1973) reported results from step-wise ramp loading of western hemlock timbers. These results suggested that the duration of load effect varied with material quality. Low perceived quality (low strength) material seemed to exhibit less duration of load effect than material perceived to be high quality, of the same species and type of specimen. For low quality material, the effect was significantly smaller than predicted from the Madison Curve for both dry and wet timbers. For the interpretation of experimental results and development of a mathematical duration of load model, conclusions from constant load tests have been linked to results from ramp load tests and have been extrapolated to the lower loads typical of design situations. This has spawned two approaches to the development of time-to-failure modelling:

- Accumulation of damage
- Fracture mechanics of viscoelastic materials

However, this research has not aimed to include this level of accuracy in any form of ‘remaining strength’ model calculation. The age of the timbers under test can only be approximated and the load and duration of load cannot be estimated with any accuracy, except to say that the materials have been under load; even if this is only the dead load of the building itself. In this case the model calculation discussed in the research analysis will only consider the duration of load calculation in the work of Pearson (1972).

During this research finding the source site for timber has been difficult; because of health and safety measures only certain personnel are allowed to enter an active demolition site and contractors are unwilling to allow anyone other than their own personnel onto site.

There is the argument that, for this research, the age of the timber is unimportant, as the timber strength is observed through testing. However, age is likely to become a factor in any model calculation aiming to illustrate the mechanical characteristics of the timber specimens.

3.3.13 Temperature considerations

As timber is cooled below normal temperatures, its properties generally increase; when heated the reverse usually occurs. The magnitude of these changes depends largely upon the moisture content of the timber. Up to 65°C, the effect of temperature is assumed to be reversible.

Table 3.3. Property adjustment factors for in-service temperature exposures (After AF&PA 1997)

	Factor		
In-service moisture content	$T \le 37°C$	$37°C < T < 52°C$	$52°C < T < 65°C$
Wet or dry	1.0	0.9	0.9
Dry	1.0	0.8	0.7
Wet	1.0	0.7	0.5

For reclaimed timbers, there is little information on the ‘in service’ temperature that it has been subjected to. However, it would be wise to keep this fact in mind and consider it when visiting demolition sites. For new structural members that will be exposed to temperatures up to 65°C, design values are multiplied by the factors given below; these should be considered in calculating the possible reclamation viability of structural timbers.

3.3.14 Ultrasonic, sound wave and X-ray grading

There exist other faster and more accurate methods of measuring the mechanical properties of timber; namely those using ultrasonic, sound wave and X-ray measurement. The inherent problems here are the complexity of some of the equipment and the need for specialist operators. This, coupled with the need for many of these methods to be laboratory based, tends to make them unsuitable for ‘on site’ testing operations, carried out on a regular basis.

Sound wave, or natural frequency, measurement of timber measures the natural frequency of the wood caused by the longitudinal vibration and calculates the velocity of the sound throughout the joist. The measurement itself is carried out by placing a vibration sensor on the joist end and hitting the log with a hammer to excite the vibration. Based on the measured natural frequency and an additional length measurement and assuming a default density value, the dynamic modulus of elasticity of the joist can be calculated.

X-ray scanning of the timber is performed by irradiating the joist from several sides while they move past the machine. The intensity of the transmitted radiation is measured on the opposite side of the irradiators. By the method, a three dimensional picture of the timber joist and its interior can be obtained and different parameters concerning the log calculated. These parameters include various density parameters, knot ratios and ring width and frequency parameters.

The ultrasound transit time of timber joists is measured by monitoring the time in which the sound travels through the timber longitudinally. The measurement is performed by attaching a starter and receiver transducer on the ends of the joist. Based on the transit time measurement and length measurement a dynamic modulus of elasticity (assuming a default density value) can be calculated; however, it should be noticed that the dynamic MOE measures this way is based on a different physical phenomenon than the one obtained by the natural frequency measurement.

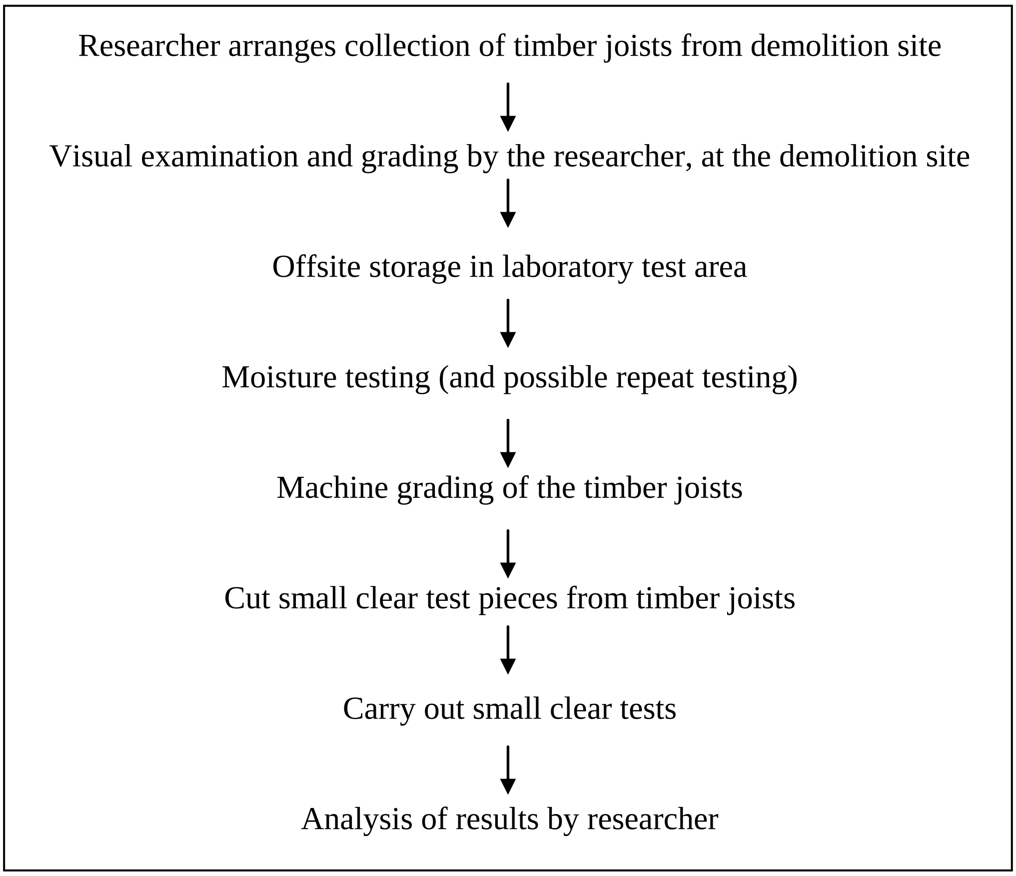
3.4 Methods suggested by this study for testing reclaimed timbers

This research suggests that there are two methods of approaching the re-grading of timbers recovered from demolition; laboratory testing and contractor ‘on site’ re-grading. Both of these will have a different set of operations attached to them; taking the reclaimed timbers from the building being demolished, through re-grading and testing, and on to reuse in another structure.

3.4.1 Laboratory testing

The methodology for laboratory testing and grading conceived for this research was separated into several phases; each phase dealing with a different material characteristic of the reclaimed timber joists. Visual grading and density measurement were carried out at the recovery site (demolition site); timber joist machine grading and small clear tests were carried out in the controlled surroundings of the laboratory test area.

<u>Figure 3.10. Process flowchart for a researcher testing timbers from demolition</u>



The intention in carrying out testing in different phases was to find a correlation in properties between visual grading, large timber joist tests and small clear tests. From these results a test methodology was formulated to visually grade reclaimed timber joists for structural use.

The important issue of recovery from site should be discussed here also. Negotiating with demolition contractors for reclaimed timber is not easy; however, this should be done, where possible. Visiting the demolition site allows the researcher to see the timber and visually inspect it as soon as possible after recovery from the building. It also allows a glimpse into the nature of the possible past loading the timber may have undergone. Furthermore, it allows the researcher to further investigate the building that the timber came from; possibly finding a date for construction, whether the building underwent any refurbishment or extension, giving an adjusted date for first use of the reclaimed timber elements.

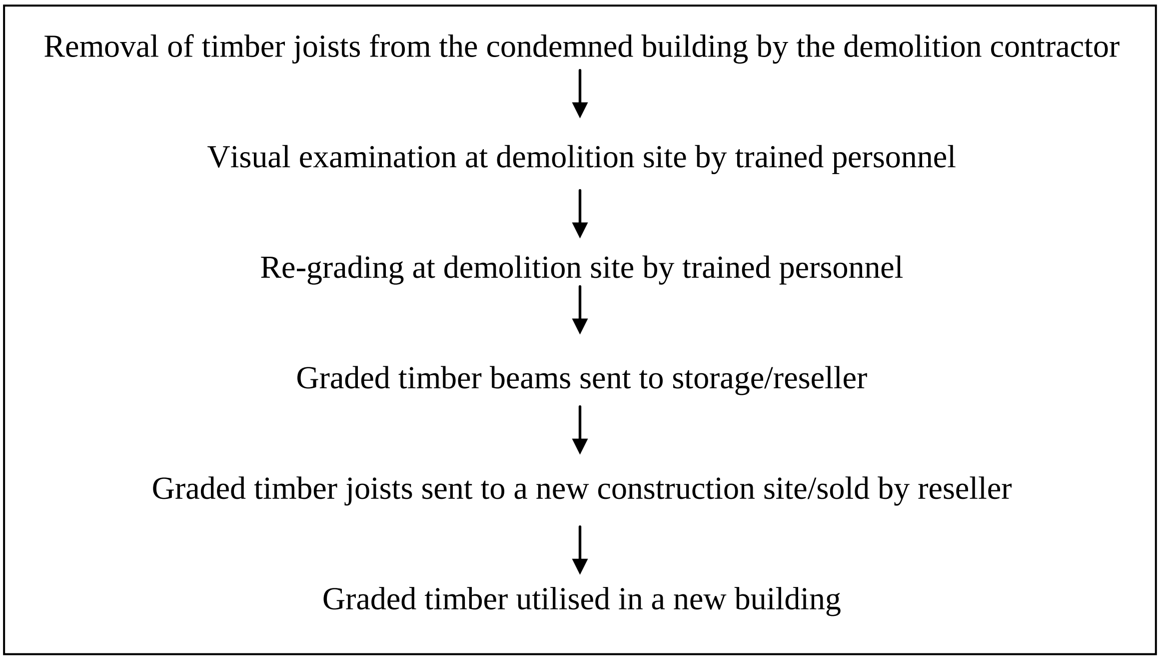
The best recovery conditions are that the timber joists should be dry, not affected by insect damage, and with no removal damage. Where this is not possible, the timber should be in good condition and the researcher should have a dry storage ready; to minimise any time in equilibrating the timbers to test conditions. Timber joists should be transported to a dry storage area as soon as possible and given at least 2 weeks to reach the ambient humidity conditions of the storage area. At this time the moisture level should be tested. If it is not at the level of the storage area, the timber should be returned to storage and tested again in a further week. This should carry on until the timber moisture level has reached the storage area conditions.

3.4.2 Contactor regrading

The methodology for regrading of timbers reclaimed from construction by trained personnel, or by the demolition contractor is, again, separated into several phases; each phase dealing with a different process in the journey of the timber, from removal from a condemned building to utilisation in a new structure, either on the same or a different site.

Visual grading and density measurement would be carried out at the recovery site (demolition site), as would the grading operation. The intention in carrying out grading by this method is to process the reclaimed timbers in as short a time span as possible, thus limiting exposure of the timber to the outside atmosphere.

Figure 3.11. Process flowchart for a contractor regrading of timbers from demolition



The issue of recovery from site should not be a difficult one of the demolition contractor. At this time the moisture level should be tested and density calculations adjusted, as per BS EN 384 (BSI, 1995).

The contractor may already have some date knowledge about the building, afforded by the demolition contract or other documentation associated with their role. They can also arrange the optimum recovery conditions; that the timber joists are dry and without damage due to removal, insects or rot. It is likely that a dedicated dry storage, where reclaimed timbers can be transported to will also be available to the contractor.

3.5 Issues surrounding timber grading suggested by this research

There are several issues related to the grading of reclaimed timbers from demolition, where this process differs from visual grading of virgin timber. These differences are important and must be considered before any methodology for the process can be constructed.

3.5.1 Visual grading of reclaimed timber

The assessment data discussed in the standard (BSI, 2011) deals with visual testing of all types of virgin timber. However, older, reclaimed timbers have other characteristics that need to be considered. Certainly, some of the timber recovered from demolition will have been visually graded as part of a batch, before its use in the original building took place. And, because at least some of the reclaimed timbers will have already been batch graded visually prior to their original use, it is likely that many of the commonly sought faults looked for in a visual timber examination will have already been weeded out. These faults would typically be due to; the presence of a hazardous amount of knots in the joist, slope of the grain in the timber rendering it too weak for construction use, the rate of growth of the timber being too high, and timber wane being present.

What an alternative grading system will be specifically looking for will be faults that have occurred in the timber since its first use as a building material. A test schedule for visually grading of reclaimed timbers is available as section 3.6.1 of this research project; being a modified version of BS 4978:1996. However, this does not automatically mean that a reclaimed timber joist will pass regrading, though it does indicate that it is likely to be perceived to be of good quality. The only facets of the timber that will be seriously in doubt, and main purpose of visual grading, are any areas of damage that have occurred during the service life of the timber.

3.5.2 Moisture content

Of all of the characteristics, at the time of testing, moisture content of the timber joist is one of the most important. Timber releases or absorbs moisture in response to changes in relative humidity in its immediate surroundings until the moisture content of the timber has stabilised at equilibrium moisture content (EMC). These moisture changes can seriously influence the strength and stiffness of the timber. This feature of timber, both old and new, is illustrated in Table 3.4.

Table 3.4. Influence of moisture content for timber joists. After Larsen (2001)

	Strength loss(%) per unit increase in moisture percentage
Tension parallel to grain	1.5
Tension perpendicular to grain	1
Compression parallel and perpendicular to grain	2.5
Bending	2
Shear	1.5
Stiffness	0.75

Moisture penetration, subsequent drying times and effects on strength, while investigated as part of the scenario of timber storage, are not included in the results or analysis of this research.

3.5.3 Previous loading

Unless an exact history of the building where the timber was originally housed is known, little can be discovered about lifetime loads, so testing cannot consider this; however, unlike most structural materials, timber is very resistant to cyclic loading. Research by the National Association of Forest Industries (NAFI) found that static tests showed that wood subjected to 30 million cycles of stress in tension parallel to the grain still retained 40% of its static strength (NAFI, 2004).

3.5.4 Insect and fungus damage

Abnormal defects, such as insect damage and fungal decay, which may have caused a decrease in strength properties to an amount which threatened the serviceability of the piece, would indicate that these timber joists were discarded from the grading process as failures. Decay, such as rot or insect attacks, causes a reduction of the cross-section, hence a reduction in the timber strength. However, in some timbers it may be difficult to ascertain whether there is damage; internal decay is often masked by the lack of evidence on the exposed surface. There are two main indicators of fungal attack:

- **Stain:** Fungi cause staining in timber, when it feeds only on food materials stored in the sapwood. Stain defect does not usually affect the strength properties of timber
- **Decay:** This is observed due to fungi breaking down the cell structure and attacking both sapwood and heartwood; reducing the strength properties of the timber.

Insect borers constitute one of the most destructive biological sources of defects in timber. However, damage from these agencies is visible in the form of tunnels and wood dust packed galleries in the timber.

As part of the visual grading, and as reclaimed timber used in the research were in mainly dry conditions during service, insect and fungus damage was at a minimum. However, decay is frequently restricted to localised points, such as those in contact with walls, where moisture collects. Where damage of this nature was found, these timbers were discarded from the grading and testing processes.

3.5.5 Tree ring frequency

Research by Mascia and Cramer (2009) illustrates that the frequency of growth rings also considerably affects the strength of timber.

This phase of the research aimed to evaluate the influence of the number of annual growth rings on the strength of the reclaimed timber specimens. In softwood, the growth rings are often difficult to see, so to adequately view the delineation of growth rings a section was cut from the main timber joist and the frequency of growth rings recorded by scanning the section on a desk scanner and counting the rings displayed within a nominated 75 mm line, normal to the growth rings.

Some complementary work in this field, involves the production of a smartphone application to count the ring frequency from a photograph taken of the end of the timber joist. This application, in its present incarnation will only attempt to calculate the number of rings on the test piece and has not yet been developed enough to make measurements in line with the recommendations of BS EN 14081 (BSI, 2011);

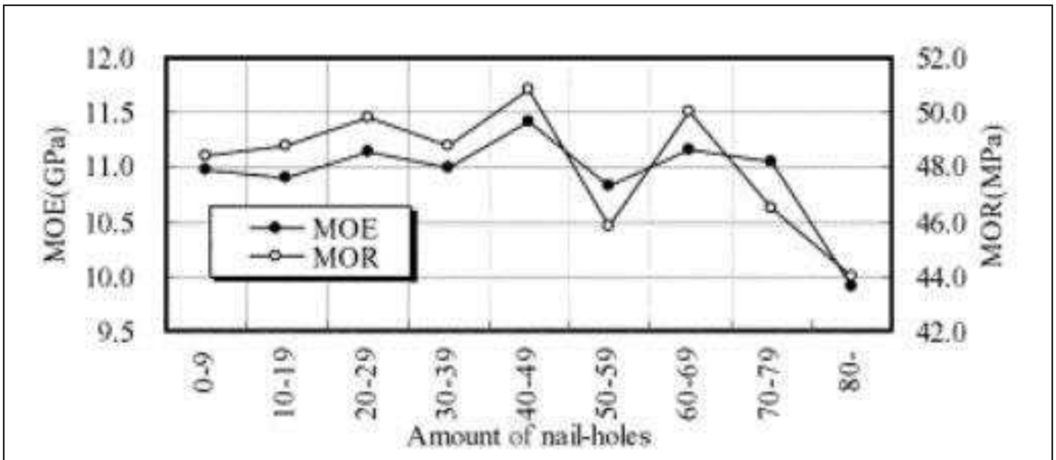
however, this facet is being further researched. The smartphone application is discussed further in the research analysis.

3.5.6 Machine and 'in service' damage

The most distinguishing feature of reclaimed timber is the presence of previous 'in service' damage. This may be a result of; the original construction processes (nail holes, bolt holes, notches, etc.), building use (in service drying defects, decay and rot), and through the deconstruction process. For purposes of this research, damage was defined as; holes as a result of nails or bolts, splits other than those caused by drying, saw cuts and, notches and decay. While it is desirable to minimise damage so that yields can be maximised, in an existing building, it is only possible to minimise damage through the deconstruction process.

The most frequent form of damage in reclaimed timber joists is nail holes and damage to the edge of the members, affecting about a third of the timbers. Following on the work of Nakajima and Murakami (2008), this research proposed a rule to grade timbers based on the effect of the number of nail holes in their various surfaces. Nakajima and Murakami observed that a decrease of MOE and MOR values occurred when the total amount of nail holes on the two narrow surfaces of the reclaimed timbers was more than 70 (over a 2 m length). A reduction in these values was also observed when the total amount of nail holes on the two broad surfaces of the lumbers was more than 50.

Figure 3.12. Effect on strength due to damage by nail holes in the joist (narrow) edge of reclaimed timbers (results in GPa = KN/mm^2 and MPa N/ mm^2). After Nakajima and Murakami (2008)



Accordingly, this research adopted a process of counting the number of nail holes on a 1 m length of the upper surface (most densely nailed surface) of the reclaimed timber joist and doubling this number. If the total is more than 40, the piece was discarded. While this process tends to give a larger total than counting every nail hole, it does save time and allows a safety margin in the estimation. As Figure 3.12 illustrates, the loss in strength through nail holes is only 10%, even at the greatest allowable quantity of nail holes.

In this research machined and drilled holes and screw holes have been treated as knots that pass through the cross section of the piece. These are covered further in Section 3.5.7, which deals specifically with timber knots; however Falk et al (2003) illustrated that a justified allowable hole, one half the allowable knot size, can be accounted for in calculations. For this research, in cases where there were holes that were larger than half the allowable knot size, those timbers were excluded from further testing.

Damage, as a result of the deconstruction process, could be lessened by careful removal of elements connected to timber joists; as could more careful removal of end nails from joists and rafters.

3.5.7 Knots in the timber

For the purposes of this research, knot area ratios were not considered other than to discard those items where the ratio was high. All instances where single knots were over 30 mm in diameter and on the surface of the timber joist, and were they were within the h/4 edge margin were discarded from further testing.

This method of filtering out unsuitable timbers may seem unduly harsh, but the visual examination is intended to be carried out on site, where calculation of the knot area ratio may not be easily managed. This is also coupled with the characteristic that seasoned timbers from older trees have very few large knots in their length and the knowledge that any timbers reclaimed are likely to have been batch tested before being originally used for construction operations.

3.5.8 Timber density

The only stipulation for density calculation relating to the reclaimed timber specimens in the laboratory is that the temperature and humidity is known. Measuring the timber density will give an indication of the condition of the timber and, when compared to the absolute density, calculated from the small clear test specimens, an estimation of the water content. Reference conditions of 20°C and 65% relative humidity should be maintained, wherever possible, in the test and timber storage areas.

3.5.9 Machine grading tests

The machine testing involved a strength and stiffness test on a rig which simulates the machine testing environment. The large specimen test rig used in this research project simulates the conditions encountered in a grading machine, except that it is not automated (see – Figure 3.16, Section 3.6.5). Each specimen is passed through and tested, to a set deflection, on the plank edge, at increments of 150 mm, and to within 800 mm of each end of the joist; the joist is turned over and then reversed and readings taken from the opposite edge. These two operations are usually done simultaneously in industry, on equipment such as the compumatic bending machine.

For this research a further static bend test was carried out on the weakest area of any visually assessed joist. This static bend test then gave a minimum strength rating for the particular timber.

3.5.10 Small clear tests

Small specimen testing is detailed in BS 373 (BSI, 1957). Small clear test specimens were cut from the larger timber joist specimens, and further machined to size before being tested to destruction on the small, purpose built test rig (see – Figure 3.19, Section 3.6.6). This test has yielded the expected absolute strength for the specimen (modulus of rupture); and hence a related absolute strength for the larger joists.

The test rig for this operation is a piece of apparatus specially designed by the researcher from the illustrations and description of the rig in BS 373 (BSI, 1957). The static bending test carried out by the central loading method on the 2 cm standard rig, has a distance between the points of support of the test piece of 280 mm. The load is applied at the central point between the supports with the loading head moving at a constant speed of 6.6 mm/min. The contour of the loading head which is in contact with the joist shall have a radiused form (of 30 mm radius). The test pieces are supported at the ends so that they are free to follow the bending action and not be restrained by friction. The deflection of the joist at mid length is measured with reference to the outer points of loading.

Fabrication of the rig structure was a relatively simple engineering exercise. The framework was built up and bolted and dowelled together, the specimen supports were running bearings, and so frictionless, and the loading head tup was milled to shape and produced from an aluminium block. A cavity for a load cell was machined into the tup and a screwed loading head machined to fit this and drive the load.

Because of the travel of the loading head and the fact that it could not be motorised, due to budget and time constraints, it was decided to produce a made for purpose screw thread for the loading head and tup body. Both the internal (body) thread and the external (loading head) thread were specially turned to a pitch of 1.1 mm. This meant that six turns of the thread per minute would equal the 6.6 mm travel required by the loading head.

Vee form threads can be extremely accurate when produced to a tight tolerance and the thread used had a 3A/3B tolerance. Classes 3A and 3B are suited for close tolerance fasteners where safety is a critical design consideration. This class of fit has restrictive tolerances and no allowance. In this instance safety was not a consideration, but accuracy was and the threads are a very close fit reflecting this.

The rig is operated by hand, the operator turning the loading head and lowering the tup at a constant rate, to approximate the mechanical lowering of the tup in the standard mechanism. The rate is easily controlled by the operator with the aid of a stopwatch and did not take long to master. The turns of the screw thread give a constant velocity for the loading head, the stopwatch a time control and the load cell a reading of the applied load.

3.6 Testing

This section explains each of the phases of testing (for laboratory testing), and visual grading, for use with both the laboratory and contractor processes. It also details the method of density calculation for contractor timber grading. Timber grading, at the demolition site, by the contractor or trained personnel is associated with the model calculation produced as the end result of this research. It will be discussed in principle here, but in detail during the research analysis.

The research consisted of static bending tests on reclaimed timber joists, and also on a small number of virgin timber joists (as a control source). The bending tests are as detailed in BS EN 408 (BSI, 1995a) and small clear tests on a purpose built rig, as detailed in BS 373 (BSI, 1957). For the large tests 200 specimens of reclaimed timber joists were used from demolition sites which were within 20 miles of Newcastle upon Tyne city centre. The virgin timbers, to be utilised as a control, were sourced from a local building materials outlet. The timber specimens from both sources consisted of joists of random sizes; from 75 mm to 200 mm width, 60 mm to 125 mm breadth, and in lengths from 1400 mm up to 3600 mm.

The small clear test specimens were cut from these larger joists. These small clear tests were all cut and machined to 20mm x 20mm x 300mm, as prescribed in BS 373 (BSI, 1957). The growth ring orientations were all placed parallel to the applied vertical load.

A small batch of the reclaimed timber specimens were first tested by an outside timber grading laboratory, at the Forest Products Research Centre, of the Buckinghamshire Chilterns University College. These tests were carried out to ascertain that the results from the joist tests of this research were in accord with the results of a professional testing laboratory. This also served to establish a set of comparison values for strengths of timber specimens.

The starting point of the grading process was to produce an alternative method of visual grading, which would eliminate inferior reclaimed timbers from those which would undergo further machine testing. The process for the grading tests and examination are detailed in the following sections.

3.6.1 Visual grading at the demolition site

This visual grading is intended to be carried out ‘on site’, ie at the demolition site or site of timber recovery, and is intended to be carried out as soon as possible after the timber joists have been removed from the building.

The density of timber joist specimens can be calculated using two methods. The laboratory method has been already discussed in Section 3.4.1. The alternative ‘on site’ method is detailed in section 7 of BS EN 384 (BSI, 1995) and states: ‘Where the moisture content is higher than 12%, the density shall be decreased by 0.5 % for every percentage point difference in moisture content and, where the moisture content is lower than 12 %, the density shall be increased by 0.5 % for every percentage point difference in moisture content’.

The timber density is then calculated from:

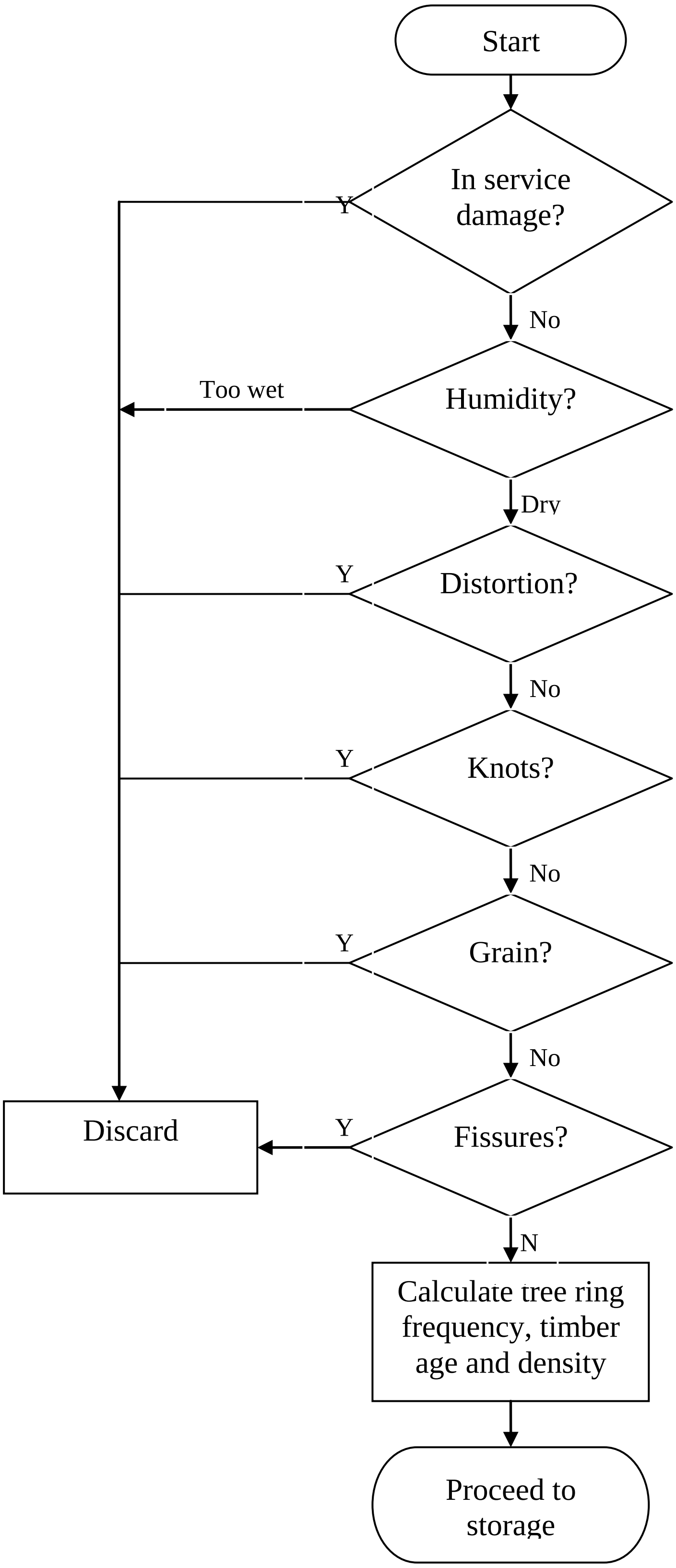
$$\rho = m/v \qquad (5)$$

Where
m = mass of the timber joist
v = volume of the timber joist

The frequency of timber growth rings was recorded by scanning the end of specimen timbers directly on a desk scanner (by cutting a piece from the end of the timber joist and scanning this), or by photographing the specimen end and scanning the resultant photograph, and ranged from 2 to 30 growth rings per inch (2.54 cm). One method, discovered during the research, of making the growth rings more visible, was to dampen the end of the timber. This enhanced the dark and light areas of tree ring delineation, making them far more visible to optical recognition.

The flow chart, on the following page, details the visual grading element of the testing. An explanation and summary of the terms used, including how they differ from the criteria given in the relevant standard, is detailed in Section 3.6.3.

Figure 3.13. Flow chart for ‘on site’ visual grading tests for reclaimed timbers



3.6.2 Visual grading for the laboratory process

The visual grading is intended to be carried out partially at the demolition site, and partially at the test laboratory. This method is used as the first phase of the complete grading test; those timber joists that pass this visual grade then go forward to further moisture/humidity testing in the laboratory, and finally, to timber grading machine testing and small clear testing.

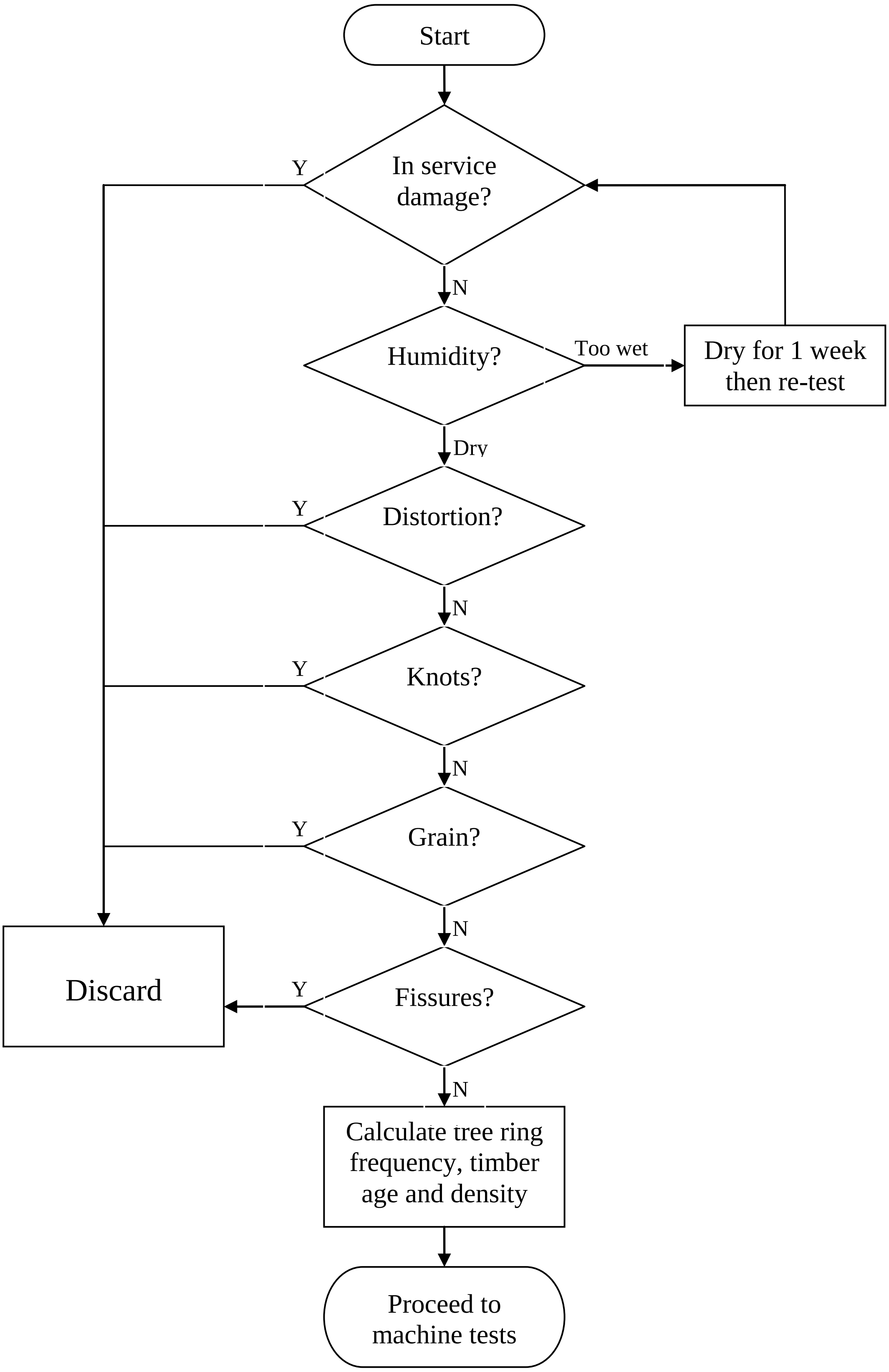
The results from these tests will, ultimately, lead to the formulation of a model calculation, which can be transposed for use in the previous ‘on site’ tests. Thus calculating the strength of reclaimed timbers directly, from data obtained at the site of recovery.

Humidity is far more of an issue, with regard to accuracy, when testing in conjunction with the generation of a model calculation. In this situation attaining a standardised level of moisture within the timber joist form is of the upmost concern for the accurate calculation of the timber joist strength and density. As well as density the strength of the timber joist can vary greatly dependent on the moisture level within its form (Gerhards, 1982).

The density of timber joist by the laboratory method has been already discussed in Section 3.4.1. The alternative ‘on site’ method, as detailed in section 7 of BS EN 384 (BSI, 1995) is not suitable for this research. The reason for this is that not all species of timber behave uniformly under changing moisture conditions. To maintain any form of accuracy the density calculation in the laboratory must be at standard temperature and pressure, thus, standard humidity conditions, and the timber must be left to normalise to these conditions. The timber density is then calculated, as before, from Equation 5 – Section 3.6.1.

The recorded densities of timber joist specimens used for this research varied between 0.29 kg/m^3 and 0.71 kg/m^3. All specimens were tested as per the documented methods contained in BS EN 408 (BSI, 1995).

Figure 3.14. Flow chart for laboratory visual grading tests for reclaimed timbers



3.6.3 Flowchart explanations for visual grading of reclaimed timbers

The following observations are intended to have a short answer, making the grading process straightforward, simple and as error free as possible.

Start

The visual grading element assumes that the reclaimed joist is 2 m or longer and has been previously used, under load, within a building (ie. it has been under at least ‘dead load’ and kept free of excess moisture and outdoor climatic conditions for its service life).

In service damage

Has the joist suffered any obvious damage? This may be in the form of notches, holes, splitting and rot – especially at the end faces.

Count the number of nail holes on a 1 m length of the upper surface (most densely nailed surface). If the total is more than 40, the piece should be discarded.

Allow holes and notches up to 15 mm wide, or in diameter, but not on the joist edge (narrow) surface. Allow notches up to 25 mm, if they are within 200 mm of the joist end – these can be machined out to give a shorter joist, if necessary.

Humidity/moisture

Where the joist has been recently removed from it’s ‘in service’ position, this should answer ‘Dry’; the joist will be dry to the touch. Timber which feels wet/damp to the touch could be damaged by rot. In this case the joist should be rejected.

Distortion

Bow - Not more than 20 mm over a length of 2 m
Spring - Not more than 12 mm over a length of 2 m
Twist - Not more than 2 mm per 25 mm width over a length of 2 m
If all of these conditions are met, the joist is a ‘Yes’; if not then it is a ‘No’ and must be rejected.

Knots

No knots of over 30 mm wide on the surface of the timber and within the h/4 edge margin. Any knots that breach this rule are failed and the specimen is rejected.

Grain, fissures and wane

Slope of clear grain should not be greater than 1 in 6. The number of fissures can be unlimited; however, they must not be longer than 600 mm on any running metre. Any timbers that breach this rule are failed and the specimen rejected. No wane (absence of edge material) of the reclaimed joist is allowed by the visual grade.

Calculate tree ring frequency, age and timber density

This criterion is explained for this method of visual grading in Section 3.6.1. Timber age can be ascertained by various methods already discussed in Section 3.3.12.

Density measurement on site is best carried out with a spring balance and tape measure. The only stipulation for density calculation at the demolition site is that the humidity of the timber joist specimen is known. Measuring the timber density may also give an indication of the condition of the timber.

For the ‘on site’ grading methodology, utilising the model expression, discussed in Section 5.2.8 of the results analysis, a grade can now be assigned to the timber joist, and the joist marked accordingly.

Proceed to storage / machine testing

This is the end of the flowchart and signals either; the movement of the visually graded timber to storage or to a reseller, or the progress of the timber joist specimen to further machine testing.

3.6.4 Summary of the permissible limits of visual grading in this research

The following table is a summary of the criteria for visual grading inspections. The relevant criteria and how the values are generated and calculated are discussed in Sections 3.5.1 to Section 3.5.7.

Table 3.15. Summary of permissible limits for the visual strength grades for reclaimed timber joists, as indicated by this research

Characteristic	**Test**
In service damage	No more than 40 nail holes per 1 m length of the upper surface (most densely nailed surface). Allow holes and notches up to 15 mm wide, or in diameter, and notches up to 25 mm, if they are within 200 mm of the joist end. Insect damage – Not permitted Chemical damage – not allowed
Distortion – bow, spring, twist, cup	Bow - Not more than 20 mm over a length of 2 m Spring - Not more than 12 mm over a length of 2 m Twist - Not more than 2 mm per 25 mm width over a length of 2 m Cup - Unlimited
Knots	No knots of over 30 mm wide on the surface of the timber and within the h/4 edge margin
Slope of grain, Fissures and Wane	Slope - Not greater than 1 in 6 Fissures - Unlimited. Not longer than 600 mm on any running metre Wane - Not allowed.
Tree ring frequency	Calculated as an average number of rings.
Age of the timbers	Only really be determined by knowing the location of the site where the piece was removed from.

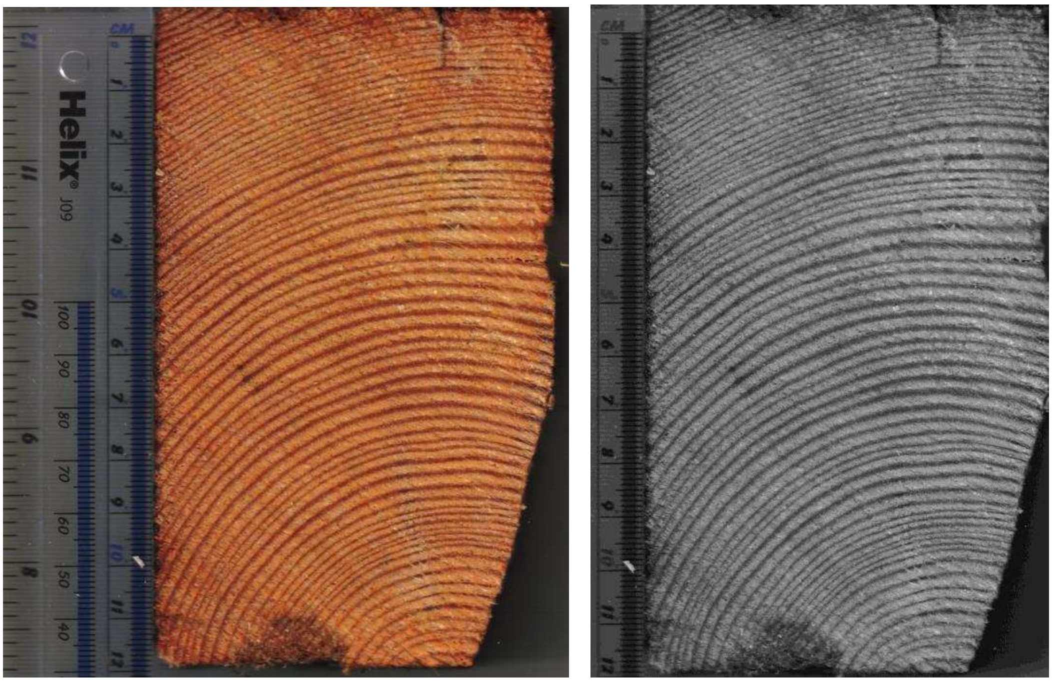
3.6.5 Tree ring frequency

Recent research by Mascia and Cramer (2009) illustrates that the frequency of growth rings can also considerably affect the modulus of elasticity of the timber. This phase of this research project also seeks to evaluate the influence of the frequency of annual growth rings on the strength of timber specimens tested thus far.

As discussed in Section 3.5.5 the frequency of growth rings is best recorded by scanning the end of the specimen. In practice it was found to be easier to scan/photograph the timber section cut from the main timber joist while it was wet. This wetting is achieved by dipping the section briefly (for no more than 30 seconds) in water and padding dry with a paper towel, to remove the excess water. The section is left damp, thus, revealing in more detail the growth ring structure. Images obtained from a document scanner are perfectly adequate for routine inspection of timber surfaces.

Document scanners have the advantage over optical microscopes of having a greater depth of field, so timber specimens need not be perfectly flat. As long as the face to be scanned is relatively plane and smooth, the rest of the specimen's form is unimportant, and does not hinder imaging. High resolution scans in the order of 2000 dpi are perfectly feasible and yield surprisingly detailed information. This method also enhanced colours in the image; making it far easier to delineate the dark and light areas of the growth rings, even when these were very close together.

Figure 3.15. Two test images for ring frequency counting (colour and monochrome) illustrating the delineation of fine growth rings



To measure the frequency of growth rings it was often necessary to print the image generated, hence the need for the ruler (Figure 3.15), and count them manually. However, in the case of very tight ring structure, the image could be enlarged, making the ring structure easier to delineate and count. In regular use the, earlier mentioned, smartphone application should prove to be of immense practical use.

3.6.6 Three point bending test for timber joists

The three-point bending test serves as a means to determine mechanical properties in flexure; modulus of elasticity, stress-strain response, yield stress and modulus of rupture. The test measures the force required to bend a joist under three point loading conditions. The main advantages of the three-point bending test are; its simplicity, ease of setup and speed of testing.

The test joist is supported at the ends and a transverse load is applied in the middle; hence, loads are applied at three points only. Each specimen is passed through and tested, to a set deflection, on the plank edge, at increments of 150 mm, and to within 800 mm of each end of the joist; the timber joist is turned over and then reversed and readings taken from the opposite edge. Strength can be calculated from the overall measurements over the two plank edges, but for this research a further static bend test was carried out on the weakest area of any visually assessed joist. The static bend test then gave a minimum strength rating for the reclaimed timber joist as a whole.

Dynamic bend test method

1. Breadth and height for the specimen are measured (in mm).
2. The specimen should be placed in the three-point bend test apparatus ensuring that the test piece is correctly oriented (the joist should be lying on its plank edge). The first test area placement is at 800 mm from the joist end.
3. The pressure anvil is lowered into position so that the tip touches the upper edge of the specimen. The micrometer indicator should be set to read zero deflection.
4. The load on the anvil should be set at 2000N. 30 seconds of loading should be allowed for the deflection to stabilise.
5. The load on the joist and the deflection obtained should be noted.
6. Items 1-5 of this test should be repeated at increments of 150 mm along the length of the joist. The test ends when the increments come to within 800 mm of the opposite end of the joist.

This method will, in graphical form, illustrate a joist deflection diagram similar to that one shown by Figure 3.17.

Figure 3.16. Large timber specimen testing rig set up for dynamic bend test

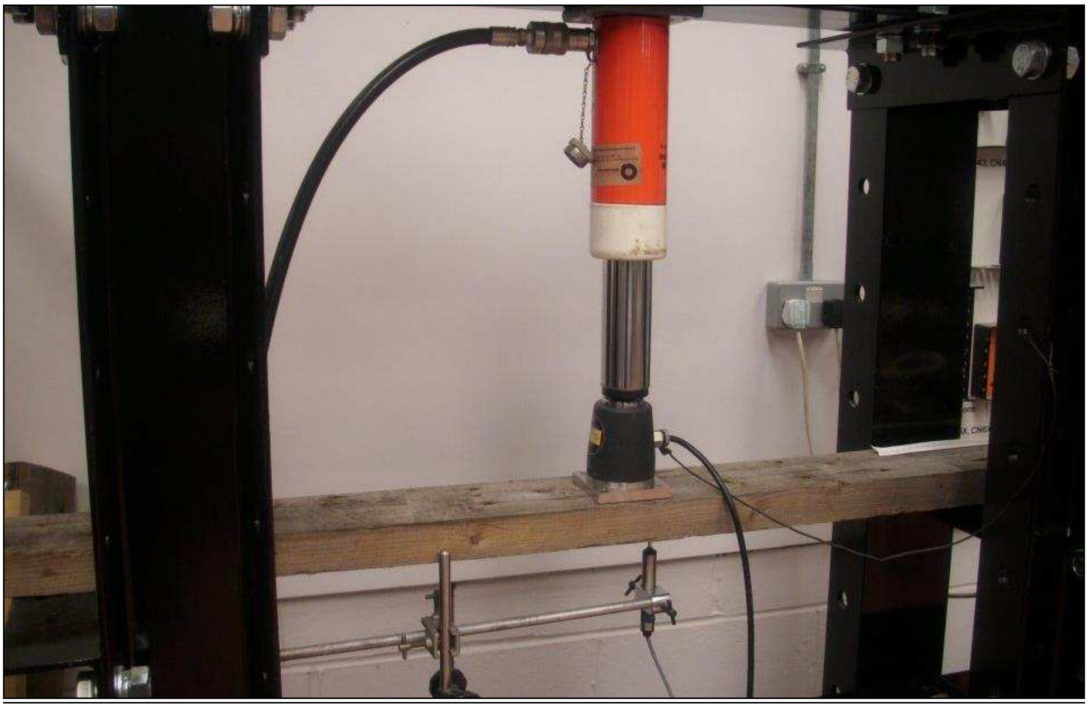
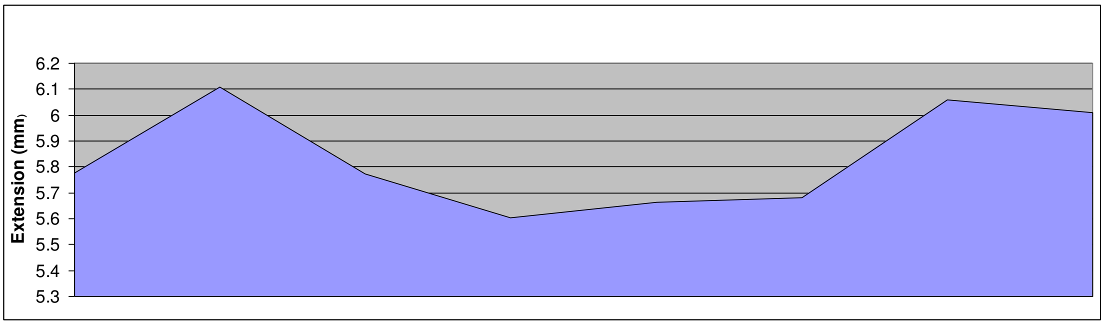


Figure 3.17. Joist load-extension graph (60 x 170 x 2400mm under 2000N load)



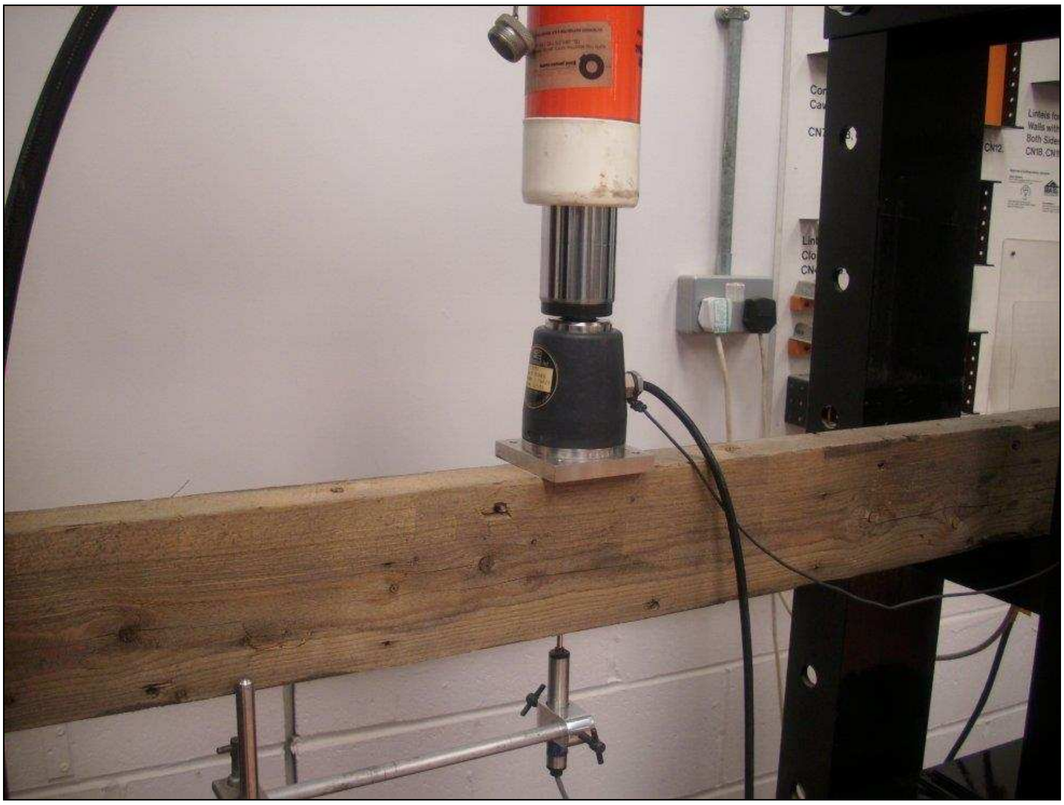
Static bend test method

1. Breadth and height for the specimen are measured (in mm).
2. The specimen should be placed in the three-point bend test apparatus ensuring that the test piece is correctly oriented (the joist should be resting on its narrow edge – see Figure 3.15). The test area placement is at the weakest point on the joist, as indicated by the results from the dynamic bend test.
3. The pressure anvil is lowered into position so that the tip touches the top of the specimen. The micrometer indicator should be set to read zero deflection.
4. The load on the anvil should be increased, by increments (of 1000N) to 10,000N; however, displacement should be kept below 5 mm (this could signal an early

conclusion of the test). 30 seconds per increment in load should be allowed for the deflection to stabilise.

5. The load on the joist and the deflection obtained should be noted and plotted as a load/deflection graph.

Figure 3.18. Large timber specimen testing rig set up for static bend test



By measuring the deflection (δ) as a function of load (m) in the three-point bend test apparatus the Modulus of elasticity of the joist can be calculated. This part of the process investigates the elastic deformation of the timber, so the test piece should not be overloaded. A total force of 10,000 N will usually be sufficient to give an accurate indication of MOE, unless the timber specimen has a particularly large cross sectional area.

The main advantage of a three point flexural test is in the ease with which the specimen is prepared; the test itself does not call for any special setup or equipment other than the rig, load apparatus and deflection indicator.

The deflection at any location along the length of a simply supported joist with a single mid-span point load can be determined by:

$$\Delta_y = \frac{Px(3L^2 - 4x^2)}{48EI} \quad (6)$$

Where

Δ_y = deflection in the vertical direction
P = load
x = point distance from supports
L = distance between supports
E = modulus of elasticity
I = moment of inertia

For a rectangular cross section, the moment of inertia is:

$$I = \frac{bh^3}{12} \quad (7)$$

Where

b = width of joist
h = height of joist

Thus, the modulus of elasticity can be resolved by rearranging Equation 6.

$$E = \frac{Px(3L^2 - 4x^2)}{48I\Delta_y} \quad (8)$$

3.6.7 Small clear tests

In the static small clear bend test the orientation of the growth rings is parallel to the direction of loading and an extensometer is usually attached to provide a load-deflection diagram from which is calculated the modulus of elasticity, as determined by BS 373 (BSI, 1957).

For this research small clear specimen test pieces should be cut from the larger timber joist specimens, and machined to size by being passed through a bench plane to acquire the 20 mm dimension expressed in the standard as accurately as possible. The machined specimen is tested to destruction on a small, purpose built test rig (see -

Figure 3.19). The standard has largely fallen out of practice since the advent of automated computerised testing of large joists; however, it has proven useful for this research in the calculation of stiffness values and where, ultimately, a smaller scale reclamation setup is being considered.

Figure 3.19. Example of a non automated ‘small clear’ test apparatus setup

Small clear test method

1. The specimen should be placed in the test apparatus ensuring that it is correctly oriented (taking careful note of the angle of the growth rings; they should be as near vertical as they can be placed).
2. The pressure anvil is lowered into position so that the tip touches the upper edge of the specimen. The load cell indicator should be zeroed.
3. The load on the anvil is gradually increased, maintaining a constant momentum of 0.11 mm/s (this equated to 6.6 mm/minute; six and a half turns of the screw guide in the piece of apparatus used for this research – Figure 3.17)
4. The reading from the load cell should be marked at each full turn of the screw guide, this will yield a load reading every 10 s, and for every 1.1 mm of deflection (The deflection of the joist at mid length is measured with reference to the outer points of loading)

5. Readings continued until the specimen either fails to support one tenth of the maximum load recorded, or is deflected by more than 60 mm; whichever occurs first.
6. A load deflection displacement diagram should be plotted for each specimen.

Three strength properties are usually determined from this test; Modulus of rupture (MOR), work to maximum load, and Total work. The MOR is a measure of the ultimate bending strength of timber for that size of specimen and that rate of loading. This is actually the equivalent stress in the extreme fibres of the specimen at the point of failure. In three-point bending the MOR is given by:

$$\text{MOR (in N/mm}^2\text{)} = \frac{3PL}{2bd^2} \qquad (9)$$

Where

P is the load in Newtons (at the point of maximum load/rupture)

L is the span length in mm,

b is the width of the joist in mm, and

d is the thickness of the joist in mm.

The second strength parameter is work to maximum load, which is a measure of the energy expended in failure and is determined from the area under the load-deflection curve up to the point of maximum load. The third parameter, total work, is the area under the load-deflection curve, and is taken to complete failure.

The intention in carrying out two different methods of strength tests is to find a correlation in properties between small clear specimens and large timber joists.

3.6.8 Density measurement in small clear tests

Measuring the timber density indicates the condition of the timber and allows estimation of the water content within the wood. To gain an absolute density measure, as well as calculating density at the test area temperature and pressure, specimens were cut from the small clear specimens, after the tests had been carried out, to further determine their moisture content using the oven dry method. The moisture content of the test piece, expressed as a percentage by mass, should be calculated to an accuracy of 1% (BSI, 1957).

Oven dry method

1. A test piece should be cut from the small clear specimen, as close to the site of rupture as possible. It should have a length along the grain of 25 mm and should include the full cross-section of the specimen.
2. The test piece should be weighed to an accuracy of 0.5 % of is mass, then dried to constant mass in a vented oven at a temperature of 103 ± 2 °C. Constant mass is considered to be reached if the loss in mass between two successive weighings carried out at an interval of 6 h is not greater than 0.5 % of the mass of the test piece.
3. After cooling, which should be sufficiently quick to avoid an increase in moisture content, the test piece should again be weighed to an accuracy of 0.5 % of its mass.

The moisture content of the test piece, expressed as a percentage by mass, should be calculated to an accuracy of 1 % from the equation:

$$D = \frac{100\,(m1 - m2)}{m2} \tag{10}$$

Where

m1 = green mass of specimen

m2 = oven dried mass of specimen

The attainment of constant mass generally occurs after drying for 24 hours as mentioned by Walker et al. (1993). The equation can also be expressed as a fraction of the mass of the water and the mass of the oven-dry wood; 0.59 kg/kg (oven dry basis) expresses the same moisture content as 59% (oven dry basis).

3.7 Summary of reclaimed timber testing

This phase of the research project involved preparing the specimens, both full length timber joists and small clear tests, measuring the test piece dimensions in each case, and carrying out the relevant bend tests on the specimens.

Careful measurements were taken of density, tree ring frequency, and the probable age of each of the specimens, calculated from the age of the building they were taken from. However, the age of the timber specimen can only be assumed, as the timber is likely to have been felled at least 5 years before the building was constructed. In more recent buildings there exists the possibility that constituent timbers may have been forced dried or kiln dried, giving any calculated date greater accuracy.

Each timber joist was tested on a 3 point bending test rig; measuring the modulus of elasticity and strength. Small clear specimens were tested to destruction, establishing the modulus of rupture.

These results thus generated, along with the previously calculated values for density, tree ring frequency and age, are discussed in the analysis, with the final aim of observing or establishing a pattern and the formulation of a rule and calculated expression to predict this in other, as yet ungraded, timber joists still to be reclaimed from demolition operations.

4 Results

The objective of this part of the project is to produce a dataset of test results, which can then be used to produce statistical and qualitative analysis and conclusions regarding the strength of timber recovered from demolition. This phase of the research illustrates tabular evidence and graphical representations of the results of the visual grading and machine simulation testing.

A control dataset was built up from observing virgin timbers sourced from a builder's merchant chain. This control data set was composed of twenty 3.6 m joists, of random cross sectional areas. All were treated in the same way as the reclaimed timbers; visually graded, stored, moisture tested and machine simulation tested. This control data acts as a comparison of the load bearing characteristics of virgin timber, compared to that of reclaimed timber.

While results are summarised in this section of the research, full results of all of machine simulation testing and small clear tests, for both reclaimed timbers and the control timbers, are shown in Appendix 1.

The following sections are arranged by first considering the visual grading characteristics, followed by machine simulation grading data.

4.1 Visual grading results

The visual grading elements of the testing, essentially, produce a pass or fail result. This is because the final test method is intended for use by site operators, in situations where value judgement over the results is not always possible; usually due to time and cost constraints.

As indicated in Table 4.1, damage affected the visual grade of 38% of the timber reclaimed and evaluated in this research; making this percentage discards from further testing. Of this, the presence of nail holes was the predominant reason (18%); while edge damage accounted for only 15% of the damaged timbers. However, edge damage was the most common form of deconstruction damage encountered, presenting itself as similar to wane. It is likely that this damage resulted from removing other timbers, which were themselves nailed to the timber joists.

Table 4.1. Percentages of timber discarded from the visual grading, by damage type

Damage type	**Percentage discarded**
Knots	2
Nails	16
Machined holes	5
Deconstruction	15
Total	**38**

Trimming the edges of damaged joists to eliminate defects, whether due to deconstruction processes or other outside agencies, will undoubtedly increase the yield of reclaimed timber; however, this trimming will also result in shorter pieces with, perhaps, a smaller cross section. For the demolition contractor this can do no real harm, if there is a market for these lesser timbers.

The remaining 62% of timbers reclaimed from demolition proceeded, after visual examination of the number of tree rings present and weighing/calculation of the timber density, to further machine simulation testing.

4.1.1 Density measurement

Specimens taken from both the large timber joist and small clear tests, revealed oven dry densities in a range from 331 kg/m^3 (corresponding to Western Red Cedar) up to 680 kg/m^3 (corresponding to Caribbean Pitch Pine).

Because the timbers were reclaimed directly from the demolition site in a timely manner, there was no cause for them to be stored for longer than was necessary for the timber surface to equalise to the test area humidity level; however, internal moisture levels were also read before testing. Timbers proved to have a moisture content which was, typically, under 10% when directly reclaimed from demolition. Many of the timbers utilised during this research were sourced from the demolition of dwelling houses, and would typically have been floor and roof joists, so it is likely that they would have spent their service life in dry conditions.

Preliminary density calculations revealed a relative abundance of timber specimens which correspond with, what is now considered to be, quite rare and expensive timber. Thus, the reclamation process illustrated the viability of reusing these timbers. Density measurements of all specimens involved in further testing are detailed in Appendix 1.

4.1.2 Tree ring frequency

Tree ring frequencies recorded throughout the data collection ranged from 4 to 15 growth rings per centimetre (cm). This may have had much to do with the prevalent economic conditions at the time of construction of the original building. Older timbers, containing a greater percentage of mature wood, had a generally greater tree ring count and timbers with a very high tree ring count predominantly came from buildings which were dated as built before 1910. Greater populations of less mature timber, though still with a high tree ring count, seemed to occur in buildings constructed before 1940.

From the timbers collected for this research, it appears that from 1940 onwards tree ring frequencies generally appeared to reduce over time, signifying either; a rise in the cost of more mature timber, or a general lack of timber supply; possibly both.

4.1.3 Age of specimens

Dated from the calculated age, or observed through relevant documentation and plans, of the building they formed a constituent of, timber joists recovered ranged from around 40 years old to 160 years old. Full figures for timber age of the specimens under test have been detailed in Appendix 1.

4.2 Machine simulation testing

The machine simulation tests are carried out in a controlled environment; standard temperature and pressure (20^{o}C and 65% relative humidity). Full data figures for these tests are given in Appendix 1.

Throughout this section linear regression is employed in an attempt to fit a model to observed data and make a significant association between the variables. Scatter plots of the data collected are illustrated with the aim of determining the strength of the relationship between the variables. This section also makes use of the correlation coefficient (R^2 value), which takes a value between -1 and 1; with 1 or -1 indicating perfect correlation (where all points in the scatter plot lie along a straight line). A correlation value close to 0 indicates no association between the variables.

The aim of using linear regression analysis at this point in the research is to illustrate the correlations between the observed phenomena and to highlight any special relationships within the content of the data.

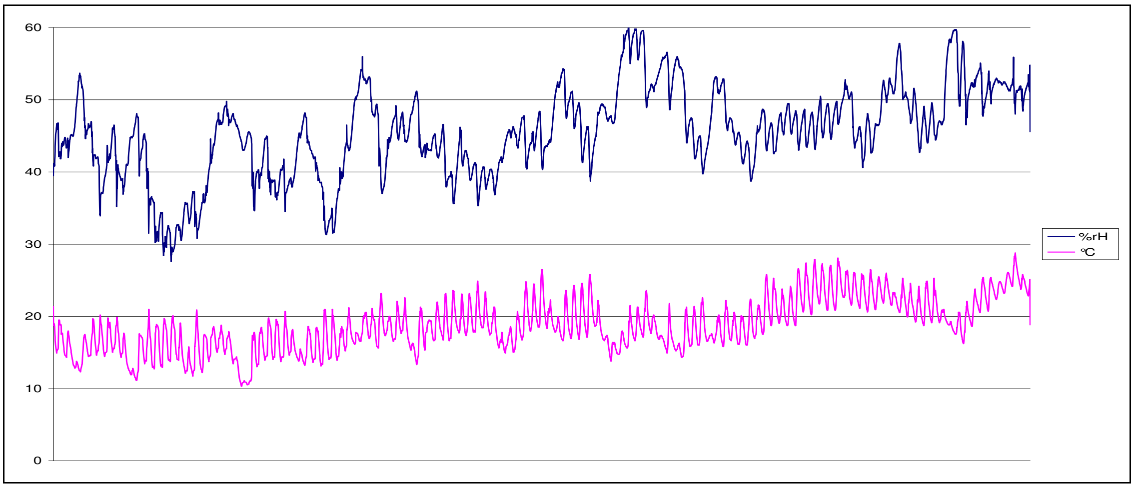
Each characteristic measured during the machine simulation test phase is illustrated in the following sections.

4.2.1 Humidity and ambient temperature

The most important points of reference in the laboratory test environment are relative humidity and ambient temperature. To monitor these conditions a temperature and humidity data logger was present in the test area for several months prior to any testing being carried out, and also present during the test phases. Variations in temperature during the times when testing took place are calculated and accounted for in the analysis of the results.

The relative humidity of the storage/test area indicates a humidity level corresponding to timber Service Class 1, characterised by a moisture content corresponding to a temperature of 20^{o}C and a relative humidity of the surrounding air only exceeding 65% for a few weeks per year. In these conditions most timber will attain an average moisture content not exceeding 12 %.

Figure 4.1. Half hourly log of temperature and relative humidity in the timber storage/test area, between 16th February 2006 and 5th July 2006 (coldest and warmest times of the year).



4.2.2 Modulus of elasticity (MOE) and density

Figure 4.2 illustrates a regular distribution pattern of density against MOE in the reclaimed timbers investigated through this research; this is not an unusual result from this type of test. The high results in the mid-density range appeared to be due to timbers which had almost no damage, very few knots, which were similar in structure to ‘clear’ specimens. Some of the excessively low results appeared to be caused by damaged timbers, which had narrowly passed the visual grade, or timbers where damage was present and not identified by the visual grading process.

Linear regression performed on this data offered a correlation value of 51% ($R^2 = 0.51$). While the data generally exhibited a regular distribution, some of the results showed very high or unexpectedly low figures that deviated from the regular pattern; however, the overall relationship remained significant.

These results also illustrated how an indiscriminate attitude to timber species seems to have been prevalent when these timbers were originally used for construction. The complete results showed that, in many cases, timbers with a range of densities originated from the same demolition site, and hence from the same building. This illustrated that , at the time of construction there appeared to be a greater focus on the strength and stiffness qualities of the timbers.

Figure 4.2. Illustration of the relationship of MOE against density in the reclaimed timbers

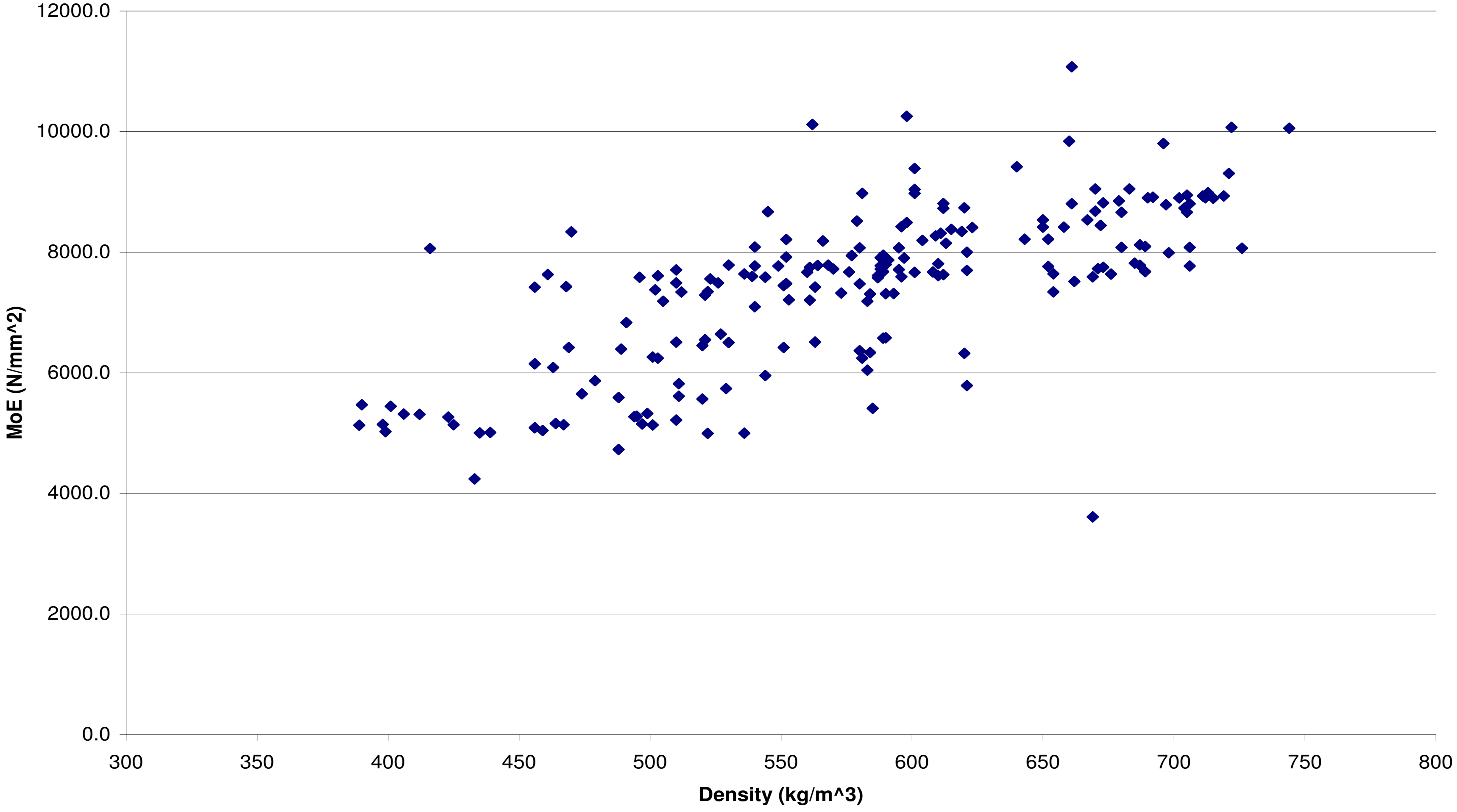


Figure 4.3.Illustration of the relationship of MOE against timber density in the control data

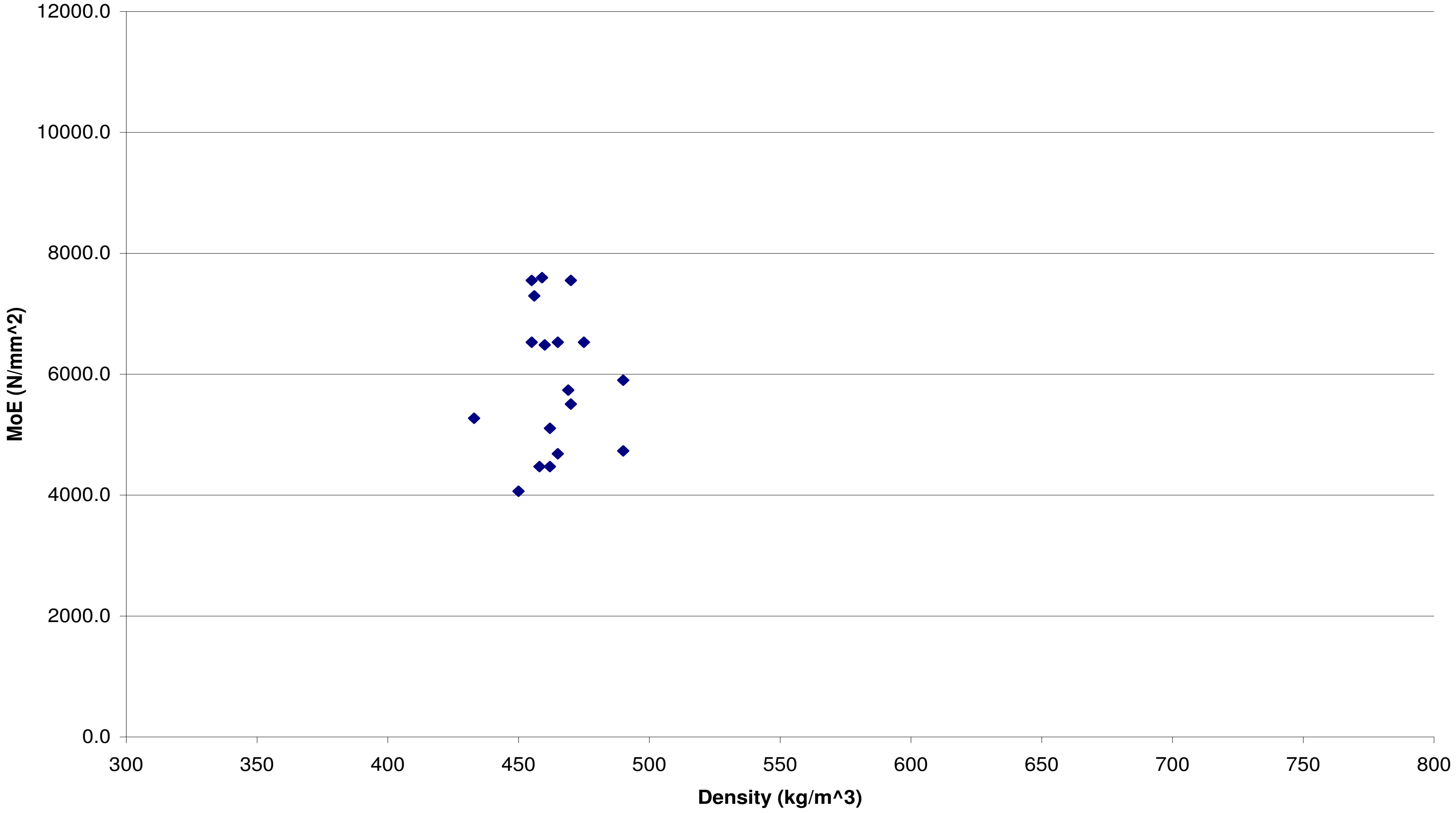


Figure 4.3 illustrates the comparison of control data for the same criteria, and shows a marked difference in the range of density measurements. The small range of observed densities evident in the graph suggests an equally small range of commercially grown timber species; whereas Figure 4.2, of reclaimed timber data, suggested a larger range of timber species. However, as many of these were sourced from demolition of the same buildings, there may have been a requirement for mechanical strength rather than species dependent characteristics.

4.2.3 Modulus of elasticity (MOE) and tree ring frequency

Figure 4.4 illustrates a distribution pattern of MOE against tree ring frequency, perhaps offering a method of grading based on the frequency of tree rings in the timber joist. The figure shows some high, and some unexpectedly low, MOE results; it is these that appear to have affected the regression analysis of the dataset. The linear regression coefficient of 38% ($R^2 = 0.38$) marks a low correlation. However, even with these results in mind, the visually close band of results suggested that they could be used as a basis for determining results from tests on reclaimed timber.

While the regression analysis showed a low correlation, around 90% of the results fell in a band 2000 kn/mm^2 above and below the average result; only one standard deviation distant from the mean. Thus, this result forms an important indicator of physical properties in relation to tree ring frequency, and a basis for further in-depth modelling during the research analysis.

Figure 4.4. Illustration of the relationship between MOE and Tree ring frequency in reclaimed timbers

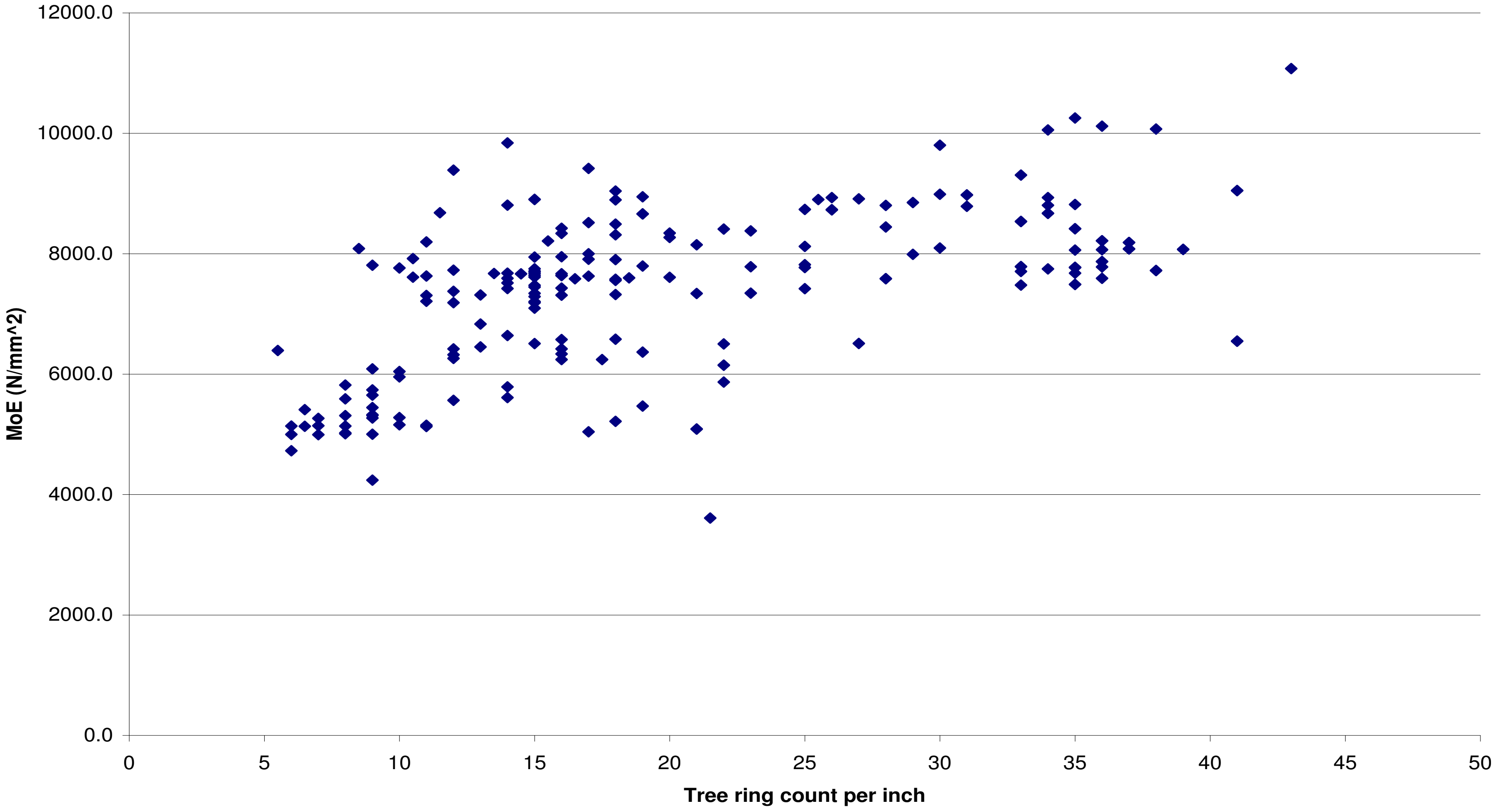
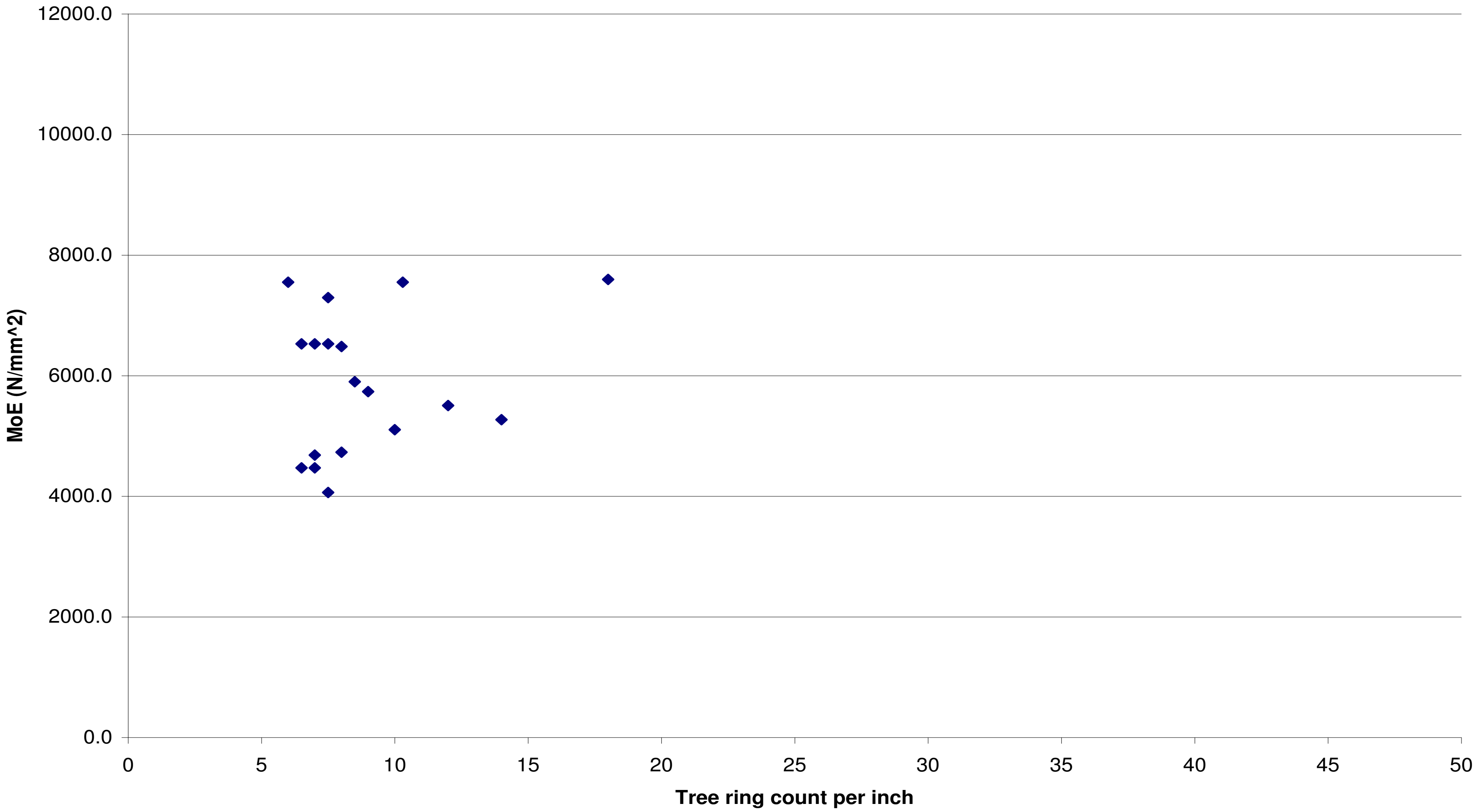


Figure 4.5. Illustration of MOE and Tree ring frequency relationship in control data



In contrast to the distribution revealed in Figure 4.4, those results illustrated in Figure 4.5 offer no regular pattern of distribution; both the MOE and tree ring count of the control data appeared to be in small, tightly controlled, bands; suggesting a small number of species grown specially for certain mechanical characteristics.

4.2.4 Density and estimated age of timbers

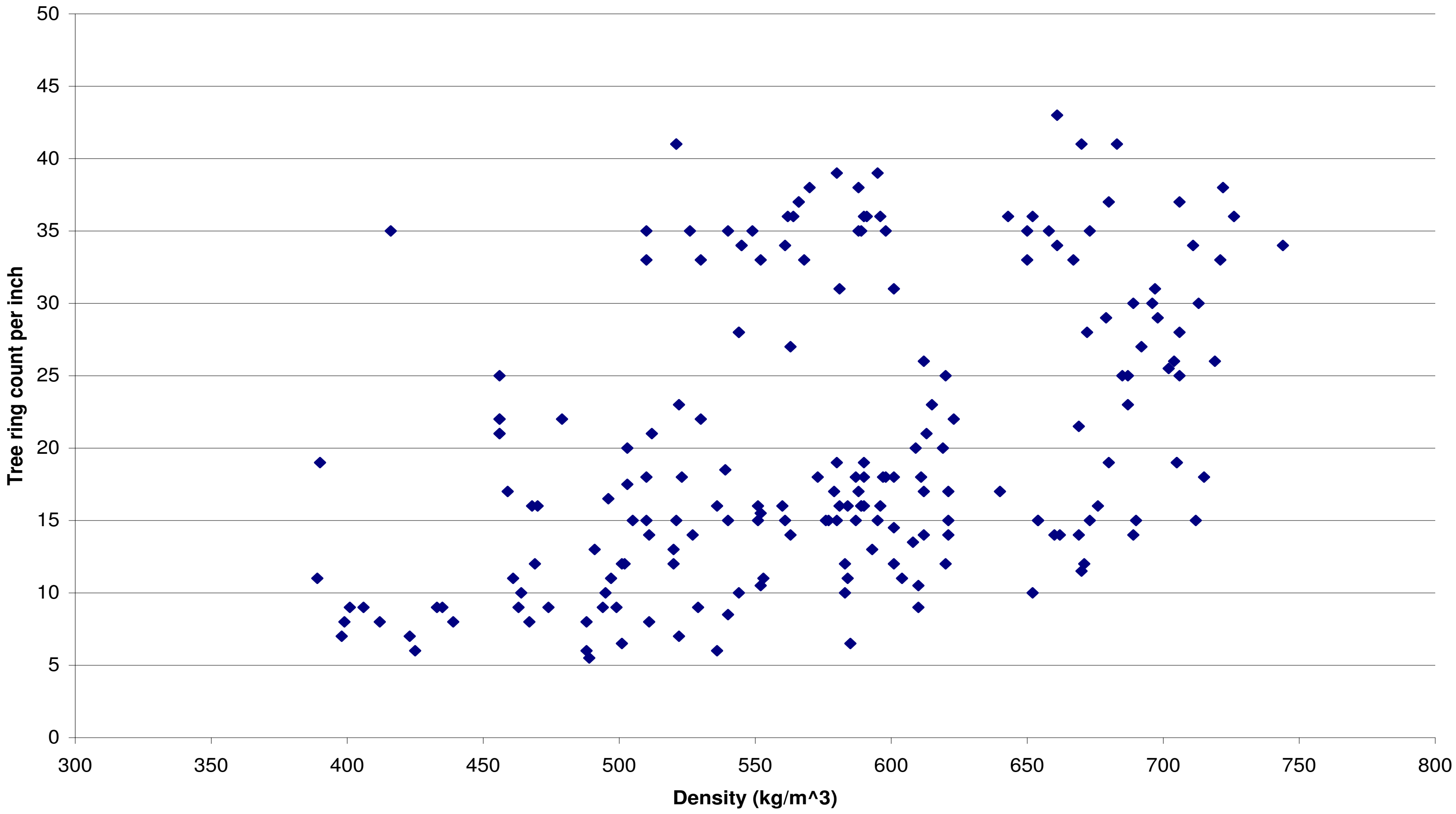
The timbers tested illustrated, on average, a lower density measurement over time; timber joists recovered from older sites usually exhibited higher densities. Those joists used on more ancient sites would have been cut from trees which were felled at a much later age than those in more modern construction use, meaning that far more of the more mature heartwood was utilised in the joist. The data findings indicated that timbers were probably quarter cut to avoid using the pith and sapwood, where possible.

The reduction in density of the timbers recovered, when considered with regard to their age, could be attributed to the shift towards utilising a smaller number of tree species throughout the decades. This appears to have resulted in a very small density range in the modern control timbers, which were obtained from a building supplier. The low density of control timbers could also be accounted for by presence of a greater abundance of sapwood.

4.2.5 Density and tree ring frequency

Figure 4.6 illustrates a considerable spread of results and a regression coefficient of 26% ($R^2 = 0.26$), marking a rather low correlation of the observed data. However, this does not make representing this data a useless exercise. Comparison of Density and tree ring frequency could be utilised to highlight a possible minimum acceptable density, or suggest a cut off point in relation to density, where the strength of a timber joist may not be any greater regardless of the tree ring count above this level. This will be explored further during the research analysis.

Figure 4.6. Relationship between timber density and tree ring frequency in reclaimed timbers



4.2.6 Modulus of elasticity and age of timber

The results of the comparison of MOE and age showed as bands of less dense timber over each decade, relative to the times where the timbers were first used. The results illustrated the general reduction of the MOE, when compared against the timber's first use in construction; however, this trend in reduced MOE measurement is more pronounced in younger timbers. Even considering the degradation, due to duration of loading, on the older timbers they still reached an acceptable level as regraded joists.

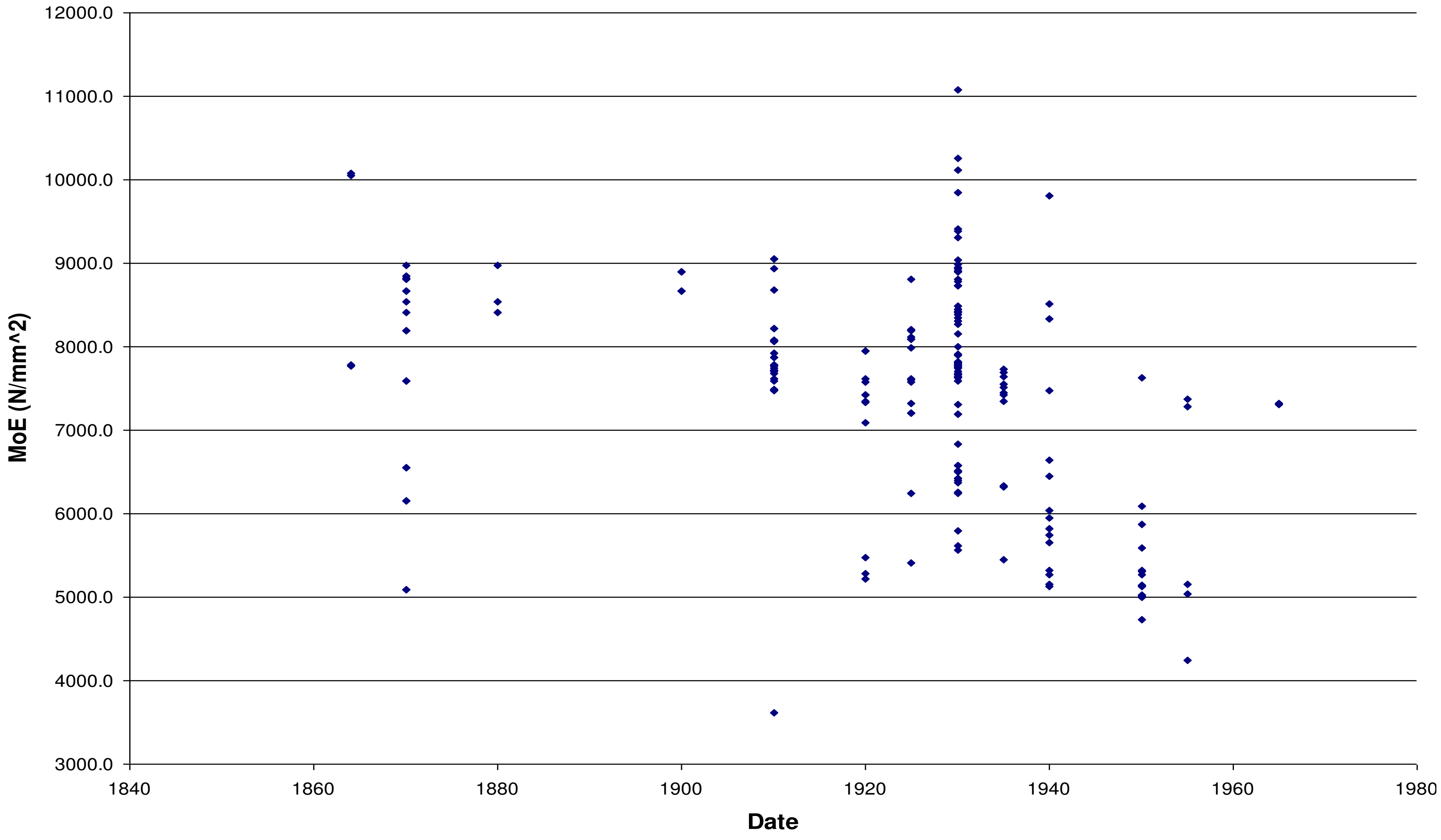
This research shows that older timbers, from mainly Victorian buildings, remain relatively strong; however, later tests showed them to be extremely brittle also. A possible explanation is that prior to the 1950s timber was almost exclusively visually graded, leaving a considerable safety margin. As the introduction of machine timber grading gave more accurate results, a reduced safety margin was necessary; and now modern timbers are influenced by the introduction of Eurocode 5 and are processed and machined to work near to their mechanical limits.

This does beg the question relating to whether there can really be a long term future in reclaiming timbers from demolition for structural reuse. As timbers are usually under load, even dead load, for all of their construction life and their strength is reduced during this time, it is likely that future reclamation and subsequent reuse opportunities may be limited.

This research results suggest that, because of the advent of machine strength grading of timber and the introduction of other forms of testing, such as ultrasonic and X-ray, both the strength and density of timber used in construction has undergone a gradual reduction.

The control timbers utilised in this research exhibited a narrow density range, and a similarly narrow range of timber strengths. This may be attributed to these timbers containing a mix of heartwood, sapwood, pith, knots and other allowable damage; all common in modern construction timbers, giving a lower level of load bearing capacity.

Figure 4.7. Relationship between MOE and Age of timber



4.2.7 Moisture content

Measurements of the density of the timbers over a period of time (both at collection and during storage) also offered an indication of the condition of the reclaimed timber and an estimation of the water content of the timber while still in service. While this was not envisaged as part of the timber test methods originally, it has proved to be insightful factor in the analysis of results.

To illustrate how much moisture the reclaimed timbers would absorb, several of them were stored underwater for 1 month. At recovery from the demolition site some of the timbers had been in very dry condition during their service life (moisture conditions of the timbers at recovery was typically measured at 8-10% humidity). The results of this experiment were revealing; water ingress to the heart of the timber was minimal, even after such a prolonged period of being wet. In all cases water penetration was less than 10mm depth from the timber surface. Furthermore, these timbers were able to be dried out to a ‘dry’ classification, in the timber storage area, taking around a week longer to normalise than timber joists collected direct from site and already in a ‘near dry’ condition. This suggests that timbers from demolition may be recovered from sites with little change to their long term properties resulting from increased moisture content.

4.3 Small clear tests

A common assumption is that the properties of wood change appreciably with time, especially if acted on by destructive or other actions that degrade the timber, specifically duration of loading. To counter this assumption, the small clear data were analysed and compared to available data on small clear test properties. The modulus of rupture for the reclaimed small clear tests was favourably comparable, when considering duration of loading, to that presented in existing literature (BRE, 1974).

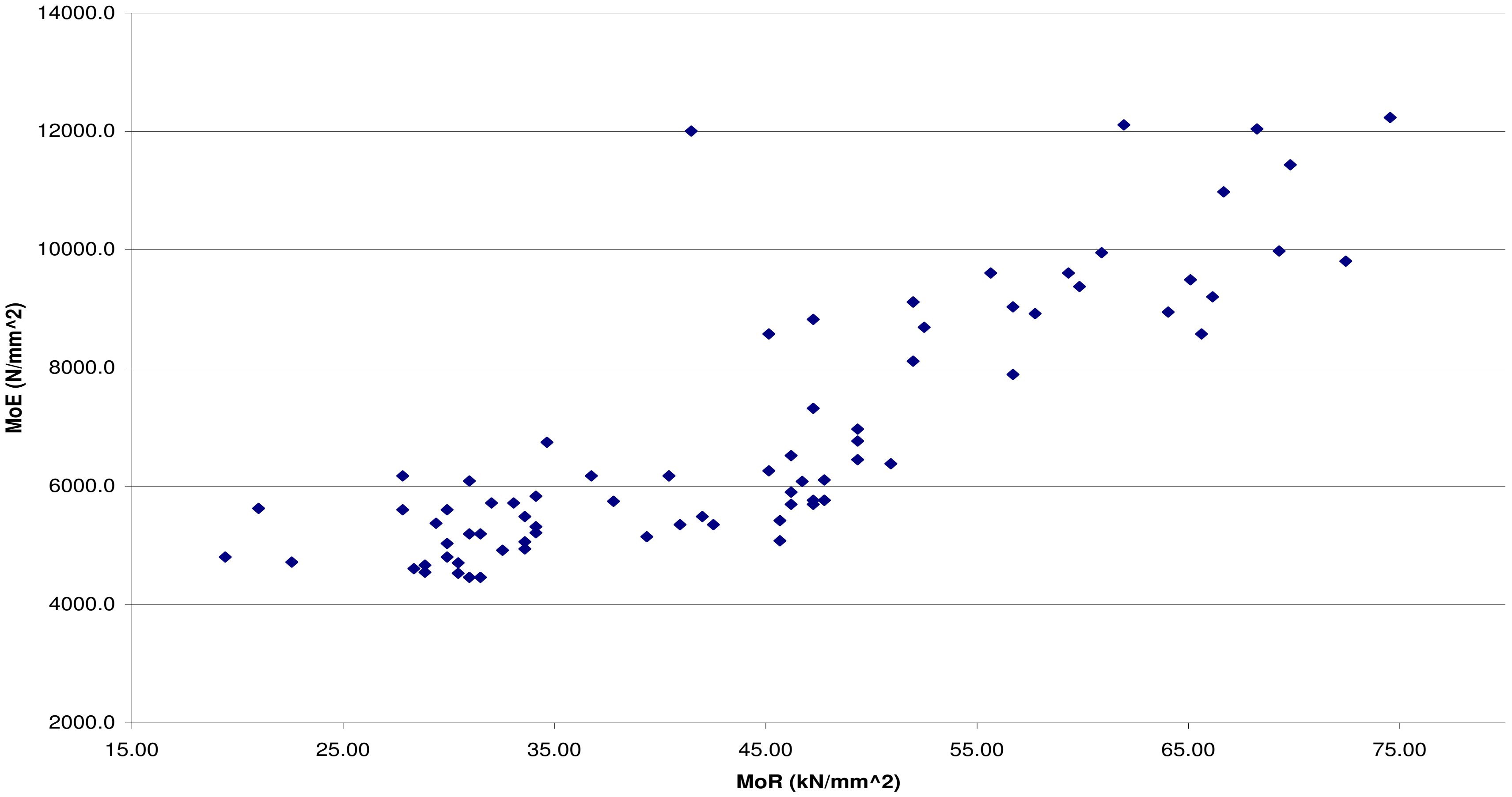
In some cases during the small clear tests, after the maximum load was attained in new timber specimens, they were still able to support a reduced load; as stated in relevant literature. However, in many of the reclaimed joist small clear tests, the specimen suffered complete failure, and was unable to support any load, after the point of rupture; many separated and snapped in half completely at the failure location. This type of failure will undoubtedly be of concern for certain applications (for example, structural systems where there is little or no load sharing between members), where a failure of the timber joist will be total and catastrophic. Though for most structural applications guidelines would direct that reclaimed joists should sit alongside others from various origins, thus sharing any imposed load between both reclaimed and virgin timbers.

4.3.1 Modulus of elasticity (MOE) and Modulus of rupture (MOR)

The linear regression fit for this combination of characteristics exhibited a consistent distribution pattern ($R^2 = 0.70$). However, when comparing the small clear test results to the full sized joist tests results ($R^2 = 0.49$), the comparison between the results of the two tests was less convincing.

The precision with which a mechanical grading system can sort lumber into strength classes (grades) is dependent upon the degree of correlation between bending strength and bending stiffness. The expected value for softwood timber is about 56% ($R^2 = 0.56$), as stated in the work of Green, Ross and McDonald (1994). The results illustrated in Figure 4.8 suggest that it may be possible to assign properties to small clear tests on a species independent basis, though larger scale testing will need to be carried out to make any firm judgement on the limitations of this.

Figure 4.8. Illustration of the relationship between MOE and MOR - small clear tests



4.3.2 Small clear test results by decade

Results from small clear tests from very early timbers suggested that, where there is a high MOE, there will also be a complimentary moderate to high count of tree rings present in the specimen; indicating a greater percentage of mature timber in the joist.

Until the advent of World War II, there appears to be a consistency in the strength results obtained from reclaimed timbers; suggesting that timber used for construction after 1850 and before 1940 may have been consistent in its material and mechanical/structural properties. The results also suggest that timbers used for construction after this time may be considered to be of a lesser quality; that they contain less mature heartwood and are more prone to strength related defects, even in joists recovered from the same building.

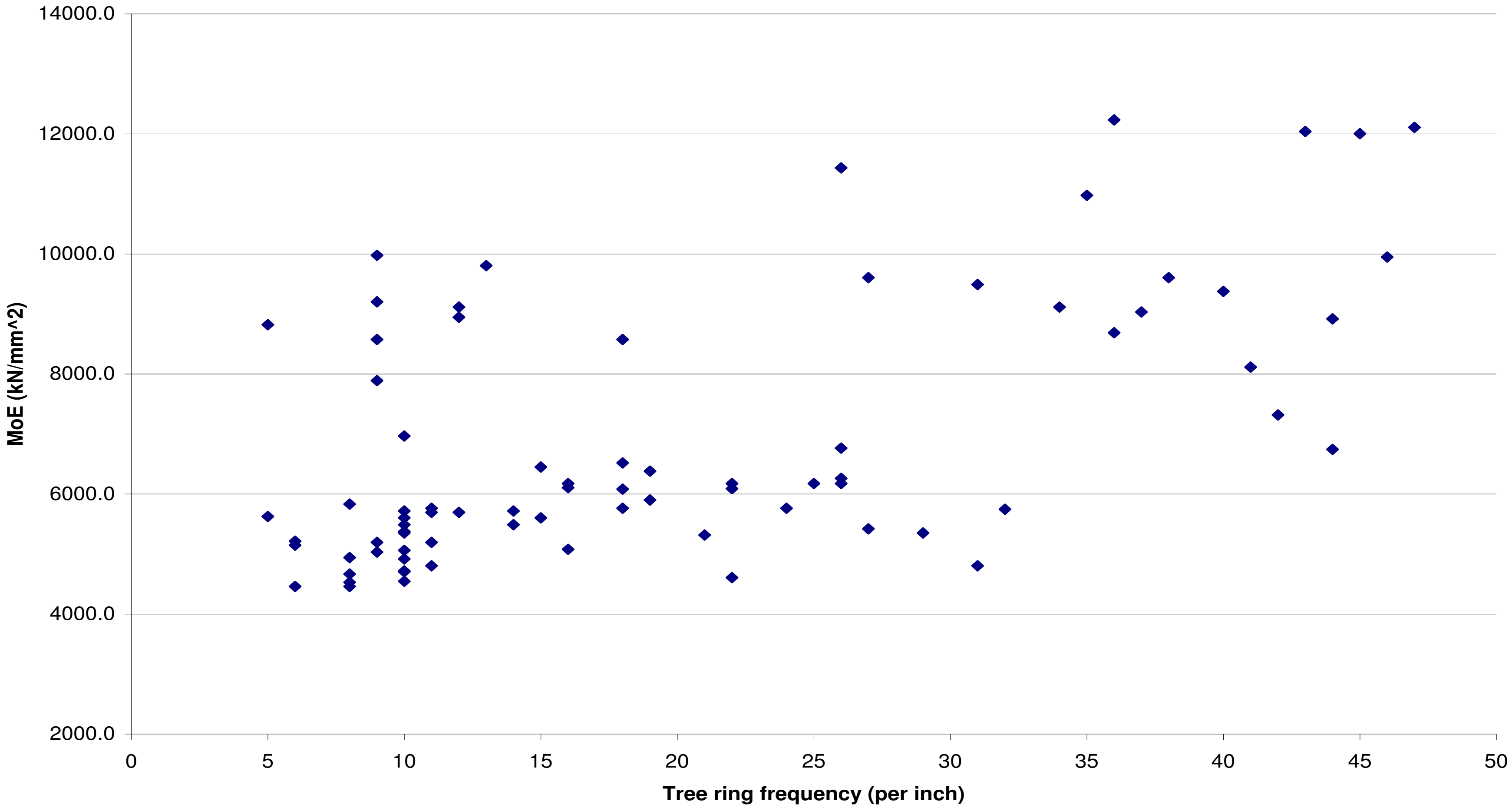
Modern construction tends toward utilising younger, fast grown, carefully managed timbers. This, in conjunction with a tightening of design standards and structural calculations, appears to have lead to a lessening of timber strengths overall. As timber has been increasingly utilised closer to its design limitations, this research suggests that its recoverability has become less economically viable.

4.3.3 Modulus of elasticity (MOE) and Tree ring frequency

The visual results of this comparison suggest that there is a regular distribution pattern of MOE against tree ring frequency; however the coefficient of correlation for these results was not high and exhibited a relatively poor pattern ($R^2 = 0.33$). These results are illustrated in Figure 4.9.

Because the results showed a regular, though sparse distribution, it can be expected that further, more extensive, testing would yield a better regression pattern and a results set that could be used as a basis for determining strength based on tree ring frequency and for comparison against other reclaimed timbers.

Figure 4.9. Illustration of the relationship between MOE and Tree ring frequency – small clear tests



4.3.4 Summary of small clear tests

The results of MOE for all small clear test specimens follow a similar pattern to the larger timber joist tests.

A general prediction of Modulus of elasticity for newly reclaimed timber joists may be able to be made with regard to tree ring frequency per inch/cm in the reclaimed joist. Further analysis will work from this point to establish a model calculation based on the relationship between MOE, tree ring frequency, approximate recovered age and density.

5 Analysis and discussion

5.1 Introduction

The continually improving accuracy of machine grading, and a better understanding by engineers and designers of ‘limit state’ designs in timber, has resulted in a narrowing of safety margins, being incorporated into timber buildings; in short, designers understand better how buildings function, so make components operate closer to the design specifications required. This means less timber, less labour, less cost.

This study has investigated the influence that several parameters have on changes in the mechanical behaviour of reclaimed timber parallel to the grain, by determining and analysing values of the modulus of elasticity of reclaimed timbers. In this way, the investigations aim to make reclaimed timber an environmental and economically viable alternative to virgin timber.

Although many results presented in this research are well established by other previous researchers, available literature does not present a complete study, with statistical analyses, of the effect that the frequency of timber growth rings has on the modulus of elasticity. Density is a well known indicator of timber properties; it is also probable that the age of the timber and the frequency of timber growth rings may also act as a further predictor of the mechanical properties of timber.

This research consisted of several separate phases; visual grading of timbers reclaimed from demolition at the recovery site (demolition site), dynamic and static bending tests on the reclaimed timber joists which had passed the visual grading process, and small clear tests on specimens cut from the reclaimed joists. The visual grading involved examining 340 timber joists at, or near to, the demolition site. For the large joist tests 201 specimens of reclaimed timber joists were further recovered after visual grading, from demolition. 67 small clear test specimens were then cut from a selection of these larger joists. The lesser number of small clear tests is accounted for because a number of the timbers joists were recovered from a reclaimed building materials supplier, delivered direct from the site of demolition; however, the materials supplier requested only non-destructive testing be carried out on the timbers, hence the visual and large bend tests results only.

The frequency of growth rings was recorded by scanning the end of the specimen, on a desk scanner, and ranged from 4 to 45 growth rings per inch (2.54 cm), as discussed in Section 3.6.5.

The density of timbers varied between 290 and 720 kg/m^3. All specimens were tested at standard temperature and pressure. During this procedure, all specimens were equilibrated to approximately 12% moisture content while in the testing laboratory, before testing began, as documented in BS EN 14081 (BSI, 2011).

5.1.1 Build-up of the analysis and model calculation

In producing a model calculation from the research results, considerable time was given to interpreting and deliberating over how the results should be represented. A key element in this process was to discern how the dataset would paint a clear and concise picture of the representative facts. A first phase involved aggregating the data collected as graphical and image representations, and investigating the patterns within these. This necessarily involved a lot of comparisons of measured data values; modulus of elasticity, modulus of rupture, tree ring frequency, density, estimated age of sample. At this point it was also decided to look not only at the results as a whole, but to split them into time frames and observe results by decade throughout the age category.

This analysis also investigates regression statistics and variance in the results dataset and how this relates the information together; enabling the generation of a model expression, with the aim of using this, coupled with the research methodology, to produce a regrading ‘rule of thumb’ to directly assess other untested timber joists reclaimed from demolition.

The final model expression is based on its accuracy when compared to the observed results and its relative simplicity of calculation. A second, slightly more approximate, model calculation is also presented, which considers a position where the operative is not aware of the age of the timbers under test.

5.1.2 Linear regression

The equation $y = mx + b$ algebraically describes a straight line for a set of data with one independent variable where x is the independent variable, y is the dependent variable, m represents the slope of the line, and b represents the y-intercept.

Multiple linear regressions can be carried out where a line represents a number of independent variables in a multiple regression analysis to an expected result; the equation of the regression line takes the form:

$$y = m_1x_1 + m_2x_2 + ... + m_nx_n + b \tag{11}$$

Where
y is the dependent variable
x_1 through to x_n are n independent variables
m_1 through m_n are the coefficients of each independent variable
and b is a constant.

5.1.3 Quadratic regression

Quadratic regression is a more complex method described by $y = ax2 + bx + c$. While, throughout this analysis multiple linear and bi-quadratic regression were the tools mainly used to generate models, tri-quadratic regression was trialled, but the results offered no greater insight than the other forms of analysis.

Tri-quadratic regression for this research was based on 3 independent variables; density, tree ring frequency and recovered age of samples. However, this generated an extremely complex expression where the results were only marginally better than other forms of analysis. A decision was made, at this point, to cease pursuing tri-quadratic regression for this research, as any model expression generated can only be as accurate as the original measurements and data. The final result of this research is an expression that can, at best and in the absence of any material or physical load measurements, offer an accurate estimation of the strength of reclaimed timbers. Using such a narrowly focussed investigation technique as tri-quadratic regression would have resulted in an imbalance of accuracies in the methodology and resultant data analysis. Effectively, a model expression containing a dozen or more variables, with the final intention of producing an approximate answer. This is explored further in the discussion (Section 5.3).

5.1.4 Regression figures utilised in this analysis

Throughout this analysis multiple linear regressions will be used as the basic form of statistical analysis to generate models. For this research the basic form of equation is:

$$E = (mx + b)(m_1x_1 + c) \tag{12}$$

Where

E is the calculated Modulus of elasticity N/mm^2

x and x_1 are n independent variables

m through m_1 are the coefficients of each independent variable

b and c are constants.

This equation can be expanded to:

$$E = bc + b^* m_1x_1 + c^*mx + mx^*m_1x_1 \tag{13}$$

This analysis also investigates the relationships in the results dataset, by utilising multiple quadratic regressions. The discussion will also comment on its effectiveness when compared to the results for linear regression. Quadratic regression for this research is centred on the expanded form of:

$$E = (mx^2 + mx + b)(m_1x_1^2 + m_1x_1 + c) \tag{14}$$

For the purposes of this analysis all equations shall use the same independent variables for: Tree ring frequency and Density. These are:

R = Tree ring frequency

p = Density

5.1.5 Duration of load figures utilised in this analysis

A further facet to the analysis will be drawn from the relationship of timber age and duration of loading, through application of the Madison Curve (Wood, 1951) as discussed in Section 3.3.12. Effectively the Madison curve can predict the logarithmic loss of strength in timber, over time; however, this criterion only affects timber under load. The assumption recognised by this research is that all timbers reclaimed from demolition have been under continuous load during their past service life.

Utilising the modulus of rupture measurements from the small clear tests, calculations can be performed to estimate the original strength of the timber joist that the small clear specimen was cut from. A re-calculation of Equation 4, relating to Pearson's (1972) expression of the effects of the Madison Curve, could show the original short term strength (S) of the original timber joist to be:

$$S = \frac{90.4 - 6.5 \log_{10} t_f}{L} \tag{15}$$

Where

t_f = time to failure in hours.

S = predicted short-term strength

L = actual stress level

Furthermore, Pearson's (1972) expression can also aid in calculating a variable relating to the loss of strength over time in timber, allowing the integration of this calculated variable into the generation of a model expression, as follows:

$$SL = 90.4 - 6.5 \log_{10} t_f \tag{16}$$

Where

t_f = time to failure in hours.

SL = predicted short-term strength over actual stress level

Utilising the result from this expression, a variable (V) can be calculated to establish a relationship with the measured modulus of elasticity from the timber static bend tests:

$$V = \frac{100}{SL} \tag{17}$$

Where

V = a numerical value relating current to original strength of the timber

SL = predicted short-term strength over actual strength

5.2 Analysis

This analysis will specifically investigate the results for the large joist dynamic and static tests, supporting this where necessary with results from the small clear tests. The intention in this analysis to create a model expression that can be used directly to give an estimation of the strength of timber joists reclaimed from demolition, without the need to follow this up directly with small clear tests or further measurement. Effectively, creating a one stop ‘rule of thumb’ that can be applied adequately at the site of timber recovery or directly during the demolition process.

5.2.1 Tree ring frequency and age calculated variable

Utilising the variable calculated in Equation 17 for each timber under test, and examining these results through regression against Tree ring frequency the basic equation is expanded to:

$$E = A + B*V + C*R + D*(VR) \qquad (18)$$

Where

V = variable calculated from the age of the timber

R = Tree ring frequency (per cm)

In this case the regression yielded a calculated model expression of:

$$E = (142.1V + 22.4R - 15.4VR - 204)*1000 \qquad (19)$$

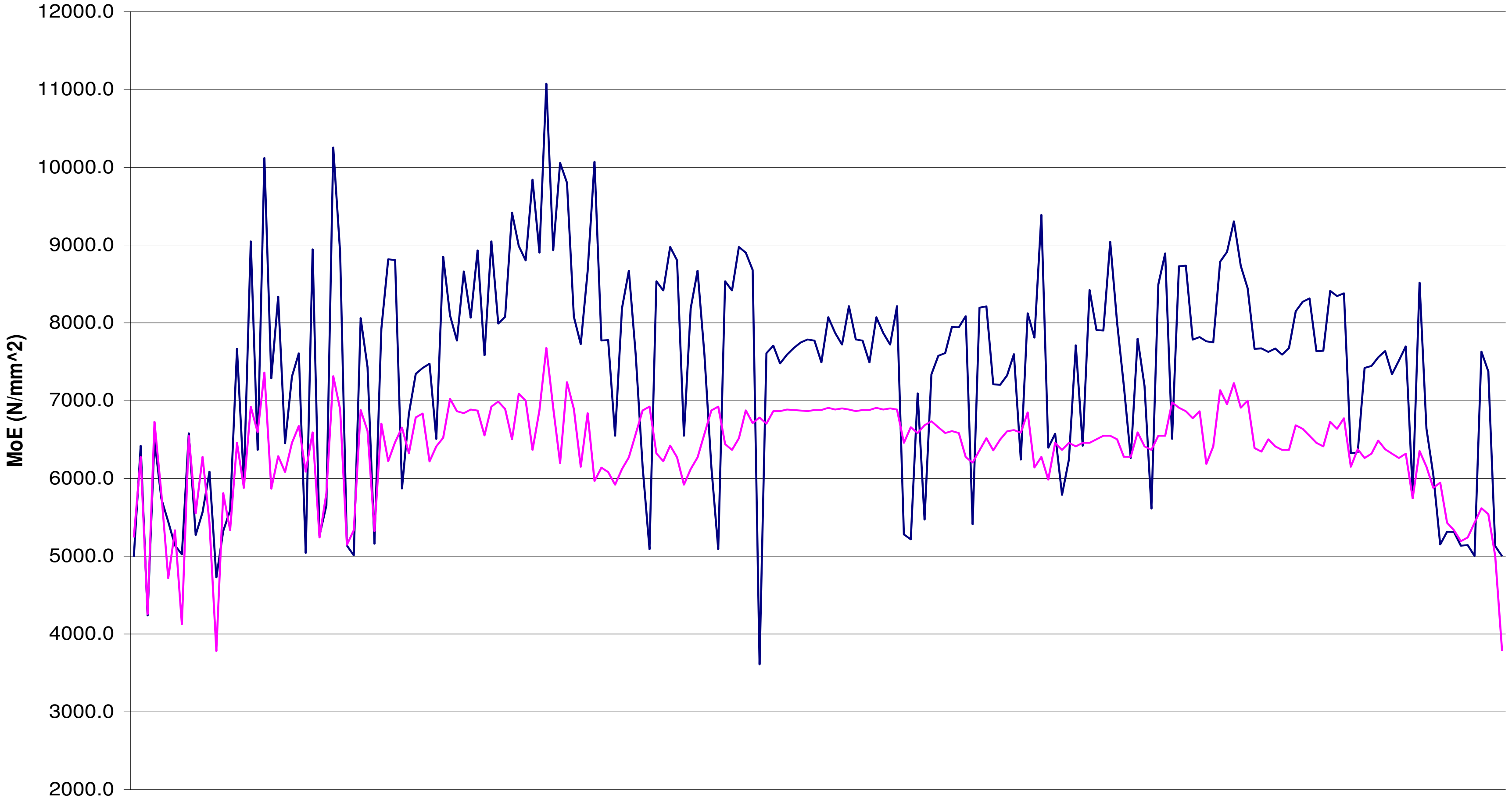
Where

E = calculated modulus of elasticity (N/mm^2)

The coefficient of determination of the regression exercise is $R^2 = 0.45$. The standard deviation for this exercise was 597.1 N/mm^2. The fit of the expression predicted values for MOE against the observed values is illustrated in Figure 5.1.

The regression results also offered a test of the significance of the R^2 result, and showed a high degree of significance of the regression analysis; effectively suggesting that the calculated results closely resembled the observed ones throughout a large section of the comparison process.

Figure 5.1. Tree ring frequency and age calculated variable - Regression analysis: Observed against predicted values illustrating deviations of predicted (shown in red) from observed (shown in blue) measurements



5.2.2 Timber density and age calculated variable

Utilising the variable calculated in Equation 17 for each timber under test, and examining these results through regression against timber density measurements the basic equation is expanded to:

$$E = A + B^*V + C^*p + D^*(Vp) \tag{20}$$

Where

V = variable calculated from the age of the timber

p = Density (kg/m^3)

In this case the regression yielded a calculated expression of:

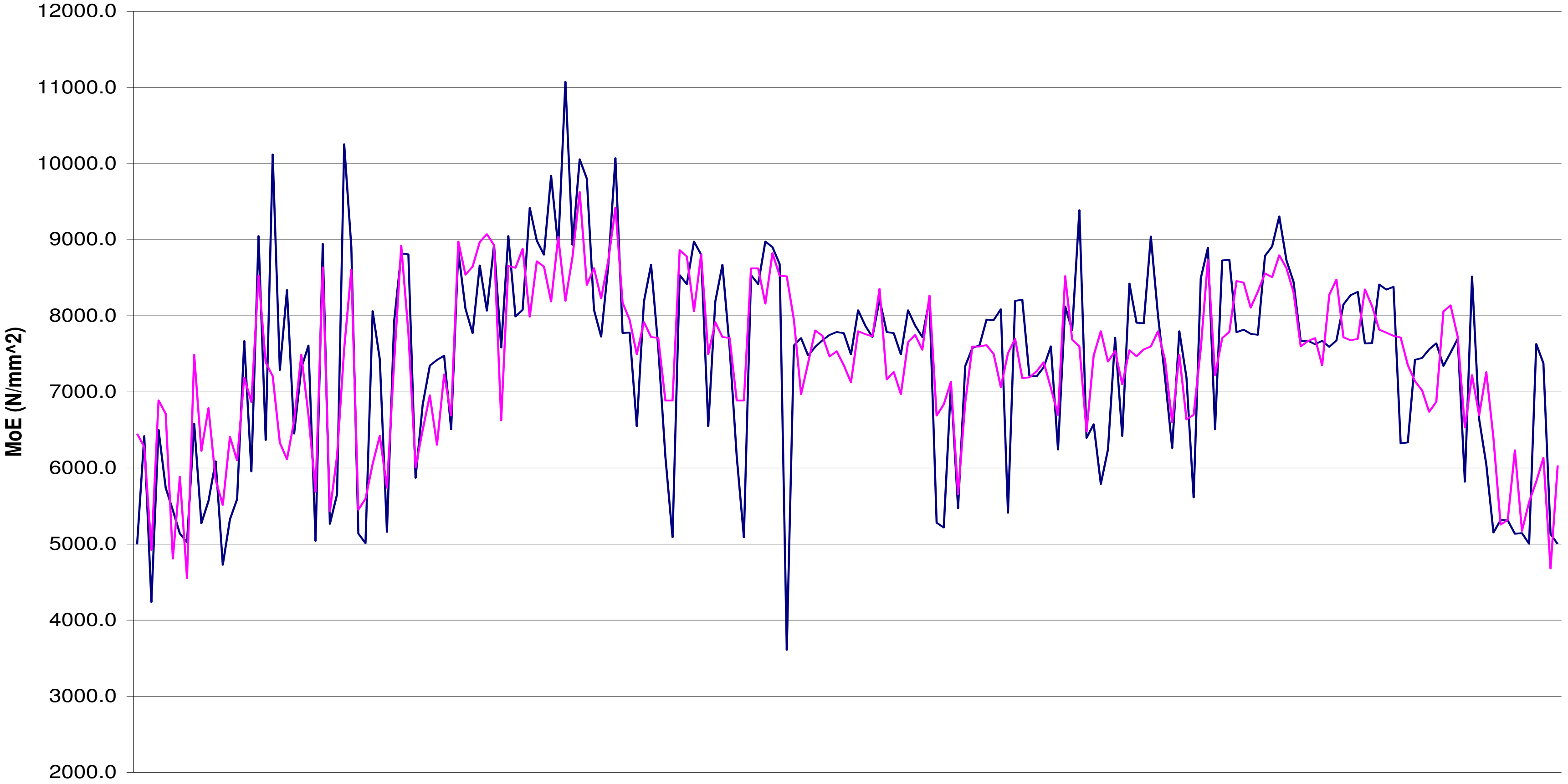
$$E = 64475V + 67.7p - 39.1Sp - 93571 \tag{21}$$

Where

E = calculated modulus of elasticity (N/mm^2)

The coefficient of determination, of the expression was $R^2 = 0.56$ and the standard deviation was 1000.7 N/mm^2. The regression results also offered a test of the significance of the result; the standard deviation suggested that the calculated results resembled the observed ones, in all but the extreme observed results (ie. unusually low or high figures).

Figure 5.2. Density and age calculated variable - Regression analysis: Observed against predicted values illustrating deviations of predicted (shown in red) from observed (shown in blue) measurements



5.2.3 Tree ring frequency and timber density

The multiple linear regression model expression based on the frequency of tree rings and timber density is the expanded form of the basic multiple linear regression equation, and expanded to:

$$E = A + B*p + C*R + D*(Rp) \tag{22}$$

Where

R = Tree ring frequency

p = Density (kg/m^3)

In this case the regression yielded a calculated model formula of:

$$E = 12.8p + 373.7R - 0.45Rp - 811 \tag{23}$$

Where

E = calculated modulus of elasticity (N/mm^2)

The coefficient of determination of the generated expression was $R^2 = 0.61$ and the standard deviation was 1060 N/mm^2. Once again the regression results offered a test of the significance of the expression; the standard deviation suggested that the calculated results resembled the observed ones, in all but the extreme observed results (ie. unusually low or high).

Once again, the graphical illustration of observed against calculated results shows a high degree of significance; the calculated results closely resemble the observed ones for a large part of the modelling process.

While other evaluations gave less clear results for the small clear tests, the regression model relating tree ring frequency to specimen density offered the best result. In this case the coefficient of determination of the generated expression was $R^2= 0.716$ and the standard deviation was 1864.5 N/mm^2, as illustrated in Figure 5.4. However, the very large standard deviation for this expression discounted it from further consideration.

Figure 5.3. Density and tree ring frequency - Regression analysis: Observed against predicted values illustrating deviations of predicted (shown in red) from observed (shown in blue) measurements

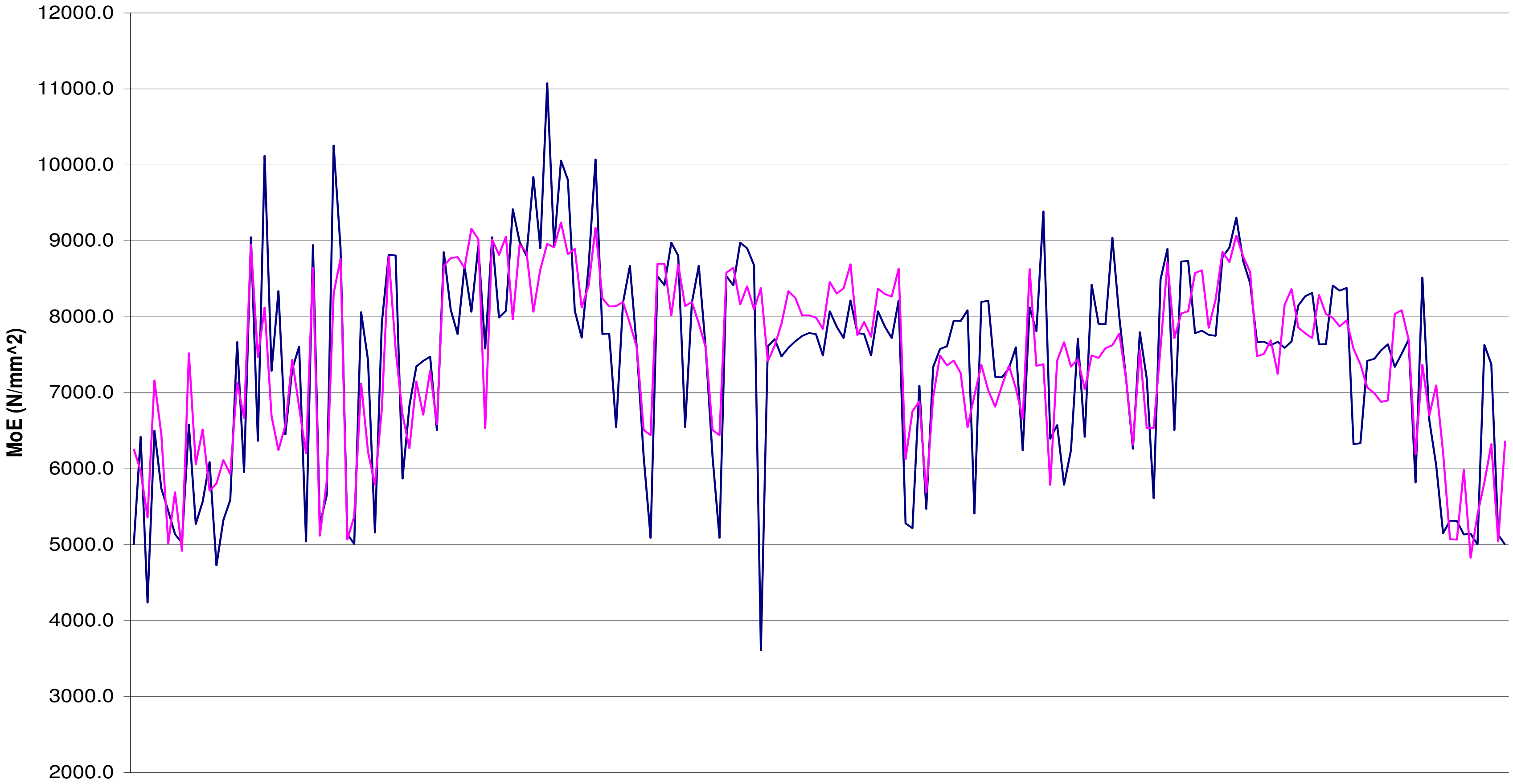
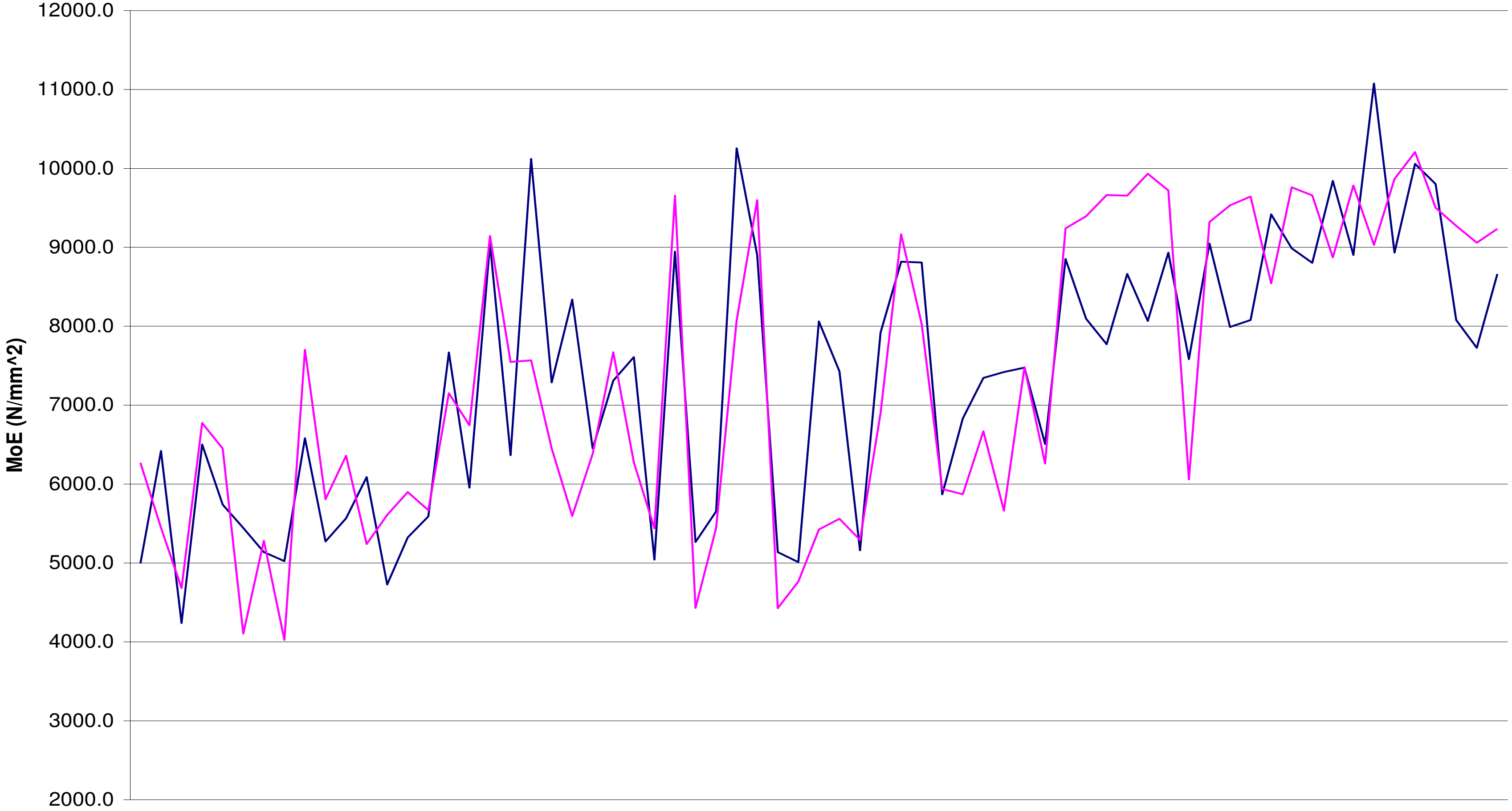


Figure 5.4. Density and tree ring frequency - Regression analysis: Observed against predicted values illustrating deviations of predicted (shown in red) from observed (shown in blue) measurements – small clear tests



5.2.4 Tri-linear regression

The expression developed through multiple linear regression is based on the frequency of tree rings, calculated variable from Equation 17, relating to the age of the timber specimen and timber density is an expansion of the basic multiple linear regression equation:

$$E = A + B*R + C*p + D*V + E*(R*p) + F*(R*V) + G*(V*p) + H*(R*p*V) \tag{24}$$

Where

V = variable calculated from the age of the timber

R = Tree ring frequency

p = Density (kg/m^3)

In this case the regression yielded a calculated expression of:

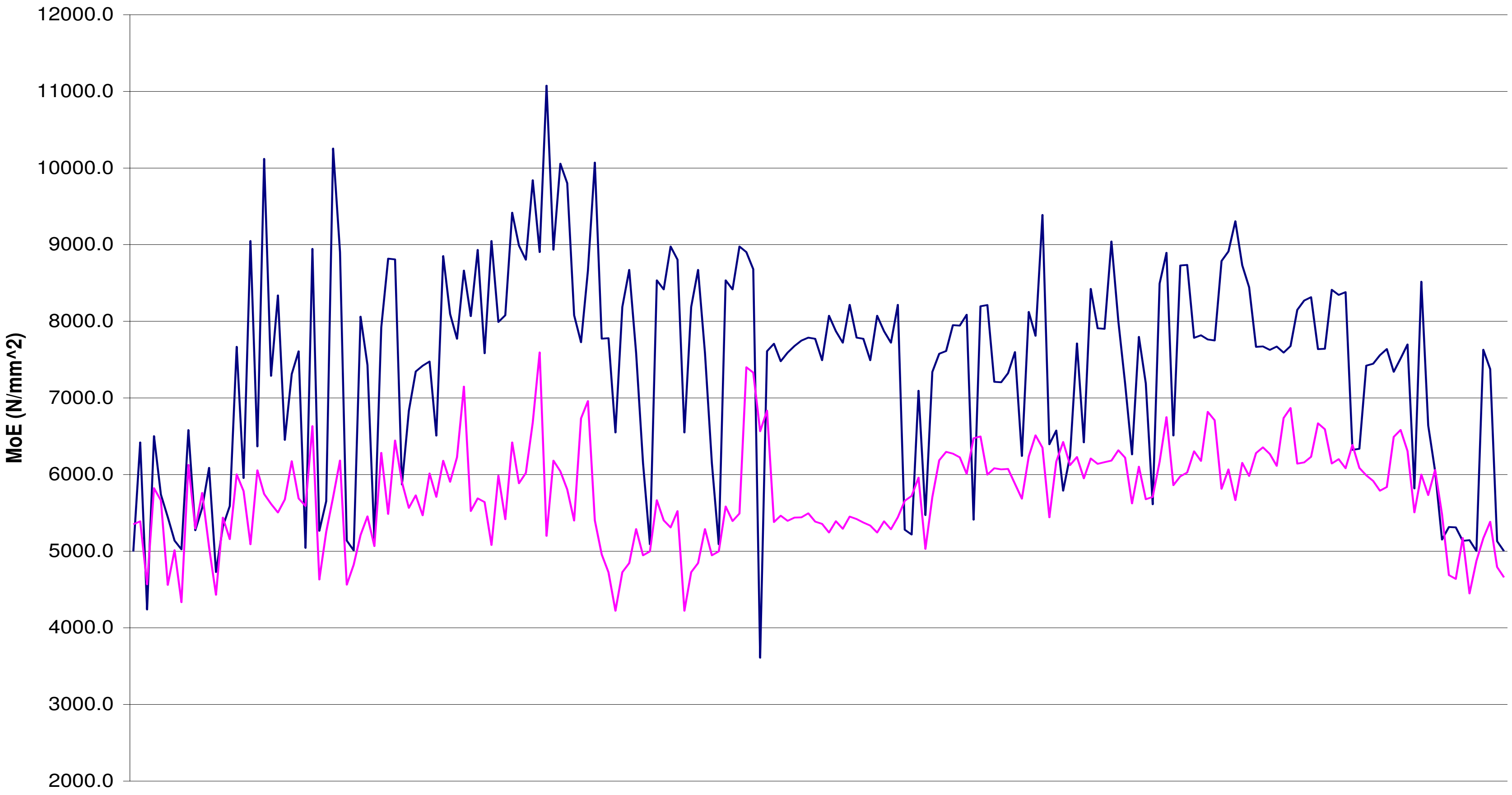
$$E = 19268 - 13356V - 260p + 31743R + 184.2Rp - 21165VR - 29Vp + 19RpV \tag{25}$$

Where

E = calculated modulus of elasticity (N/mm^2)

The coefficient of determination of the expression was $R^2 = 0.64$ and the standard deviation was 624.8 N/mm^2. While the observed comparison of results from the calculated against observed results showed a digression, the regression analysis revealed a high degree of significance of the results. However, this did not make presentation of the data a useless exercise. Figure 5.4 could be used to highlight possible minimum acceptance criteria, or suggest a cut off point in relation to density, where the strength of a sample may not be any greater regardless of the tree ring count above this level. This will be explored further during the analysis discussion.

Figure 5.5. Density, tree ring frequency and age calculated variable - Regression analysis: Observed against predicted values illustrating deviations of predicted (shown in red) from observed (shown in blue) measurements



5.2.5 Bi-quadratic analysis

The multiple quadratic regression model calculations based on the observed variables were based on the expanded form of the basic quadratic regression equation

$$E = (mx^2 + mx + b)(m_1x_1^2 + m_1x_1 + c) \qquad (26)$$

Utilising this form of regression analysis yielded model expressions which were totally out of context for the calculation to be performed; dealing in multiples of a million to gain a result which was no more accurate than the other forms of regression analysis.

Determination coefficients for quadratic regression exercises ranged from $R^2 = 0.59$ to $R^2 = 0.69$. In all cases the exercise offered a very high figure for the degree of significance in the results from the regressions. This can often signify that, rather than there being a very close relationship between the observed and calculated results, there is in fact no relationship and that the generated values may be nearly random.

5.2.6 Tri-quadratic analysis

As mentioned earlier a trial of tri-quadratic regression was also carried out. This being the expanded form of:

$$E = (mx^2 + mx + b)(m_1x_1^2 + m_1x_1 + c)(m_2x_2^2 + m_2x_2 + c) \qquad (27)$$

This expansion leads to an extremely complex model, with as many as 15 variables for input. Furthermore, the generated model expression, while it is undoubtedly useful, offers no further accuracy or insight into the prediction of MOE results than does the simpler forms of regression modelling. It also offers no greater surety of results to the operative who performs the calculation.

5.2.7 Modulus of rupture in small clear tests

Modulus of rupture (MOR) is the maximum moment in the member when failure in tension occurs. A property relationship between MOR and Modulus of Elasticity (MOE) seems to follow the trends expected for the timbers recovered. Thus, there is no reason to doubt the ratio between MOR and MOE of 0.55, as given in certain standards (ASTM, 2011).

In plotting available MOR for the small clear specimens against MOE in the static joist tests, the coefficient of determination of the regression was $R^2 = 0.57$ with a standard deviation of 1100.1 N/mm^2. Furthermore, the R^2 result showed a high degree of significance from the regression analysis; hence, the model results very closely resemble the observed ones for a large part of the modelling process. However, this is to be expected if a relationship exists between MOE and MOR.

5.3 Final model expression

The best fit model expression, based on regression analysis gave a coefficient of determination of $R^2 = 0.61$ and a standard deviation, in relation to this, of 1060 N/mm^2. This based upon the final generated model expression:

$$E = 12.8p + 373.7R - 0.45Rp - 811 \tag{23}$$

Where

E = calculated modulus of elasticity (N/mm^2)

R = Tree ring frequency

p = Density (kg/m^3)

This expression is the preferred end result because of several limiting factors. The reported results for timber age and the resultant calculation of a variable for inclusion into the regression statistics appear to yield figures that cannot offer any extra accuracy or greater efficacy to the model expression. The inclusion of the age of the timber specimen, in any form, does not add considerably to the accuracy of the coefficient of determination, or to the accuracy of the model expression. Hence, the expression can be used whether the age of the timber sample is known or not, and as an approximation of the timber strength, will be as accurate. This is discussed further in Section 5.3.

From the calculated value for MOE, the MOR can also be further calculated. The relationship between MOR and MOE, established by BRE through regression analysis (Dinwoodie, 2000), exhibits the formula:

$$MOR = 0.002065*MOE \tag{28}$$

Where the units for MOR are established in N/mm^2

This is one of the basic facets of machine timber grading and establishes the grade class of the timber. Of the timber specimens used in this research project, around 20% would not have passed the strength grade, based on MOR calculated from the observed MOE. BS EN 338 (BSI, 2009) provides data for a number of strength classes, each designated by a number indicating the value of bending strength.

Measurement errors for the set of results which make up the analysis data set could add or subtract 5% to any observed figures. However, this is a calculated error based on the results of testing how the test equipment crushed the timber samples, and a comparison to certified laboratory test results.

The standard deviation can be used to calculate confidence intervals for the true population mean. For a 95% 2-sided confidence interval, the Upper Confidence Limit (UCL) and Lower Confidence Limit (LCL) are calculated as:

$$
\begin{aligned}
95\%\text{UCL} &= \text{Mean} + 1.96*\text{StDev} \\
95\%\text{LCL} &= \text{Mean} - 1.96*\text{StDev}
\end{aligned} \qquad (29)
$$

The value 1.96 represents the 97.5 percentile of the standard normal distribution. Using these formulae there is 95% confidence that the calculated model results, based on the test data used, will fall within 1060 N/mm^2 of the actual observed result. The final expression (Equation 23) also offered the simplest solution to the calculation of modulus of elasticity in reclaimed timbers.

5.4 Discussion

From the statistical analysis, the timber grading methods suggested by this research exhibit an adequate correlation with the measured parameters. And despite the limits of the research (number of specimens and inherent visual grading errors from hidden anomalies), some important criteria remain to be examined.

Dedicated on-site visual grading criteria must be established, taking into account the incidence of defects leading to the reduction in modulus of elasticity in reclaimed timber elements.

The reported test results for timber age can be erroneous, or at best doubtful; however, the regression analysis highlighted that this information did not greatly impact on the final outcome of the analysis. It also highlighted some of the complexities of assumption on the identity of the characteristics of old timbers.

The model expression derived serves the existing data set and is also the least complex model to use; reinforcing its suitability as an on-site ‘rule of thumb’ or approximate calculation. It can be utilised on site, at the time of recovery, to offer an instant result for the expected MOE of the reclaimed timber, without resorting to the use of any specialist measuring equipment. This model expression also generated test results that show a generally a narrow dispersion pattern, with many results falling between the upper and lower quartile of the calculated data. The model expression does not display the disturbances to results occasioned by extreme values; effectively, the expression closely shadows the observed results.

The analysis and model expression also show a high degree of positive correlation between tree ring frequency and specimen density observed in the results; the coefficient of determination $R^2 = 0.61$ illustrates that as tree ring frequency increases, and specimen density increases, the associated MOE of the timber also increases (up to the limits of the test). While the model expression offers an accurate approximation of the actual timber MOE, it is based upon mechanical qualities that are not uniform in each timber sample; hence, any calculated value will only be as accurate as visual grading and the homogeneity of the timber specimen being tested permits.

While the analysis of observed results from the small clear tests reveals a higher degree of positive correlation between the measured characteristics; tree ring frequency, specimen density and specimen age, the results are based upon mechanical qualities that are more uniform throughout both the individual specimens and the range of timber samples; effectively, small clear tests have minimal anomalies in their structure to affect their mechanical properties and so offer clearer relationships between the observed results. However, Madsen (1992) claims that the traditional method of deriving allowable stresses by testing small clear wood specimens is inaccurate and a more realistic way to derive them is to test structural size specimens containing defects. For this reason and because of the small number of test subjects and large standard deviation resulting from the application of the generated expression, the model expression has been derived from the structural sized specimens with only a guiding reference to the small clear tests.

The following discussions offer some insights into the method and some of the assumptions made about quality and other characteristics of the timber used for this research.

5.4.1 Visual grading

In practice, damage affected the visual grading process of 38% of the timber reclaimed and evaluated in this research; making this percentage of the joists discards from further testing. Of these discards, the presence of nail holes was the predominant reason (18%) for their failure; while edge damage accounted for a smaller amount (15%). The edge damaged timbers were almost exclusively damaged during the deconstruction and recovery phase.

While surface defects were adequately identified by visual grading, some timbers passed through the process, but had internal damage. Without any suitable method of interpretation of internal defects, the visual grading process will not be as reliable as machine grading. However, for small numbers of timber specimens, undergoing visual examination at the demolition site, this form of examination is, and is likely to remain, cost effective.

5.4.2 Discounted results

In the test results for analysis there was a very small percentage (2%) of very low and very high MOE timber specimens. For the purposes of generating a model expression based on the median of the set of results observed, it was decided to leave this percentage in the data set. Including these results would widen the range of the expression, effectively lengthening the range of the Gaussian curve produced by results, as the extremes were taken into account. This lengthening of the curve also affected the standard deviation from the median result; in its turn widening the range of the model expression.

The analysis and model expression predict that any sample taken and inspected through visual grading and the application of the final model expression, discussed in Section 5.2.8, should have an observed MOE that is within 2 standard deviations of the calculated MOE as defined by this research; in other words, the model expression will predict the value of around 95% of the tests carried out, to within 1060 N/mm^2 of the actual observed MOE.

5.4.3 Choice of regression model

The results of more complex regression models did not generate a sufficient improvement over simpler models to warrant proceeding with them. The Tri-quadratic regression model (using 3 variables) also generated an extremely complex and cumbersome model calculation, with more than a dozen variables. This opens up to discussion the argument of sufficient accuracy. An operator working outside, and away from a laboratory, would not be able to achieve adequate results from such a complex and laborious process of calculation; especially as the final result is an approximate value. The expression generated from this research is one that can be used, with an adequate level of complexity, but still generate an accurate approximation of the true value.

The regression model that yields the model expression is based on the density and tree ring frequency of the timber sample. This is used for two reasons; because the variables in question gave the best regression results for the test data presented, and because they can be directly calculated/counted from the physical timber specimen without any further investigation of mechanical properties.

5.4.4 Measurement uncertainty

While the large joist and small clear test equipment was uncalibrated, there were control tests carried out on timbers to establish a calibration baseline. The large joist tests were calibrated against tests carried out by the Forest Products Research Centre (FPRC), of Buckinghamshire Chiltern University College, and by lab testing with a Dennison bending machine (Model - T42U). This latter had been calibrated in the year before this research began (Cert. No. 59477). The Dennison machine, results from the FPRC, and tests on the large joist bending rig were consistent over the samples tested. However, because of high costs involved, only a small batch at the beginning of the research period was tested by an established laboratory.

The small clear tests results were verified by also testing on a Lloyd LR100K Plus bending machine. This machine was installed new, during the research programme, and was certified at installation. The majority of the small clear tests were carried out on the small bending rig, illustrated in chapter 3, because of availability for use and constraints of research time of the Lloyd bending machine. However, once again, in the case of the small tests the Lloyd machine and the small bending rig offered similar and consistent results.

One major factor which affected the results from the Dennison bending machine was ‘timber crush’ at the loading contacts (rollers). This was in part mitigated by the use of larger, custom made loading rollers, but without the FPRC test results on which to base calculations, the Dennison produced an error of up to 10% to measured Moduli of Elasticity.

The issue of timber size, and cross sectional area, also factors in the results. Large timber cross sections experienced greater ‘timber crush’ even when the loading head was at its maximum size. Fortunately this was more of a factor in measuring the control timbers; older timbers, perhaps through being denser, appeared to be more resistant to this.

Factoring together the variations in the timber sizes and how these affect the measurements, coupled with the control results from certified laboratory tested timbers, uncertainties in the results are small. This research estimated that there were as little as 5% errors in most machine measurements.

5.4.5 Remainders and constants

The question of a constant or remainder to account for the anomalies in the actual results, over the predicted results, remains an open one. Because of its non-homogeneous nature, there will always be occurrences of anomalous results which stand out from the norm, whether they are higher or lower than expected. The test of significance of the R^2 value from regression analysis; which is itself a measure of the frequency of attainment of the average, shows a greater degree of homogeneity between timber joists where the material density is high.

This research considers a wide range of different species of timber, most of which were unknown other than through estimation based on timber density at the time of testing, aswell as a wide range of ages of sample. However, even under these conditions a relatively high degree of significance of results was achieved. It is for these reasons that this research does not use a remainder calculation or a correcting constant.

5.4.6 Nail-hole damage to samples

Nail-holes are almost always present in reclaimed timber and, while they are found predominantly on the narrow faces of the joist, can be found on almost every face. Narrow edge-nail holes are commonly found on joists along an entire length of a joist. Usually these are the result from the prior attachment of cladding or floorboards. Face-nail holes (those marks found on the wide face) are typically caused by nailing of bridging or hardware.

Narrow edge-nail holes can potentially reduce bending strength if the face of the joist containing the nail holes is loaded in tension. To determine how narrow edge-nail holes affected the timber joist properties, the orientation of the timber edge containing the greater proportion of nail holes was tracked during testing. This edge was oriented to be on the top in the test rig (so that the nail holes were in the compression zone) or on the bottom (nail holes in tension zone). Certain American grading rules, for example WCLIB Standard No. 17 (WCLIB, 1996) contain provisions for grading large and small holes. Under these rules nail holes would be defined as either a pin hole (if less than 3.2 mm diameter) or medium (small) hole if less than 6.5 mm diameter. The grading rules do not contain specific guidelines for the measurement of edge-nail holes, they simply state that holes that extend only partially through a piece may also be designated as surface pits. In an earlier study, Falk, Green and Lantz (1999) also investigated edge-nail hole orientation with respect to the direction of loading. In the study, when nail holes were present in the piece, the grader summed up the nail holes and equated this area to an equivalent knot size for grade determination. For bolt holes, the grader allowed holes half the size of an allowable knot.

However, this research proposed a rule to grade timbers based on the effect of the number of nail holes in their various surfaces, after Nakajima and Murakami (2008), discussed in Section 3.5.6. This gave results which were achieved more quickly and with greater accuracy than through measuring nail-hole sizes and extrapolating knot sizes from the collected data. This method of estimating nail-hole damage saves time and allows a safety margin in the estimation process.

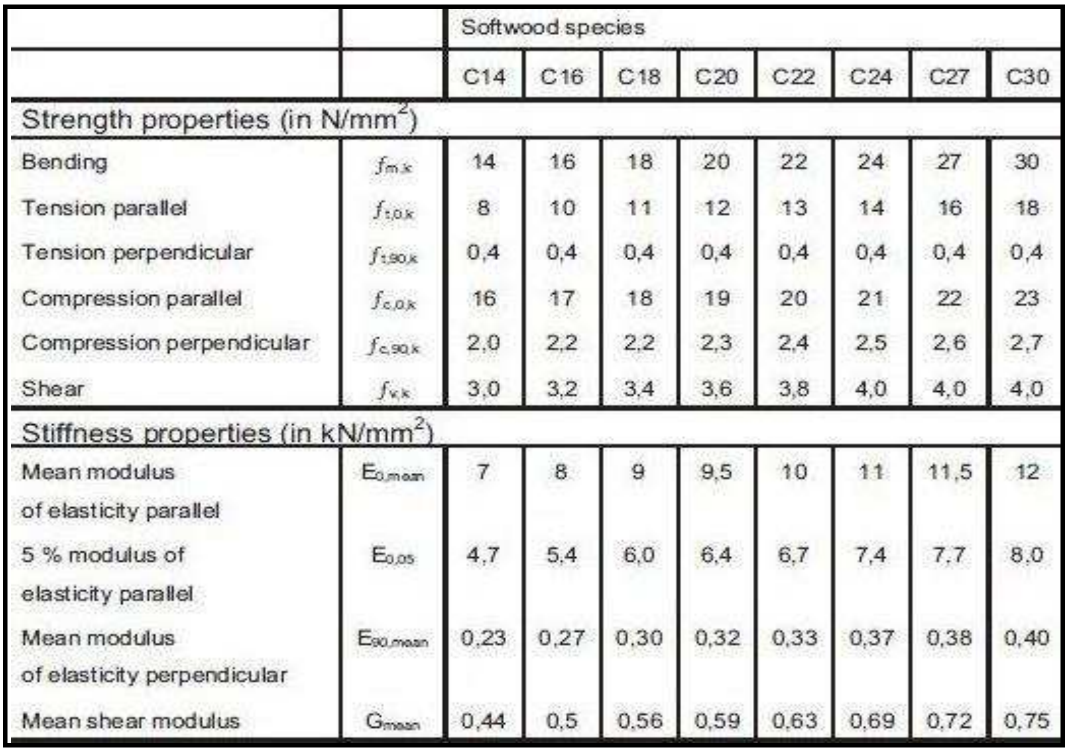
In general, nail holes need to be located at the region of highest load stress to have an effect in the fracture process and hence, the MOE. Also, cracks need to be able to form on the tension edge, where failure begins, for these nail holes to come into play. However, it is worth considering that Eurocode 5 does not count certain damage in the grading process, though this does refer to virgin timber, namely nails and screws with a diameter of 6 mm or less, which are driven (hammered home) without pre-drilling.

There is a direct resistance by processors to carry out any processing of damage caused by nails, bolts and notching. The reason for this is purely an economic one; they do not wish to machine reclaimed timber that may contain nails. This can damage equipment, plus there is the associated cost of removing nails before processing; a timber saw blade can be very quickly ruined by a stray nail in a piece of timber. Other than nails that are protruding from the surface, this is not a cost effective measure. The loss associated with this form of timber processing would amount to a high cost to any organisation carrying out this kind of work.

5.4.7 Eurocodes

The results of the modulus of elasticity results indicate that, without reverting to species data, many of the reclaimed timbers are able to pass the minimum MOE and stiffness grades to be classified as structural timber in the UK (timber grade C14), with many making the higher structural grade of C16. Around 85% of the observed results fall within 2 Standard Deviations (2SD) of the mean, as calculated by the model expression. Thus, in a modern industrial grading pattern it is likely that the reclaimed data set, as a batch, would be allocated standard UK construction grades.

Table 5.1. Strength properties of timber for softwoods: characteristic values, after BS EN 338 (BSI, 2009)



		Softwood species							
		C14	C16	C18	C20	C22	C24	C27	C30
Strength properties (in N/mm^2)									
Bending	$f_{m,k}$	14	16	18	20	22	24	27	30
Tension parallel	$f_{t,0,k}$	8	10	11	12	13	14	16	18
Tension perpendicular	$f_{t,90,k}$	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4
Compression parallel	$f_{c,0,k}$	16	17	18	19	20	21	22	23
Compression perpendicular	$f_{c,90,k}$	2,0	2,2	2,2	2,3	2,4	2,5	2,6	2,7
Shear	$f_{v,k}$	3,0	3,2	3,4	3,6	3,8	4,0	4,0	4,0
Stiffness properties (in kN/mm^2)									
Mean modulus of elasticity parallel	$E_{0,mean}$	7	8	9	9,5	10	11	11,5	12
5 % modulus of elasticity parallel	$E_{0,05}$	4,7	5,4	6,0	6,4	6,7	7,4	7,7	8,0
Mean modulus of elasticity perpendicular	$E_{90,mean}$	0,23	0,27	0,30	0,32	0,33	0,37	0,38	0,40
Mean shear modulus	G_{mean}	0,44	0,5	0,56	0,59	0,63	0,69	0,72	0,75

Timber is now grown, cut and prepared to work nearer to its limit state than ever before. Coupled with this is the loss of the 'permissible stress' approach to design, which worked by ensuring that stresses in the timber materials remained below a certain threshold to cover a range of performance criteria. The 'limit states' approach adopted by the Eurocodes is very different from what has been previously used for construction, in that it attempts to address separately various concepts of failure through rules based on reliability theory. In the past it was strength that governed design, but now modulus of elasticity and density are also important for both ultimate and serviceability limit states in structural timber. In effect, mechanical characteristics are now the arbiters of how timber is chosen for construction and timber species is no longer as important, save for matters of durability and aesthetics. These ideas make reclamation a more viable and sensible approach to sourcing structural timber, as much of it will still pass the requisite grade parameters suggested by the Eurocodes.

Eurocode 5 suggests that, in the absence of species data, direct grading to a use class is the only exigency that is called for. Certain species, with identical mechanical characteristics, could be interchangeably used in construction without altering the structural expectations of the design. This quality would allow reclaimed timbers to be grouped with regard to mechanical characteristics, rather than species characteristics. In reclaimed timbers this factor could help to make inroads to a species independent softwood grading system, based solely on the mechanical properties of the timbers. Eurocode 5 asks only that the following be considered by the structural analysis of timber for construction:

- deviations from straightness;
- inhomogeneities of the material.
- reductions in the cross-sectional area

The Eurocodes suggest ‘working to limit states’, where the materials operate at their safe maximum loading capacities. In the case of timber, this is coupled with the gradual decline in strength of timber under load. These factors pose the question: For how long can we reclaim previously used timber? The results and findings of this research would suggest that the introduction of the Eurocodes (early 2000s) as a method of structural calculation may signal the turning point for this. However, the introduction of machine grading in the early 1970s could be seen as a better date.

The introduction of ‘limit states’ no longer allows extra structural capacity to be built in to construction designs, whether by design, aesthetics or applied safety margin. This suggests that through ‘duration of load’ timbers may no longer support the same maximum load that they would have when newly cut, processed and graded as virgin timber, hence, these structural elements may no longer achieve a useful grade when assessed after reclamation.

This also poses a question about the relevancy of this current research to future generations. Will timber produced and utilised in construction projects now, cut and machined to perform to its ‘limit state’, be ‘worn out’ by the fatigues and loading during its service lifetime, and less likely to be viable for reuse. If, as the results of this research suggest, this is the case; future recovery of timbers from modern buildings may yield no structurally reusable material.

5.4.8 Load capacity

Timber load capacity decreases from its virgin static maximum load value on a logarithmic scale, if it is under service load (the Madison Curve). Thus, a timber joists subjected to a continuous bending load for 100 years may carry approximately 52% of the load required to produce failure in a static test on the timber when it was new. However, much of the timber which can currently be reclaimed tends to be older and from a period when over specification was the norm in timber structural design. Thus, many recovered timbers, while they may not be as strong as when first utilised are still gradable for general structural construction use.

Creep is additional time-dependent deflection over that resulting from elastic deformation which occurs when timber is subjected to a constant load over a period of time. Changes in climatic conditions during a duration of load or creep test may produce a lower load capacity and more creep than that observed under constant conditions of temperature and moisture content. These effects can be quite substantial for small wood specimens. Fortunately, such changes are moderate for most wood structural members in typical service environments.

However, general results show that timber joists, kept dry during their working life are still in a reusable condition. Results from research by Falk and Green (1999a) indicate that the quality of reclaimed timber is, on average, only slightly less than that of freshly sawn timber, more often as a result of damage incurred during deconstruction than through service life effects.

5.4.9 Density

The dry wood of most species float in water, so it is evident that part of the volume of a piece of wood is occupied by cell cavities and pores. Variations in the size of these characteristics cause some species to have more wood substance than others. In the absence of knots and other defects, density is an excellent indicator of the amount of wood substance present. The influence of a knot on mechanical properties, especially density, is primarily due to the interruption of continuity and change in direction of fibres around the knot. The influence of a knot on the performance of timber depends upon the size, location, and shape of the knot. In many older timbers, because of slow growth to maturity, many of the deviations in substance associated with new timbers are not present, or exist in very small numbers and volumes; thus, density in reclaimed timber is a good indicator of mechanical properties, as it is relatively unaffected by the presence of knots.

The longer aged timber joists from the research exhibit a better range of homogeneity in this respect. They generally have a more compact structure, with fewer, less expansive knots and generally smaller areas of anomalies in their make up. This again illustrates a long growth cycle and careful cutting to recover the maximum mechanical strength per cross sectional area for each timber joist.

5.4.10 Moisture and temperature

Many mechanical properties are affected by changes in moisture content below the fibre saturation point. Generally, most mechanical properties increase as wood is dried, up to a certain point. Similarly temperature can have both immediate (reversible) and permanent effects on wood properties. In general, one immediate effect is that mechanical properties tend to decrease as the temperature is increased.

To mitigate this, timber samples were stored in a stable environment, equilibrating the humidity to around 12% at all times. This situation was monitored by a temperature and humidity logger, placed in the test/storage area.

5.4.11 Specification by builders/architects

Reclamation organisation Salvo estimate in their report a ‘Reclamation protocol’ that only 1% of building materials are currently from reclaimed sources; whereas some 5-

10% of the building materials demand could potentially be met from this source (Salvo, 1995). Green organisations have been pressing for legislation for reclaimed materials to make up at least 5% of the total project materials by value, measured by recording the value of all construction materials used on the project. If this form of legislation is introduced, specifiers and builders would need to consider the following before utilising any timber from reclamation:

- Early discussions with reclaimed materials dealers and salvage experts will help to identify materials that are easily available at the right quality and quantity
- Early design information helps in sourcing of reclaimed timber
- On site storage either on site, nearby or else at the demolition site can be helpful in matching up phasing
- Material specifications for the project need to be flexible enough to allow for the variations in reclaimed timber
- Agree on a sample first; sometimes a selection of samples will be needed to show a range of colours or states of wear that are acceptable
- Always consider the price; some basic modern salvage direct from demolition is cheap or sometimes free, while older antique or reclaimed materials from salvage yards and stockholders, may be much more, costly.

5.4.12 Why not use electronic test methods?

While electronic methods of strength measurement may give equally accurate results, they are not well suited for use with regard to reclaimed materials. Furthermore, electronic methods are often prone to giving false readings when encountering anomalies in the timber joists; these include knots, cracks and splits, as well as nails and bolts, which can all severely affect the accuracy of readings from electronic equipment.

The other main reason that this research does not rely on electronic measurements is at the very heart of its focus; and that is simplicity. This research aimed to produce a method of regrading that could offer an approximation of the modulus of elasticity of reclaimed timber, requiring only the minimum of equipment to carry out the process.

5.5 Testing of the model expression

Some limited testing has been carried out to date on a selection of newly reclaimed timber joists, not associated with the timbers already involved in this research.

19 timber joists were recovered from 3 separate sites (North Shields NE29, Whitley Bay NE26 and Peterlee SR8) and visually graded using the methodology set out in Section 3.6.1. Of these 19 specimens, 8 were rejected by the visual grading process (a slightly high figure when compared to the average rejection rate throughout this research), 2 specimens were rejected through excessive nail damage and 6 through damage caused by the demolition and recovery process.

Comparing the observed results in these specimens against the calculations of modulus of elasticity produced from the model expression (Equation 23) produced observed figures which fell very close to the expected range of the model expression values, plus the standard deviation of 1060 N/mm^2. These test results are reproduced in Table 5.2. The figures were based on the final generated model expression:

$$E = 12.8p + 373.7R - 0.45Rp - 811 \qquad (23)$$

Where

E = calculated modulus of elasticity (N/mm^2)

R = Tree ring frequency

p = Density (kg/m^3)

Table 5.2. Results from tests of reclaimed timber - calculated values against observed values for MOE

Breadth (mm)	Height (mm)	Date	Density (kg/m^3)	MOE - observed (N/mm^2)	Tree rings (per cm)	MOE – calculated (N/mm^2)
54.0	155.0	1910	609	8670.5	4.6	7569.5
54.0	155.0	1910	609	9006.7	6.6	7650.8
64.0	150.0	1910	613	7898.5	7.4	7759.6
64.0	165.0	1910	589	8567.3	8	7596.0
64.0	165.0	1930	611	8111.7	7	7866.0
54.0	155.0	1930	616	6322.0	6.4	7641.8
54.0	155.0	1930	554	7635.7	5	6902.2
45.0	125.0	1940	523	7810.3	6.8	6824.2
45.0	125.0	1940	519	6326.1	5	6532.9
75.0	150.0	1940	491	7220.5	6	6390.3
45.0	125.0	1940	515	7819.2	6.2	6661.1

Figure 5.6. Results for model expression - observed results against calculated figures

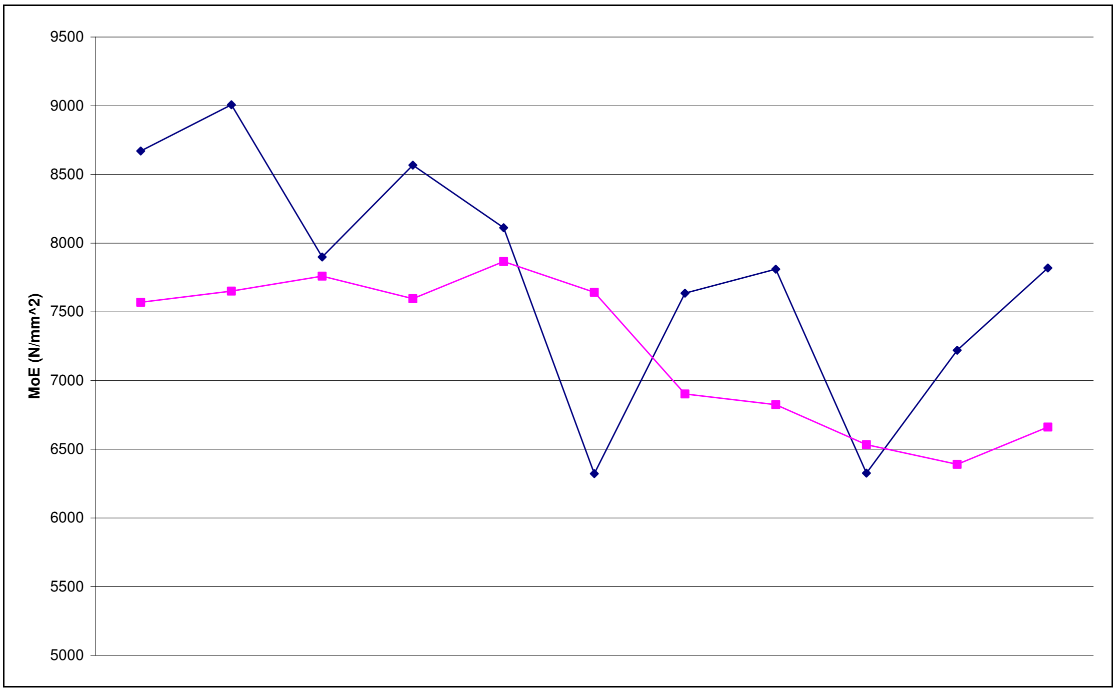


Figure 5.6 graphically illustrates the relationship between the observed and calculated values for MOE in the test timbers. In this batch of results all but 2 of the observed values fall outside the standard deviation range of the calculated values. For the higher of the two results, there is no adequate explanation, except that the timber joist had been in good condition at recovery and had little ‘in service’ damage. The lower result of these two anomalies had substantial nail damage to both narrow edges of the joist.

While these, very limited, test figures show the analysis and associated model expression to be sound and performing within calculated parameters, more wide ranging future testing will be required to prove the method.

6 Conclusions and areas of further work

The objective of this research was to establish a process of visually grading reclaimed timber so that it could be directly used in future construction work. It achieved this by first investigating the current state of the art in timber grading; considering the rules, equipment and expertise that are employed by the timber supply industry. The research next considered the mechanism by which the current grading system could be adapted or modified to produce an alternate visual grading, accounting for the special characteristics of reclaimed timber. This research also carried out basic grading tests on reclaimed timber joists and small clear specimens to prove previous assumptions and to, by analysis, generate a model expression to estimate by calculation the modulus of elasticity (MOE) of a timber joist. Finally, the methodology procedure generated a visual grading process and a model expression to examine reclaimed timber joists and calculate their expected MOE, without the need to identify the timber species.

The research produced an alternate visual timber grading process, allowing an operative to take into account damage caused by ‘in service’ conditions and damage caused during the recovery process. The examination and calculation method generated through this research can be carried out on site on reclaimed timber recovered from demolition. To accomplish this it was necessary to change the way in which reclaimed timber is viewed; the following sections illustrate the changes made through the application of this research.

6.1 Modified visual grading

The research produced a modified visual grading method, involving a follow through process by which faults and damage are identified in reclaimed timbers. This lead to a ‘keep or reject’ end decision, filtering out potentially unusable timbers. In practice this step filtered out around 40% of timbers during the visual grading phase; however, this figure was severely dependent on the care which was taken by demolition site operatives during the deconstruction process. At certain sites the failure rate caused by recovery damage in the visual grading examination was as high as 60%.

6.1.1 Produce a grading system that is independent of timber species

The introduction of Eurocode 5 means that timber can be graded directly to a strength grade, without considering the timber species, requiring that timber for construction can be sought on the basis of the MOE and calculated strength, as an alternative to species and strength grade. The introduction of an alternate facility to satisfy the requirements Eurocodes is likely to have an important impact on how reclaimed timber is sourced and processed for construction operations.

6.1.2 Set up a testing model for large timber joists

The mean bending strength of reclaimed timbers (MOR) was found to be about 20% lower than the control data for the virgin timbers of the same density. However, nail holes possibly caused a skewing of the comparison. Nail holes reduced the MOR only when closely spaced, were near to the loading point or if they had created further splitting, especially at the tension edge. This is typically exhibited in results where the MOE is low, but the timber is from older stock and narrowly passed visual grading.

The number of reclaimed timbers which progressed to bending tests and still showed damage was small; suggesting that the grading rules applied by this research may be too conservative. However, in the interests of facilitating a safety margin, no changes are anticipated to the visual grade. Reclaimed timber failing at points of damage, such as holes, notches and areas of extensive nail damage (which passed the visual examination) frequently exhibited higher MOE results than virgin timbers which consequently failed through the presence of knots.

6.1.3 Set up a testing model for small clear timber tests

Results of mean MOR in the small clear tests were essentially as expected; there was an expected reduction in MOE and the timber specimens were far more brittle. However, these were within expectations for older timbers, in relation to results of small clear tests from historical data, namely, the Strength properties of timber (BRE, 1974). While there was a drop in MOE in the small clear tests this was not enough to affect the potential strength grade; though it is clear that they would have fallen closer to the lower reaches of the strength class.

The small clear tests offer strength ratings which can be applied, to the larger timber joists from which they were cut. However, the issue of damage to the timber joist, the time taken in conducting small clear tests and the need for specialist equipment means that they are unsuitable for further use beyond establishing a comparative data set to serve as an initial test of the model expression and as a correlation of the tests carried out on the structural joists.

6.1.4 Calculate the density of reclaimed timber joists

Density calculation proved to be an important part of the model equation, and a general indicator of the quality and moisture content of the reclaimed timber; in extremes it also offered an indication of the timber species. This research has shown that timber recovered during demolition operations is, under most circumstances, of low moisture content and high quality, regardless of age.

Density in reclaimed timber joists essentially offers a facility for the estimation of the MOE of the material, and hence its strength.

6.1.5 Calculate the tree ring frequency in reclaimed timber joists

Calculating, or counting, the ring frequency (per cm) in reclaimed timber joists offered a method estimating the strength of the joist based on its age and cell structure at the time that the tree was felled. A greater count of tree rings signifies older timber containing more mature heartwood, which is known to exhibit greater mechanical properties than younger wood. Mature wood also has greater constituent properties against crush (compression) and tension.

Slow growing trees, often associated with older, more traditional types of culture and construction, have a greater tree ring frequency than timber from trees felled for modern construction, where they are fast grown, containing fewer tree rings and a more open cell structure. Older timbers, because of their cell structure, retain an amount of their original, higher strength when compared to modern timbers. This feature makes them worthy of reclamation and reuse as structural members.

6.1.6 Analyse the test results and formulate a model expression

Using the results from visual, large structural tests and small clear testing, this research has formulated a model expression to calculate the MOE to estimate the strength grade class for reclaimed timber joists from demolition operations. The model expression is built up from analysis of the relationship between the density and the frequency of tree rings in each reclaimed timber specimen.

The inclusion of ‘age of timber sample’ data has proven to be ambiguous and difficult to manage. Even considering the date of construction of the building, useful data is difficult to capture; timber felling may predate construction by as much as a decade on older sites. Furthermore, the duration of load approximation, even if applied to the analysis, offers no greater accuracy in the final expression.

However, even in the face of this omission, the expression still gives an accurate approximation of the timber joist MOE, which for general building and construction, where the joist is part of a multiple element structure, will suffice.

In analysing the data from the visual grading and machine simulation tests, it has become plain that a larger set of test data may have given a different analysis results. The model expression generated here, however, is suited to all ages of reclaimed timber, failing no more than is necessary, making it the most effective when utilised in conjunction with the alternate visual grade, also developed as part of this research.

In testing the model expression and visual grade method, the volume of test data used to make the model calculation could come into question. To be totally certain of the validity of the research, further research and larger scale timber joist testing against the model expression would need to be carried out.

6.2 Concluding statements

This research has enhanced the viability of reclaiming timber joists from demolition and regrading them for further use, by producing a cost efficient methodology for visual grading that can be easily carried out at the recovery site. This adds considerably to the reuse potential of timber elements reclaimed from demolition operations.

It is important to emphasize that the conclusions drawn here are restricted to the experimental data and limited testing of the model expression, represented in the research results and analysis.

This project has looked at several characteristics of reclaimed timber and, considering them together, generated a model expression and visual grading methodology to process these materials for structural reuse in construction. These are:

- **Tree ring frequency -** The effect that the average number of growth rings has on the modulus of elasticity is relevant, especially when considered in conjunction with density. On its own tree ring frequency can give an indication of the approximate strength of the timber, though this can only be an accurate estimation when coupled with the material density.
- **Density -** The effect of density on reclaimed timber joists has a direct relationship to their strength at standard temperature and pressure, and constant moisture content. A high density joist will be of greater strength than a low density one. This relationship appears to be proportional in the data used for this research, within the limits of reclaimed timber densities of around 350kg/m^3 up to 710kg/m^3.

The visual grading system generated as a product of this research can be used to examine all forms of reclaimed softwood timber, but is aimed specifically at structural joists, processing them into either a pass or fail result. Passed timber joists can be assessed against the model expression to generate an estimate of their MOE.

Failed joists have suffered too much damage during their working life to be of any further structural use; there is also the possibility of their total collapse if overloaded. While a virgin timber joist will break or crack and still carry a reduced load, many older reclaimed timbers exhibit a tendency towards total collapse when the rupture point is reached, supporting no load thereafter.

The model expression generated through this research can be utilised to estimate the MOE, and hence the strength, of timber joists that have first been visually examined.

This research began in the belief that there would soon have been a regulatory call to directly reuse, without further processing, more timber recovered from demolition operations. While this has not been the case directly, the introduction of the Eurocodes in the UK, and Site Waste Management Plans (SWMPs) have gone part of the way on this in suggesting that material strength is a major consideration and making mandatory recovery of construction materials from demolition for reuse on site. The results of this research indicate that there are no technical barriers to establishing a regrading rule for reclaimed timbers, and that this would help immensely in more precise assignment of timbers from demolition than is currently possible.

6.3 Recommendations

This research suggests that timber reclaimed from demolition is a viable and needed commodity that can be structurally reused effectively. The recommendations from this research are a natural next step, and their implementation could considerably add to the reuse potential of reclaimed timber from demolition:

- Reclaimed timber joists should be graded, by whatever means, and reused for construction purposes.
- Grading rules, and architects' and design practices, should formally recognize reclaimed timber as a suitable and environmentally efficient construction material and provide guidance regarding appropriate reuse.
- In line with the requirements of Eurocode 5, designers and architects should consider using reclaimed timber based on 'limit state' theory, selecting reclaimed timber for its mechanical properties
- Designers and architects should recognize the impracticality of identifying the exact species of each piece of reused timber, and accommodate some degree of species mixing.
- The visual grading method and model expression produced as part of this research could be adopted as a 'rule of thumb' or good site practice for the reclamation of timber from demolition.
- In reusing timber, edges should be marked such that regular edge-nail holes are placed in the compression zone, or away from the highest tension zone in design.

In recommending these points consideration must also be given to the legislative aspects of reclamation. These recommendations will only be seriously considered when there is a regulatory call to use reclaimed materials, such as timber, in new construction. Therefore, the next step is up to government, to make a regulatory call for the reuse of demolition materials, especially timber.

6.4 Areas of further work

This research has discussed the production of an iPhone/Android phone application to photograph tree ring structures and count the frequency of rings. This application is at present only in the discussion stage; however, a prototype which can count tree rings from scanned images is at the beta stage. A complete working version is envisaged that will count tree rings from a photograph, taken by the device’s camera; then calculate the estimated MOE and MOR from other values input by the site operative, giving an immediate result.

A further use of this application is the possibilities for Dendrochronology in an application that can count tree rings from a photograph, then compare them to an online database of past images, mapping them over one another.

An evaluation of this system for grading timbers insitu would be a logical extension of this research. This would involve measuring the timber joist density insitu, probably by electronic methods or by physical sampling. Also, using the two model calculations together could result in a further process of being able to estimate the age of timbers reclaimed from demolition, by rearranging the calculations.

Further ongoing testing of the model and rerunning the multiple regression statistics should tighten the model, as greater amounts of information feed into the original research data set. It is unclear at this time what effect a larger data set will have on the regressions and model calculations, though it is expected that the model calculation will reach a limit state, where further data will not affect its outcome. However, these facets of the research will require further investigation.

7 Publications arising from the research

1. Re-use of by products and materials in the construction industry

This research work will inform a book chapter in Reuse of materials and byproducts in construction: Waste minimization and recycling (Richardson, 2013). This book addresses the use of waste and by products in the construction industry. The specialist author contributions cover many areas associated with sustainable construction aiming to encourage best practice. This research will contribute to Chapter 5 - Use of recycled and reclaimed timbers, and will discuss:

- Development of modern timber construction
- Reuse of timber in construction
- Timber as a reusable material
- Effect of processing on the reuse of timber
- Future challenges to timber reuse

2. Visual strength-grading and estimation of strength in reclaimed timbers

This paper was submitted to the International Wood Products Journal, in August 2012. The paper discusses the reuse potential of reclaimed timbers, through the use of visual strength-grading coupled with the use of a model expression. The aim of the paper is to highlight the difficulties and shortcomings that can occur in the assessment of reclaimed timber joists from demolition. The paper also gives some indications about the effectiveness of the grading criteria applied to reclaimed timbers and the level of accuracy to be expected from the model expression.

3. Investigation into the physical properties of reclaimed timber joists, to generate a simplified method of regrading for construction

This paper was presented to the World Conference on Timber Engineering 2010, Trentino, Italy, in June 2010. The paper investigates how the previous structural use of timber may affect its properties in terms of being fit for purpose for re-use as building elements. The paper also suggests that the number of growth rings in a piece of timber has an effect on the modulus of elasticity, and that this characteristic can serve as a good predictor of timber strength.

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Appendix 1 – test data

Control data

The control data for his research was generated from materials procured, off the shelf, from a leading builder's merchant chain.

Table A.1 Control data

Index No.	Breadth (mm)	Depth (mm)	Rings per cm	MoE (N/mm^2)	Density (kg/m^3)	Calculated MOR (kN/mm^2)
1001	75	150	4.5	7550.5	455	15.6
1002	75	150	3	7294.6	456	15.1
1004	70	175	2.5	4471.9	458	9.2
1006	60	150	3.5	5736.7	469	11.8
1007	45	145	5	5270.5	433	10.9
1010	45	170	4	5901.7	490	12.2
1012	45	145	7	7597.1	459	15.7
1013	60	170	4.8	5506.2	470	11.4
1014	60	170	3.2	6485.1	460	13.4
1015	75	145	2.8	6528.8	475	13.5
1016	75	145	206	6528.8	455	13.5
1017	75	145	3	6528.8	465	13.5
1018	60	170	3.2	4732.1	490	9.8
1019	60	170	2.8	4684.5	465	9.7
1020	70	175	2.8	4471.9	462	9.2
1021	65	170	4	5105.7	462	10.5
1022	65	200	3	4063.8	450	8.4
1003	75	150	2.4	7551.8	470	15.6
1178	54	155	5.2	7315.4	473	15.1
1179	54	155	4.4	7306.7	484	15.1

Test data

Timbers for testing were procured from demolition sites and building contractors throughout the North of England. Careful measurements were taken of density, tree ring frequency, and the probable age of each of the specimens. Each timber beam was tested on a 3 point bending test rig; measuring the modulus of elasticity. Small clear specimens were tested to destruction, establishing the modulus of rupture; these figures are only applicable to some of the structural beams and are in blue text.

In the test data table (following pages) commercial premises are shops and small offices, and industrial premises refer specifically to factories.

Table A.2 Test data

Index No	Breadth	Depth	Date	Density	MoE	Rings per cm	MOR	SCT-MoR	SCT-MoE	Building type
1005	40	165	1910	552	7920.2	4.2	16.4	16.7	8080	Domestic dwelling - North Shields NE29
1009	45	175	1925	540	8086.1	3.4	16.7			Domestic dwelling – Wallsend NE28
1023	70	200	1965	401	5444.1	3.6	11.2	18.3	5699.3	Commercial premises – Cullercoats NE25
1024	65	175	1935	620	6322	4.8	13.1			Industrial premises – Newcastle NE1
1025	65	170	1910	670	8679.9	4.6	17.9			Domestic dwelling - North Shields NE29
1026	80	225	1910	669	3609.3	8.6	7.5			Domestic dwelling - North Shields NE29
1027	60	175	1935	584	6336.1	6.4	13.1			Industrial premises – Newcastle NE1
1028	55	130	1920	495	5279.8	4	10.9			Domestic dwelling – Low Walker NE6
1029	55	130	1920	510	5216.1	7.2	10.8			Domestic dwelling – Low Walker NE6
1030	55	130	1920	540	7094.6	6	14.7			Domestic dwelling – Low Walker NE6
1031	50	170	1920	390	5470.2	7.6	11.3			Domestic dwelling – Low Walker NE6
1032	50	170	1940	474	5651.8	3.6	11.7	42.5	5350.8	Domestic dwelling – Low Walker NE6
1033	50	170	1940	511	5817.9	3.2	12.0			Domestic dwelling – Newcastle west NE4
1034	50	170	1940	529	5738.1	3.6	11.8	27.8	5602.3	Domestic dwelling – Newcastle west NE4
1035	45	125	1940	579	8516.2	6.8	17.6			Domestic dwelling – Newcastle west NE4
1036	45	125	1940	470	8337.7	6.4	17.2	19.3	5145	Domestic dwelling – Newcastle west NE4
1037	45	125	1940	696	9801.9	12	20.2	29.6	11433	Domestic dwelling – Newcastle west NE4
1038	45	125	1940	580	7475.6	6	15.4	19.3	6966	Domestic dwelling – Newcastle west NE4
1039	45	125	1940	527	6640.3	5.6	13.7			Domestic dwelling – Newcastle west NE4
1040	50	180	1925	585	5410.3	2.6	11.2			Commercial premises – Gateshead NE9
1041	50	180	1925	604	8195.4	4.4	16.9			Commercial premises – Gateshead NE9
1042	55	150	1930	610	7809.1	3.6	16.1			Commercial premises – Durham DH4
1043	54	155	1930	601	9387.9	4.8	19.4			Commercial premises – Durham DH4
1044	64	165	1930	660	9840.5	5.6	20.3	35.1	9489.6	Commercial premises – Durham DH4
1045	54	155	1910	610	7610.5	4.2	15.7			Commercial premises – Ashington NE63
1046	64	165	1930	590	6580.1	7.2	13.6	19.9	6502	Domestic dwelling – Sunderland SR1
1047	54	155	1930	489	6393.9	2.2	13.2			Domestic dwelling – Sunderland SR1

Index No	Breadth	Depth	Date	Density	MoE	Rings per cm	MOR	SCT-MoR	SCT-MoE	Building type
1048	54	155	1930	510	6507.1	6	13.4	20.9	6379	Domestic dwelling – Sunderland SR1
1049	54	155	1930	589	6574.8	6.4	13.6			Domestic dwelling – Sunderland SR1
1050	54	155	1930	621	5788.9	5.6	12.0			Domestic dwelling – Sunderland SR1
1051	54	155	1930	581	6243	6.4	12.9			Domestic dwelling – Sunderland SR1
1052	64	165	1930	640	9416.6	6.8	19.4	30.9	9947	Commercial premises – Newcastle NE1
1053	64	165	1930	595	7710.8	6	15.9			Commercial premises – Newcastle NE1
1054	54	165	1930	551	6419.9	6.4	13.3			Commercial premises – Newcastle NE1
1055	54	165	1930	596	8422.9	6.4	17.4			Commercial premises – Newcastle NE1
1056	54	165	1930	588	7908.6	6.8	16.3			Commercial premises – Newcastle NE1
1057	54	145	1930	597	7901.2	7.2	16.3			Domestic dwelling – Manchester M28
1058	54	145	1930	560	7667.9	6.4	15.8	14.1	5316	Domestic dwelling – Manchester M28
1059	64	165	1930	601	9041.9	7.2	18.7			Domestic dwelling – Newcastle NE4
1060	64	165	1930	621	8000.3	6.8	16.5			Domestic dwelling – Newcastle NE4
1061	64	165	1930	583	7187.5	4.8	14.8			Domestic dwelling – Newcastle NE4
1062	64	165	1930	530	6501.3	8.8	13.4	17.8	6147	Domestic dwelling – Newcastle NE4
1063	64	165	1930	580	6366.9	7.6	13.1	16.7	6174	Domestic dwelling – Newcastle NE4
1064	64	165	1930	501	6262.2	4.8	12.9			Domestic dwelling – Newcastle NE4
1065	64	165	1930	661	11074.6	17.2	22.9	26.8	10967	Domestic dwelling – Newcastle NE3
1066	64	165	1930	598	10255.3	14	21.2	15.1	6259.7	Domestic dwelling – Newcastle NE3
1067	65	165	1935	562	10119.6	14.4	20.9	13.8	5745	Domestic dwelling – Newcastle NE3
1068	65	165	1935	590	7796.1	7.6	16.1			Domestic dwelling – Newcastle NE3
1069	65	165	1935	505	7187.5	6	14.8			Domestic dwelling – Newcastle NE3
1070	65	165	1935	590	7310.2	6.4	15.1	20.4	6175	Domestic dwelling – Newcastle NE3
1071	54	155	1930	511	5610.6	5.6	11.6			Commercial premises – Blyth NE24
1072	54	155	1930	520	5565.1	4.8	11.5	20.9	6088	Commercial premises – Blyth NE24
1073	45	155	1910	510	7706.4	13.2	15.9			Commercial premises – Wallsend NE28
1074	45	155	1910	552	7477.9	13.2	15.4			Commercial premises – Wallsend NE28
1081	55	155	1910	416	8060.7	14	16.6	16.2	6517	Commercial premises – Wallsend NE28
1082	64	150	1930	598	8492	7.2	17.5			Industrial premises – Wardley NE10

Index No	Breadth	Depth	Date	Density	MoE	Rings per cm	MOR	SCT-MoR	SCT-MoE	Building type
1083	64	165	1930	705	8945.6	7.6	18.5	31.5	12005	Industrial premises – Wardley NE10
1084	64	165	1930	715	8893.5	7.2	18.4			Industrial premises – Wardley NE10
1087	54	155	1930	469	6419.6	4.8	13.3	11	5625.2	Industrial premises – Wardley NE10
1088	54	155	1930	563	6508.7	11	13.4			Industrial premises – Wardley NE10
1089	45	155	1920	512	7338.7	8.4	15.2			Domestic dwelling – Corbridge NE45
1090	45	155	1920	522	7344.2	9.2	15.2	19.3	6764	Domestic dwelling – Corbridge NE45
1091	50	125	1920	456	7419.6	10	15.3	19.3	6448.8	Domestic dwelling – Corbridge NE45
1092	50	125	1920	468	7428.5	6.4	15.3	16.2	5899.6	Domestic dwelling – Corbridge NE45
1093	45	125	1925	552	8211.4	6.2	17.0			Domestic dwelling – South Shields NE33
1094	50	125	1972	399	5022.3	3.2	10.4	19.4	5806.6	School - North Shields NE29
1095	50	170	1950	406	5315	3.6	11.0			School – Whitley Bay NE26
1096	50	170	1950	412	5310.3	3.2	11.0			School – Whitley Bay NE26
1097	50	170	1950	488	5589.3	3.2	11.5	13.6	5659.1	School – Whitley Bay NE26
1098	50	170	1950	467	5137.2	3.2	10.6	8.8	4554.7	School – Whitley Bay NE26
1099	50	175	1950	522	4993.9	2.8	10.3	9.4	4802.5	School – Whitley Bay NE26
1100	50	175	1950	501	5134.1	2.6	10.6			School – Whitley Bay NE26
1101	65	180	1925	553	7210.3	4.4	14.9			Domestic dwelling – South Shields NE33
1102	65	180	1925	561	7204.1	6	14.9			Domestic dwelling – South Shields NE33
1103	65	180	1925	573	7322.6	7.2	15.1			Domestic dwelling – South Shields NE33
1104	45	125	1930	612	8728.2	10.4	18.0			Domestic dwelling – Shiremoor NE27
1105	45	125	1930	620	8735.8	10	18.0			Domestic dwelling – Shiremoor NE27
1106	50	125	1935	563	7420.5	5.6	15.3			Domestic dwelling – Wallsend NE28
1107	50	125	1935	551	7445.3	6	15.4			Domestic dwelling – Wallsend NE28
1108	50	125	1935	523	7557.2	7.2	15.6			Domestic dwelling – Wallsend NE28
1109	50	125	1935	536	7638.5	6.4	15.8			Domestic dwelling – Wallsend NE28
1110	75	175	1910	711	8931.9	13.6	18.4	26.7	9032	Domestic dwelling – North Shields NE29
1111	64	165	1930	706	8802.1	11.2	18.2	34	8944	Industrial premises – Blyth NE24
1112	54	165	1935	706	7771.3	10	16.0	27.9	9114	Industrial premises – Boldon NE35
1113	54	165	1935	687	7782.9	9.2	16.1			Industrial premises – Boldon NE35

Index No	Breadth	Depth	Date	Density	MoE	Rings per cm	MOR	SCT-MoR	SCT-MoE	Building type
1114	54	165	1935	685	7817.6	10	16.1			Industrial premises – Boldon NE35
1115	54	145	1930	652	7762.4	4	16.0			Industrial premises – Blyth NE24
1116	54	145	1930	673	7749	6	16.0			Industrial premises – Blyth NE24
1117	64	165	1935	719	8932.7	10.4	18.4	38.3	12040	Domestic dwelling – Seaham SR7
1118	64	165	1935	713	8987.1	12	18.6	31.9	12110	Domestic dwelling – Seaham SR7
1119	64	165	1935	702	8900.4	10.2	18.4	25.18	8575	Domestic dwelling – Seaham SR7
1120	64	165	1935	697	8787.1	12.4	18.1			Domestic dwelling – Seaham SR7
1121	64	165	1935	692	8911.2	10.8	18.4			Domestic dwelling – Seaham SR7
1122	64	165	1935	721	9305.7	13.2	19.2			Domestic dwelling – Seaham SR7
1123	64	165	1935	704	8731.2	10.4	18.0			Domestic dwelling – Seaham SR7
1124	64	165	1935	672	8443	11.2	17.4			Domestic dwelling – Seaham SR7
1125	65	165	1935	601	7665.9	5.8	15.8			Domestic dwelling – Seaham SR7
1126	65	165	1935	608	7671.6	5.4	15.8			Domestic dwelling – Seaham SR7
1127	65	165	1935	612	7626.6	6.8	15.7			Domestic dwelling – Seaham SR7
1128	65	165	1935	576	7670.5	6	15.8			Domestic dwelling – Seaham SR7
1129	54	155	1930	669	7590.5	5.6	15.7			Domestic dwelling – Longbenton NE12
1130	45	155	1910	596	7590.9	14.4	15.7			Domestic dwelling – North Shields NE29
1130	54	155	1930	689	7676.7	5.6	15.9			Domestic dwelling – Longbenton NE12
1131	45	155	1910	589	7677.3	14	15.9			Domestic dwelling – North Shields NE29
1138	55	155	1910	726	8067	14.4	16.7	25.6	9604	Domestic dwelling – North Shields NE29
1139	64	150	1930	613	8148.5	8.4	16.8			Domestic dwelling – Longbenton NE12
1140	64	165	1930	609	8270.3	8	17.1			Domestic dwelling – Longbenton NE12
1141	64	165	1930	611	8313.7	7.2	17.2			Domestic dwelling – Longbenton NE12
1144	54	155	1930	676	7637.1	6.4	15.8			Domestic dwelling – Longbenton NE12
1145	54	155	1930	654	7640.7	6	15.8			Domestic dwelling – Longbenton NE12
1146	45	155	1920	587	7576	7.2	15.6			Domestic dwelling – South Shields NE33
1147	45	155	1920	587	7612.1	6	15.7			Domestic dwelling – South Shields NE33
1148	50	125	1920	589	7949	6.4	16.4			Domestic dwelling – South Shields NE33
1149	50	125	1920	577	7943.6	6	16.4			Domestic dwelling – South Shields NE33

Index No	Breadth	Depth	Date	Density	MoE	Rings per cm	MOR	SCT-MoR	SCT-MoE	Building type
1150	45	125	1925	612	8807	5.6	18.2	21.2	8820	Domestic dwelling – South Shields NE33
1151	50	125	1950	463	6087.8	3.6	12.6	20.9	4459.3	Domestic dwelling – Cramlington NE23
1152	50	170	1950	479	5868.9	8.8	12.1	27.2	5639.9	Domestic dwelling – Cramlington NE23
1153	50	170	1972	488	4726.9	2.4	9.8	10.5	5233.7	School – Whitley Bay NE25
1154	50	170	1972	536	4998.9	2.4	10.3			School – Whitley Bay NE25
1155	50	170	1950	425	5136.8	2.4	10.6	25.4	5076.4	Industrial premises – Cramlington NE23
1156	50	175	1950	398	5143.7	2.8	10.6			Industrial premises – Cramlington NE23
1157	50	175	1950	423	5265.2	2.8	10.9	22	5923.5	Industrial premises – Cramlington NE23
1158	65	180	1925	496	7582.9	6.6	15.7	26.7	7888.8	Commercial premises – Gateshead NE11
1159	65	180	1925	503	7609.1	8	15.7	21.2	7821	Commercial premises – Gateshead NE11
1160	65	180	1925	539	7598.3	7.4	15.7			Commercial premises – Gateshead NE11
1161	45	125	1930	623	8410.3	8.8	17.4			Domestic dwelling – Longbenton NE12
1162	45	125	1930	619	8343.4	8	17.2			Domestic dwelling – Longbenton NE12
1163	75	150	1930	491	6831.5	5.2	14.1	17.7	6105.5	Domestic dwelling – Longbenton NE12
1164	45	125	1930	615	8379.6	9.2	17.3			Domestic dwelling – Longbenton NE12
1165	75	150	1910	561	7748.2	13.6	16.0			Domestic dwelling – North Shields NE29
1167	75	150	1910	568	7786.2	13.2	16.1			Domestic dwelling – North Shields NE29
1168	75	150	1910	549	7771.3	14	16.0			Domestic dwelling – North Shields NE29
1169	75	150	1910	526	7490.7	14	15.5			Domestic dwelling – North Shields NE29
1169a	45	125	1955	502	7376	4.8	15.2			School – Shiremoor NE27
1170	55	155	1910	706	8078.7	14.8	16.7	29.8	9375	Domestic dwelling – North Shields NE29
1170a	45	125	1955	521	7286.9	6	15.0	28.3	7759.6	School – Shiremoor NE27
1171	64	150	1910	595	8071.8	15.6	16.7			Domestic dwelling – North Shields NE29
1171a	65	162	1935	520	6451.2	5.2	13.3	20.3	6275	Domestic dwelling – Consett DH8
1172	64	165	1910	591	7869.7	14.4	16.3			Domestic dwelling – North Shields NE29
1173	64	165	1910	683	9048.1	16.4	18.7	27.5	8918	Domestic dwelling – North Shields NE29
1174	45	155	1910	588	7720.1	15.2	15.9			Domestic dwelling – North Shields NE29
1175	45	155	1910	652	8214	14.4	17.0			Domestic dwelling – North Shields NE29
1176	50	180	1900	705	8661.2	7.6	17.9	22.5	8686	Domestic dwelling – Tynemouth NE30

Index No	Breadth	Depth	Date	Density	MoE	Rings per cm	MOR	SCT-MoR	SCT-MoE	Building type
1176	65	165	1955	464	5158.9	4	10.7	26.2	6201.5	School – Shiremoor NE27
1177	50	180	1900	712	8902.1	6	18.4	25.6	8575	Domestic dwelling – Tynemouth NE30
1177a	65	165	1955	459	5042.1	6.8	10.4	21.4	5530.5	School – Shiremoor NE27
1178	62	162	1870	521	6548.1	16.4	13.5			Domestic dwelling – Tynemouth NE30
1179	62	162	1870	566	8186.1	14.8	16.9			Domestic dwelling – Tynemouth NE30
1180	65	162	1870	545	8670.4	13.6	17.9			Domestic dwelling – Tynemouth NE30
1181	65	162	1870	544	7585.3	11.2	15.7			Domestic dwelling – Tynemouth NE30
1181a	70	200	1925	503	6241.9	7	12.9			
1182	65	162	1870	456	6149.3	8.8	12.7			School - North Shields NE29
1182a	65	175	1950	435	5002.9	3.6	10.3			Commercial premises – Newcastle NE1
1183	65	162	1870	456	5088.8	8.4	10.5			School - North Shields NE29
1183a	65	170	1950	439	5010.2	3.2	10.3	25.6	5621.9	Commercial premises – Newcastle NE1
1184	62	162	1870	667	8534.8	13.2	17.6			School - North Shields NE29
1184a	65	170	1950	461	7628.6	4.4	15.8			Commercial premises – Newcastle NE1
1185	62	162	1870	658	8415.9	14	17.4			School - North Shields NE29
1185a	60	175	1965	389	5129.5	4.4	10.6			Commercial premises – Cullercoats NE25
1186	65	162	1870	581	8976.2	12.4	18.5			School - North Shields NE29
1186a	55	130	1925	698	7989.8	11.6	16.5	29.3	9604	Domestic dwelling – Newcastle NE4
1187	65	162	1870	679	8850.9	11.6	18.3	21.2	8115	School - North Shields NE29
1187a	55	130	1925	689	8094.7	12	16.7	31.9	9114	Domestic dwelling – Newcastle NE4
1188	65	162	1870	661	8804.4	13.6	18.2			School - North Shields NE29
1188a	55	130	1925	687	8121.6	10	16.8			Domestic dwelling – Newcastle NE4
1189	65	162	1870	673	8816.9	14	18.2	17.2	7310	School - North Shields NE29
1189a	50	170	1935	654	7340.8	6	15.2			Domestic dwelling – Consett DH8
1190	65	165	1864	712	10070.9	15.2	20.8			School - North Shields NE29
1190a	50	170	1935	662	7514.1	5.6	15.5			Domestic dwelling – Consett DH8
1191	65	165	1864	714	10056.4	13.6	20.8	29.3	9976	School – North Shields NE29
1191a	50	170	1935	671	7726.1	4.8	16.0	14.5	8233.6	Domestic dwelling – Consett DH8
1192	65	165	1864	588	7773.6	14	16.1			School - North Shields NE29

Index No	Breadth	Depth	Date	Density	MoE	Rings per cm	MOR	SCT-MoR	SCT-MoE	Building type
1192a	50	170	1935	621	7698.7	6	15.9			Domestic dwelling – Consett DH8
1193	65	165	1864	564	7779.2	14.4	16.1			School - North Shields NE29
1193a	45	125	1940	583	6043.4	4	12.5			Domestic dwelling – Wallsend NE28
1194	75	150	1910	530	7786.2	13.2	16.1			Domestic dwelling – Newcastle NE6
1194a	45	125	1947	494	5271.7	3.6	10.9	10.4	4527	Commercial premises – Wallsend NE28
1195	75	150	1910	540	7771.3	14	16.0			Domestic dwelling – Newcastle NE6
1195a	45	125	1940	499	5324.2	3.6	11.0	13.6	4939.6	Domestic dwelling – Wallsend NE28
1196	75	150	1910	510	7490.7	14	15.5			Domestic dwelling – Newcastle NE6
1196a	45	125	1940	497	5150.6	4.4	10.6			Domestic dwelling – Wallsend NE28
1197	55	155	1910	680	8078.7	14.8	16.7	22.5	9804	Domestic dwelling – Newcastle NE6
1197a	45	125	1940	544	5954.3	4	12.3	14.1	5213	Domestic dwelling – Wallsend NE28
1198	64	150	1910	580	8071.8	15.6	16.7			Domestic dwelling – Tynemouth NE30
1199	64	165	1910	590	7869.7	14.4	16.3			Domestic dwelling – Tynemouth NE30
1200	64	165	1910	670	9048.1	16.4	18.7	14.6	7743.7	Domestic dwelling – Tynemouth NE30
1200a	65	170	1972	433	4238.2	3.5	8.8	15.7	5022.2	School - Whitley Bay NE26
1201	45	155	1910	570	7720.1	15.2	15.9			Domestic dwelling – Tynemouth NE30
1202	45	155	1910	643	8214	14.4	17.0			Domestic dwelling – Tynemouth NE30
1203	50	180	1900	680	8661.2	7.6	17.9	26	9202	Domestic dwelling – Tynemouth NE30
1204	50	180	1900	690	8902.1	6	18.4			Domestic dwelling – Tynemouth NE30
1205	65	162	1870	521	6548.1	16.4	13.5			Domestic dwelling – North Shields NE29
1206	65	162	1870	566	8186.1	14.8	16.9			Domestic dwelling – North Shields NE29
1207	65	162	1870	545	8670.4	13.6	17.9			Domestic dwelling – North Shields NE29
1208	65	162	1870	544	7585.3	11.2	15.7			Domestic dwelling – North Shields NE29
1209	65	162	1870	456	6149.3	8.8	12.7			Domestic dwelling – North Shields NE29
1210	65	162	1870	456	8088.8	8.4	17.5			Domestic dwelling – North Shields NE29
1211	62	162	1880	650	8534.8	13.2	17.6			Domestic dwelling – Longbenton NE7
1212	62	162	1880	650	8415.9	14	17.4			Domestic dwelling – Longbenton NE7
1213	65	162	1880	601	8976.2	12.4	18.5			Domestic dwelling – Longbenton NE7