Building skills for conserving seventeenth- and eighteenth-century Scottish built heritage: the initial assessment of timber roof structures

Anna Serafini

A thesis presented in fulfilment of the requirements for the degree of Doctor of Philosophy

University of Strathclyde

Department of Architecture

Architectural Design and Conservation Research Unit

2019

Signed:

Date:

TABLE OF CONTENTS

VOLUME 1

List of Figures

List of Tables

Glossary

The need for a glossary stems from the fact that this thesis includes different subjects such as history of architecture, construction history, conservation, assessment and diagnosis of historic structures, wood technology and engineering: there are dictionaries addressing each of these subjects, but none of them includes all of the terms used in this work, even because some terms are specifically Scottish. Moreover, the definition of some terms remains controversial, as types of roof structures, elements and connections have different names in different countries, and even the terminology associated to different damage/failures types is not always clear for English-as-a-second-language speakers. Thereafter the need to define them graphically as well as verbally, as follows.

Arch brace	A curved brace, usually used in pairs to support a roof frame and give the effect of an arch (Ching, 2011, Harris, 2006) (Figure 1).

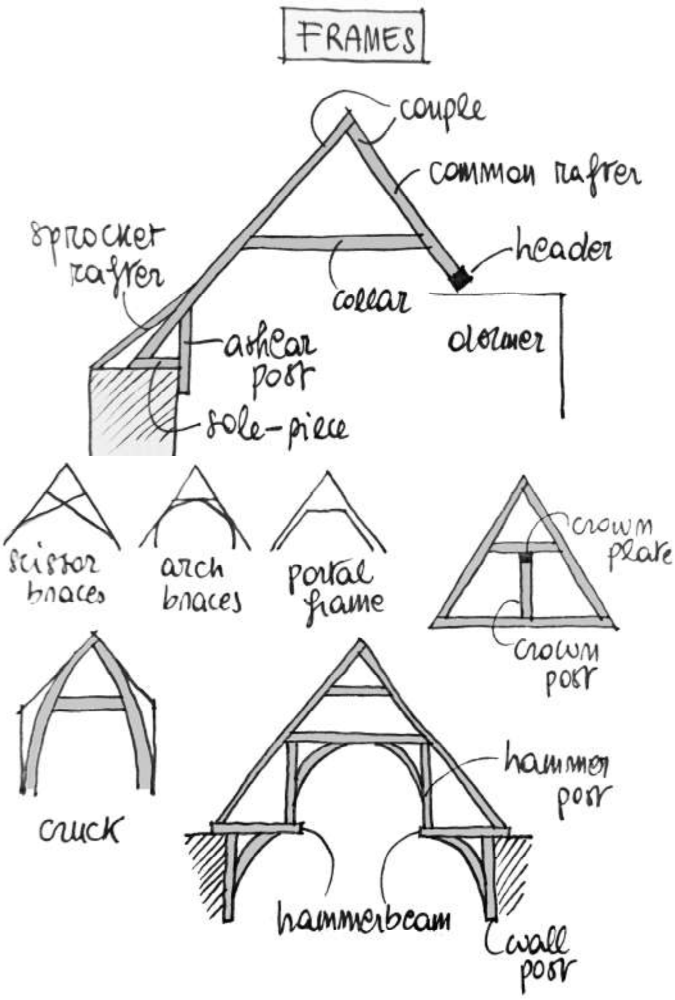


Figure 1: Elements composing a simple frame and other types of frames

Ashlar post ashlaring	In a traditional timber roof construction, a short post running from a wall plate to a principal rafter as part of ashlaring (Davies and Jokiniemi, 2012). In garrets, the short wood upright pieces between the floor beams and

ashlering	rafters, to which wall lath is attached (Harris, 1977). In Scottish roofs ashlar posts connect common rafters to sole pieces (Figure 1) or to tie-beams.
Batten	In roofing, a wood strip applied over boards or roof structural members; used as a base for the attachment of slate, wood, or clay-tile shingles (Harris, 2006) (Figure 2).

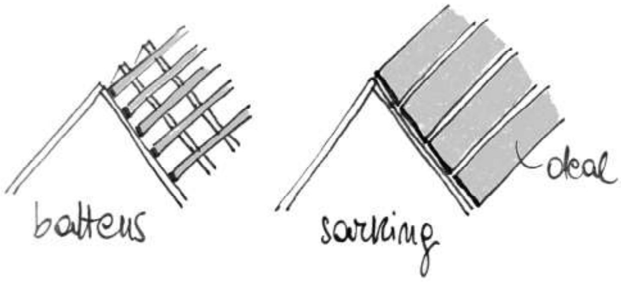


Figure 2: The difference between battens and sarking, and the elements composing the sarking

Balk baulk	A squared timber used in building construction (Harris, 2006).
Birdsmouth	A re-entrant angle at the end of a piece of timber to allow the end to sit astride the corner of a supporting timber (Corkhill, 1948) (Figure 3).
Brace	In frame structures, any structural element which stiffens and reinforces the angle between two members; a diagonal structural member, strut or rod providing rigidity to a frame; 'bracing' is any system of structural members designed to maintain the rigidity of a structure, frame, etc (Davies and Jokiniemi, 2008).
Bridle joint	Joint in which a slot is cut in the end of one member to fit over part of the adjoining member against which it abuts; usually used at the foot of a principal rafter or inclined strut (BS 6100, 1992). A joint similar to the stub mortice and tenon joint, but with the positions of the mortice and tenon reversed; it is often used for angles less than right angles (Corkhill, 1948) (Figure 3).
Butt-purlin tenon purlin tenoned purlin	In timber roof construction, a purlin that is tenoned into the side of principal rafters (Davies and Jokiniemi, 2008) (Figure 4).
Chamfer	The splayed surface formed when a corner is removed from an acute or right angle, usually at 45° (Davies and Jokiniemi, 2008) (Figure 3).
Chase mortice	Mortice that is extended in the length of the member in which it is formed, its depth tapering out to the surface, to enable the tenon of a framed member to be slid into position when the supporting member is already fixed (BS 6100, 1992). A mortice for a stub tenon with a chase so that the tenon can slide into position (Corkhill, 1948) (Figure 3).
Check	A longitudinal shake in wood that does not go through the whole of the cross-section, due to rapid and faulty seasoning (Corkhill, 1948). A small crack running parallel to the grain in wood and across the rings; usually caused by shrinkage during drying (Harris, 2006) (Figure 5).
Circular saw	A power-operated saw in the form of a circular steel blade with teeth along

buzz saw
mechanical saw

the perimeter (Harris, 2006) (Figure 6).

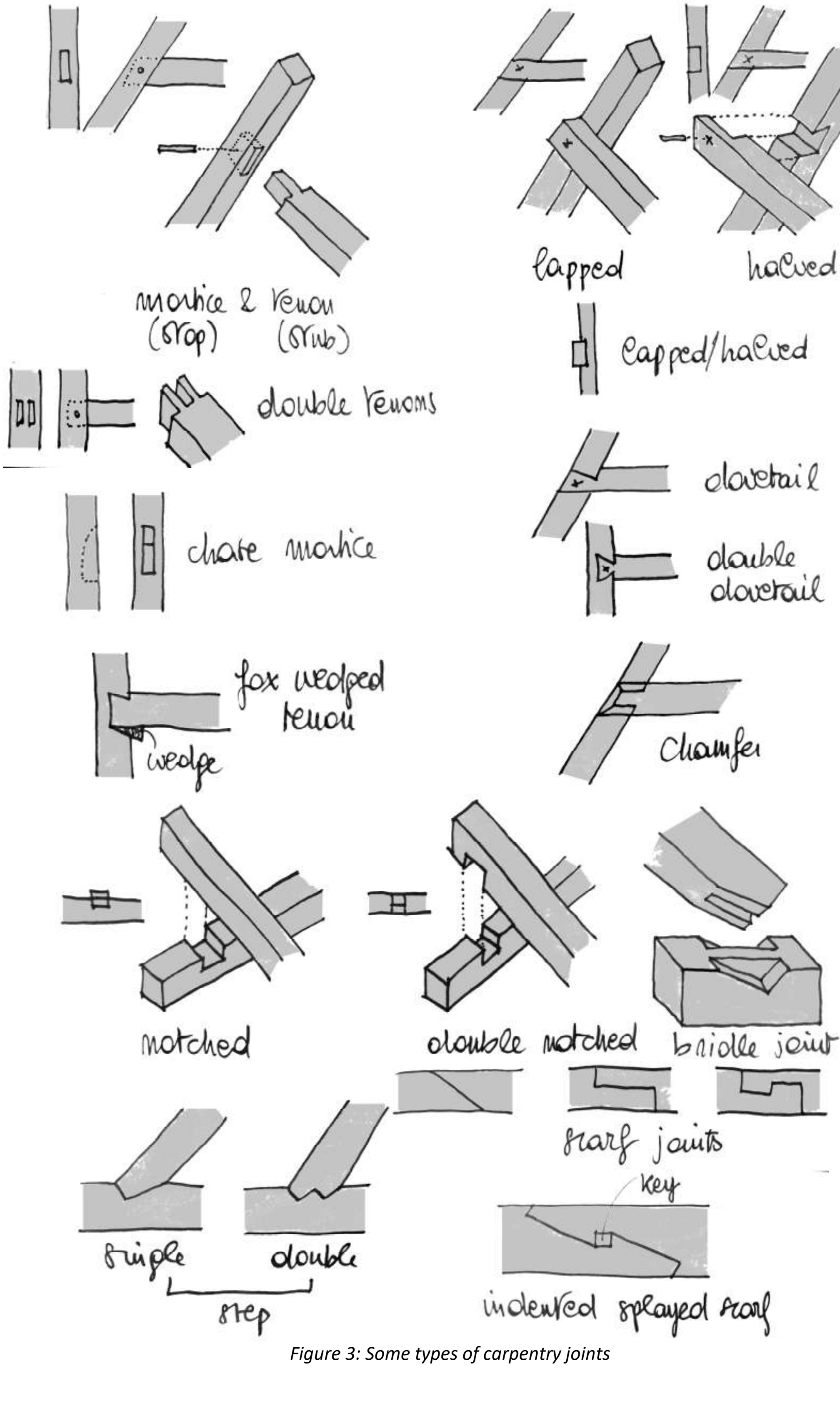


Figure 3: Some types of carpentry joints

Clasped purlin — Purlin carried directly by the collar and clasped between this and the principal rafter (Yeomans, 1992) (Figure 4).

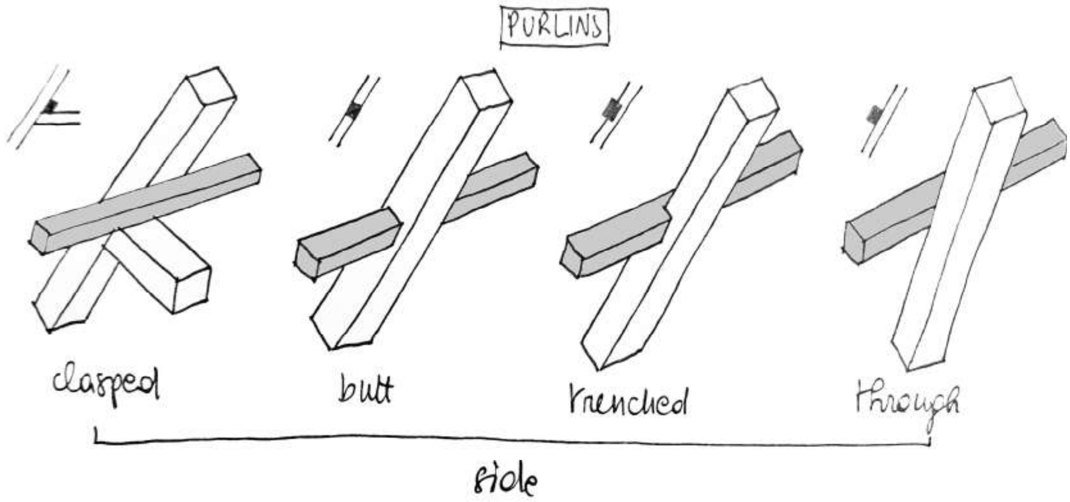


Figure 4: Different types of side purlins

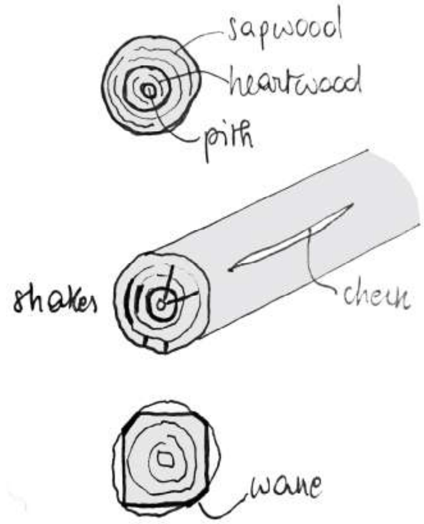


Figure 5: Main parts and defects of a timber log

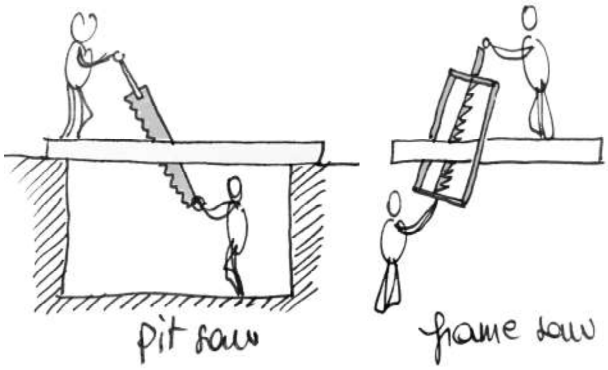


Figure 6: Types of hand saws used for wood

Cleat — A small block or strip of wood nailed on a member or on a surface; used to support a brace or to hold a member or object in place temporarily (Harris, 2006). A block receiving the thrust from an inclined member (Corkhill, 1948). In Scottish roofs it is used to reinforce joints of struts (Figure 7) and purlins.

Collar
collar-beam
spanpiece
sparpiece
top beam
wind beam — A horizontal member which ties together (and stiffens) two opposite common rafters, usually at a point about halfway up the rafters in a collar beam roof (Harris, 2006). The tie-beam of a roof truss when at a higher level than the feet of the rafters, or above wall-plate level (Corkhill, 1948) (Figure 1).

Common rafter
auxiliary rafter — One of a series of rafters of uniform size regularly spaced along the length of a pitched roof, or placed as intermediates between principals, with one end attached to the wall-plate and the other to the opposite common

cushion rafter — rafter at the ridge; a pair of common rafters is a couple (Stevens Curl, 2006) (Figure 8, Figure 1).

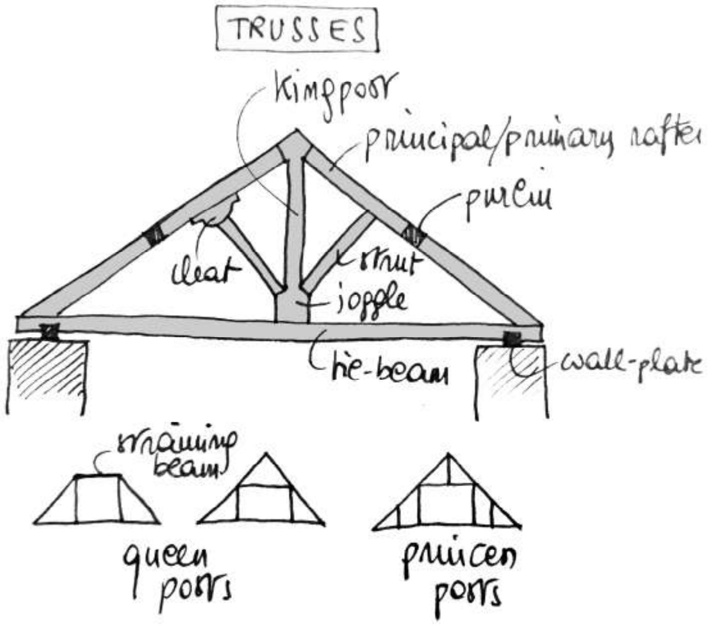


Figure 7: Elements composing a king-post truss and other types of trusses

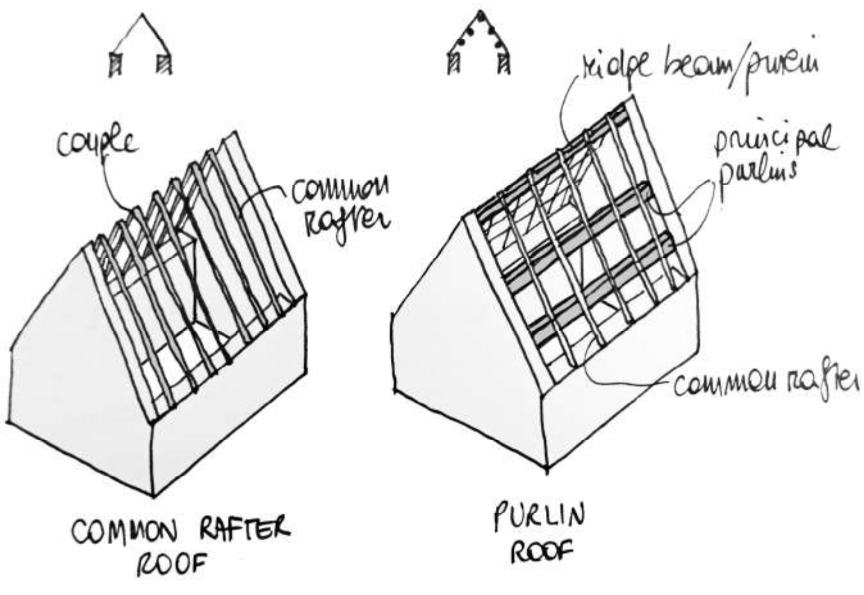


Figure 8: The difference between rafter roofs and purlin roofs and the elements composing them

Common rafter roof collar(-beam/-tie) roof common roof couple roof single roof	A roof of small span consisting of pairs of rafters or one formed of close couples (with tie-beam) or collar-beam rafters (Corkhill, 1948). A roof supported only by common rafters; principals, purlins, and roof trusses are not used (Harris, 2006). *Sparrendach* in German: a pair of *Sparren*, or rafters, are tightly joined at the apex, while their feet are fixed somehow against shifting (Lohrum and King, 2006) (Figure 8).
Conical roof	A roof in the shape of an inverted cone (Harris, 2006) (Figure 9).
Crown plate	Longitudinal timber in a crown-post roof, supported on crown-posts and

collar plate collar purlin	bearing the collars (Stevens Curl, 2006) (Figure 1).

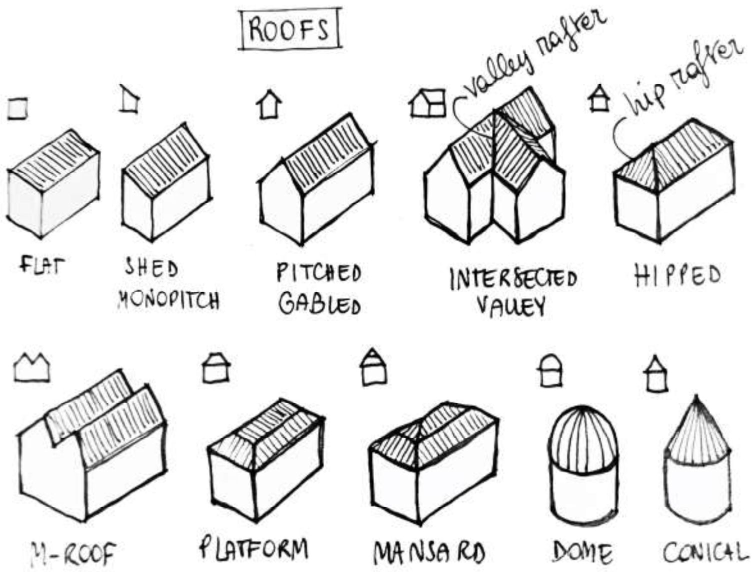


Figure 9: Different roof geometries

Crown post	The vertical member in a crown-post roof that spans from the tie beam to the crown plate, which in turn supports the collars (Gorse et al., 2013) (Figure 1).
Cruck	One of a pair of naturally curved timbers, forming one of several arched frames supporting the roof of an old English cottage or farm building (Ching, 2011).
Deal	Late variant of daill dele (deil, delle, deile, deyll, deale, deal); sawn plank (Robinson, 1999). A term applied to converted softwoods between 2 and 4 inches in thickness and 9 and 11 inches in width; the sizes vary at different ports (Corkhill, 1948). In Scotland deals were also used for the sarking (Figure 2); for different types and dimensions used in Scotland see Newland (2010).
Dome	Curved roof structure spherical in shape (Harris, 2006) (Figure 9).
Double notch joint	See *notched joint* (Figure 3).
Double tenons	Two tenons within the thickness of a member (BS 6100, 1992) (Figure 3).
Dovetail joint	Joint in which a projection is formed in a member so that when fitted into a recess of corresponding shape it will resist withdrawal by tension in the direction of its length (BS 6100, 1992) (Figure 3).
Dragon beam	A short, horizontal piece of timber which bisects the angle formed by the wall plate at the corner of a woodframe building; one end serves to receive and support the foot of a hip rafter, the other end is supported by a dragon tie (Harris, 2006) (Figure 10).
Dragon tie angle tie	An angle brace which supports one end of a dragon beam (Harris, 2006) (Figure 10).

Flat roof	A horizontal roof either having no slope, or a slope sufficient only to effect drainage, its pitch being ususally less than 10° (Harris, 2006) (Figure 9).
Fox wedged tenon	Stub tenon fitted into a stopped mortice of slightly dovetailed shape, having one or more small wedges inserted into sawcuts in the end of the tenon before the tenon is inserted into the mortice so that, as the tenon is driven home, the wedges spread the sides of the tenon to fit the dovetailed shape of the mortice (BS 6100, 1992) (Figure 3).

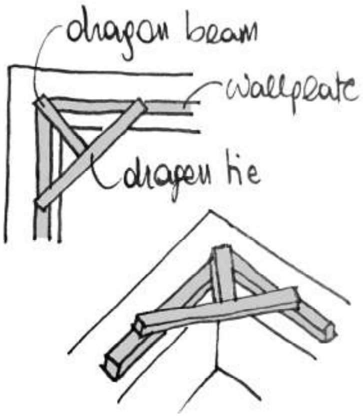


Figure 10: The dragon tie and the dragon beam

(Roof) Frame	The timberwork that encloses and supports structural components of a building (Harris, 2006). Usually applied to an assembly of pieces connected by halving, housing, mortice and tenon joints, or similar connections, and serving as a support or enclosure (Corkhill, 1948) (Figure 1).
Frame saw	A saw with several blades in one frame, used to cut several pieces of wood in one pass (Gorse et al., 2013) (Figure 6).
Gabled roof	Roof having a single slope on each side of a central ridge; usually with a gable at one or at both ends of the roof (Harris, 2006). A roof finishing against a gable and open to the rafters (Corkhill, 1948) (Figure 9).
Halving joint	Joint at the intersection of two members of equal thickness, flush with one another, in which half the thickness of each is removed so that they fit together (BS 6100, 1992) (Figure 3).
Hammer-beam	One of a pair of short horizontal members attached to the foot of a principal rafter at the level of the wall plate, used in place of a tie-beam (Ching, 2011) (Figure 1).
Hammer-beam roof	A roof supported by hammer beams (Ching, 2011) (Figure 1).
Hammer post	A vertical timber set on the inner end of a hammer beam and braced to a collar beam above to support a purlin (Ching, 2011) (Figure 1).
Header	A framing member which crosses and supports the ends of joists, rafters, etc., transferring the weight of the latter to parallel joists, rafters, etc. (Harris, 2006) (Figure 1).
Heartwood duramen	Wood at the core of an exogenous tree; normally darker and much more durable than sapwood (Harris, 2006) (Figure 5).

Hip rafter angle rafter	A rafter placed at the junction of the inclined planes forming a hipped roof (Harris, 2006) (Figure 9).
Hipped roof	A roof comprising adjacent flat surfaces that slope upward from all sides of the perimeter of the building, requiring a hip rafter along each intersection of the inclined surfaces (Harris, 2006). A roof with inclined ends instead of with gable (Corkhill, 1948) (Figure 9).
Indented splayed scarf	A fished joint in which both plate and beam are cut, or idnented, to prevent the sliding of one surface on the other due to shear or tension (Corkhill, 1948) (Figure 3).
Intersected roof valley roof	Any pitched roof that has one or more valleys (Harris, 2006) (Figure 9).
Joggle	A small projection on the end of a framed member to strengthen morticed and other forms of angle joints; in structural work it allows for housing, and provides a better bearing resistance (Corkhill, 1948). An enlarged area of a post for supporting the foot of a strut or brace (Ching, 2011) (Figure 7).
Key	Piece of timber inserted in a joint to prevent movement between adjacent surfaces (BS 6100, 1992) (Figure 3).
King-post	In a truss, as for a roof, a vertical member extending from the apex of the inclined rafters to the tie beam (Harris, 2006). The vertical member at the middle of a king-post roof truss, which is the usual type of wood roof truss for spans between 20 and 30 feet (Corkhill, 1948) (Figure 7).
King-post truss king truss	A pitched truss having a king-post (Ching, 2011) (Figure 7).
Lapped joint	Joint in which one member overlaps the other and the members are secured by nails, bolts, adhesives or other (BS 6100, 1992) (Figure 3).
M-roof happer roof (Scottish) ridge and valley roof	A roof formed by joining two parallel gable roofs, creating a valley between them, resembling the capital letter M in section (Harris, 2006) (Figure 9).
Mansard roof curb roof double pitched roof	A roof that has two slopes on each face, with the lower at a steeper angle than the upper slope, also known as a French roof (Gorse et al., 2013) (Figure 9).
Mortice and tenon joint	Joint in which a tenon on the end of one member is fitted into a mortice cut in the other member (BS 6100, 1992) (Figure 3). For different types see *chase, double, fox wedged, joggle, notch, slot, stopped*.
Notched joint	Joint in which a notched member is supported by another, that, in the case of a double notched joint, is itself notched (BS 6100, 1992) (Figure 3).
Pit saw	An old method of handsawing timber lengthwise; the log is supported over a pit to provide easy access by men using a double-ended saw (Harris, 2006) (Figure 6).
Pitched roof double pitched roof two-slope roof	A steep gable roof having the same pitch on each side of a central ridge. Occasionally, a synonym for a gable roof (Harris, 2006) (Figure 9).

Pith	The soft central core of a log (Harris, 2006) (Figure 5).
Plank	A long, wide, square-sawn thick piece of timber (Harris, 2006). For different types and dimensions used in Scotland see Newland (2010).
Platform roof	A roof which terminates in a horizontal plane; any roof which is truncated (Harris, 2006) (Figure 9).
Portal frame multi-tiered structure trestle	Structural frame consisting of two stanchions connected to beams fixed at angles corresponding to the roof-pitch and rigidly joined at the apex and the tops of the stanchions (Curl and Wilson, 2015) (Figure 1).
Post	A vertical timber acting as a support (Corkhill, 1948). A strong, stiff, vertical structural member or column, usually of wood, stone, or metal, capable of supporting a framing member of the structure above it and/or providing a firm point of lateral attachment (Harris, 2006). See *crown*, *king, princess, queen*.
Princess-post side post	In a truss, a vertical post between the queen post and the wall to supplement the support of the queen post (Harris, 2006); auxiliary posts in a queen-post roof truss; the truss itself is often called a princess-post truss (Corkhill, 1948) (Figure 7).
Principal purlin arcade plate plate purlin under purlin	Timber section used as a bearing for other members; note: always supported along its length (BS 6100, 1992). Any timber, e.g. a wall-plate, laid horizontally on posts or walls serving as the support for other timbers above, its main functions being to provide fixings and to distribute the loads (Stevens Curl, 2006) (Figure 8).
Principal rafter primary rafter	The main rafter in a traditional trussed roof that provides support for the purlins; the purlins then provide support for the common rafters (Gorse et al., 2013) (Figure 7).
Purlin perling purline	In roof construction, a horizontal beam running parallel to the ridge to give added intermediate support for roof joists or rafters (Davies and Jokiniemi, 2008). See *butt, clasped, principal, side, through, trenched.*
Purlin roof double roof	A roof in which purlins are supported directly on walls rather than rafters (DictionaryOfConstruction.com, 2017). *Pfettendach* in German: a pair of inclined pieces called *Rofen*, or common rafters, are carried by *Pfette*, purlins (Lohrum and King, 2006) (Figure 8).
Queen-post	One of the two vertical supports in a queen-post truss (Harris, 2006). The two vertical members in a queen post roof truss, or the two principal posts of any framed truss (Corkhill, 1948) (Figure 7).
Queen post truss queen truss	A roof truss having two vertical posts between the rafters and the tie beam; the upper ends of the vertical posts are connected by a straining piece (Harris, 2006) (Figure 7).
Rafter	The sloping beam that spans from the ridge to the eaves of a roof (Gorse et al., 2013). See *common* and *principal.*
Raised tie-beam	See collar
Ridge beam ridge board	A beam at the upper ends of the rafters, below the ridge of a roof (Harris, 2006). The horizontal timber to which the tops of the common rafters are

ridge pole	fixed (Corkhill, 1948) (Figure 8).
Sapwood alburnum	The wood of a tree between the bark and heartwood; normally lighter in color than the heartwood; equal in strength to heartwood but usually not as decay-resistant (Harris, 2006) (Figure 5).
Sarking (board) roofers	A thin board for sheathing, laid under tiles or slating of a roof construction (Harris, 2006). Close boarding to carry roof tiles, shingles, or slates (Corkhill, 1948). In Scotland it is made with deals (Newland, 2010) (Figure 2).
Scarf joint scarph fish	Heading joint (joint in which the two pieces are in line end to end) in which the ends of the members are tapered and overlap one another, part of each being cut away so that the overall cross section remains constant - it is indented when the mating surfaces are notched together to provide resistance to stress in tension (BS 6100, 1992) (Figure 3).
Scissor brace	Ties that cross each other and are connected to the opposite rafters at an intermediate point along their length (Harris, 2006) (Figure 1).
Shake	A cleavage, or split, in wood; a separation between adjacent layers of fibres (Corkhill, 1948). A separation in wood between or along the annual rings (Harris, 2006) (Figure 5).
Shed roof half-span lean-to mono-pitch pent single pitch to-fall	A roof consisting of one sloping surface (Corkhill, 1948) (Figure 9).
Side purlin bridging rib side timber side weaver	Horizontal beam carried on roof trusses in order to give intermediate support to the common rafters (Curl and Wilson, 2015). Horizontal beam lying on the backs of the principal rafters of a roof truss, between ridge and wall-plate, to carry the common rafters (Corkhill, 1948) (Figure 4).
Sole-piece sole-plate	Short timber laid across a wall (i.e. with its length at 90° to the naked of the wall), supporting the foot of a rafter and an ashlar-piece in a timber roof (Stevens Curl, 2006) (Figure 1).
Sprocket rafter sprocket sprocket piece	Short rafters fixed at a less pitch at the feet of common rafters to form projecting eaves; they form a break in the roof surface and are used for aesthetic reasons and to shorten the common rafters (Corkhill, 1948) (Figure 1).
Step joint	A structural notched joint; when it has more than one notch it is a double-step joint (Corkhill, 1948) (Figure 3).
Stop mortice & stub tenon blind mortice	Mortice that does not penetrate the full width or thickness of the member in which it is formed; tenon not passing completely through the member in which the mortice is formed (BS 6100, 1992) (Figure 3).
Straining beam straining piece	A horizontal timber between the heads of queen posts; a horizontal strut in structural framing (Corkhill, 1948) (Figure 7).

Strut	A brace or any piece of a frame which resists thrusts in the direction of its own length; may be upright, diagonal, or horizontal (Harris, 2006). An inclined compression member of a frame, as in a roof truss, centre, etc (Corkhill, 1948) (Figure 7).
Through purlin	Continuous through the length of the structure, as opposed to butt-purlins (Hourihane, 2012). A purlin resting on the backs of the principal rafters (Davies and Jokiniemi, 2008) (Figure 4).
Tie-beam	In roof framing, a horizontal timber connecting two opposite rafters at their lower ends to prevent them from spreading (Harris, 2006) (Figure 7).
Trenched purlin	Purlin carried on the backs of the principal rafters with the latter trenched to receive it (Yeomans, 1992). A purlin notched into the upper surface of principal rafters (Davies and Jokiniemi, 2008) (Figure 4).
(Roof) Truss	A rigid triangulated framework of wood or iron, designed and arranged to transfer the loads acting on the frame to the supports; triangulation = arranging the members of a frame or truss in triangles to build up a structurally perfect frame, which allows for accurate and rigid designs (Corkhill, 1948). A structure composed of a combination of members (such as chords, diagonals, and web members), usually in some triangular arrangement so as to constitute a rigid framework (Harris, 2006). A structure with hanging posts that act as ties, 'trussing up' the tie-beam and thus counteracting its deflection and creating an efficient triangulation (Yeomans, 1992) (Figure 7).
Valley rafter	In a roof framing system, the rafter in the line of the valley; it connects the ridge to the wall plate along the meeting line of two inclined sides of a roof which are perpendicular to each other (Harris, 2006) (Figure 9).
Wall-plate	Structural member along the top of a wall or built into its length, that distributes the forces from joists, rafters or roof trusses (BS 6100, 1992) (Figure 7).
Wall-post	Post next to a wall (BS 6100, 1992) (Figure 1).
Wane	A rounded edge or bark along an edge or at a corner of a piece of lumber (Harris, 2006). Applied to converted wood in which the corner is missing at the circumference of the log, due to too economical conversion; the defect denotes the presence of sapwood (Corkhill, 1948) (Figure 5).
Wright (Scottish)	A constructive workman, one who deals with wood, a carpenter, a joiner (Oxford English Dictionary, 2016). A woodwright, a carpenter (Robinson, 1999). From wryhta/wurtha: a workman, one by whom anything is framed, from wyrc-an = to work (Jamieson, 1808). A craftsman, a woodwright, a carpenter (Historic Environment Scotland, 2011). An outdated or vernacular word for a carpenter (Davies and Jokiniemi, 2012).

List of abbreviations

ADCRU	Architectural Design and Conservation Research Unit at the University of Strathclyde (Glasgow)
BARR	Buildings At Risk Register in Scotland
BNS	British National Standards
CARE	Conservation Accreditation Register for Engineers
COST	Intergovernmental framework for European Cooperation in Science and Technology
E5	Eurocode 5
ECA	Edinburgh City Archives
EM	Electromagnetic
EUL	Edinburgh University Library
GH	George Heriot School private archives
GPR	Ground Penetrating Radar
GTM	Global Testing Methods
HES	Historic Environment Scotland
HS	Historic Scotland (now incorporated in Historic Environment Scotland)
IHBC	Institute of Historic Building Conservation
IRT	Infrared thermography
LTM	Local Testing Mehods
MC	Moisture Content
MDT	Minor Destructive Tests
MLG	Mitchell Library in Glasgow
NDT	Non-destructive tests
NHTG	National Heritage Training Group
NLS	National Library of Scotland
NTS	National Trust for Scotland
NRS	National Records of Scotland
RCAHMS	Royal Commission on Ancient and Historic Monuments of Scotland (now incorporated in Historic Environment Scotland)
SCAN	Scottish Archive Network

SDT	Semi-destructive tests
SML	Soane Museum in London
STSM	Short Term Scientific Mission
TCH	Touch House private archives
TDH	Glasgow Trades Hall private archives
TG3	Task Group 3
TLS	Terrestrial laser scanning
TWH	Tweeddale House private archives
WG1	Working Group 1

Acknowledgements

This PhD thesis is part of a wider research being carried out at the Architectural Design and Conservation Research Unit (ADCRU), led by the first supervisor of this work, Dr Cristina Gonzalez Longo. I thank her for selecting me to take the scholarship provided by the University of Strathclyde with a contribution of Historic Environment Scotland and for introducing me to researchers and professionals who have helped me throughout this work: Mr. John Addison, Dr. John Barber, Dr. Anne Crone, Prof. A. Macdonald, Dr. Aonghus Mackechnie, Dr. Katherine Newland, Miss Sonsoles Puntos, Mr. Colin Tennant, Dr. Dimitris Theodossopoulos. I am grateful for her supervision and guidance throughout the research work as well. I also acknowledge and thank Dr. Andrew Agapiou, my second supervisor, and Dr. Michael Grant, my reviewer at the annual and interim reviews.

This research was made possible by the help, support and guidance received from many people and institutions. First of all, I thank Dr. Daniel Ridley Ellis (Napier University) for his constant support on the subject of wood technology, for lending me his ultrasonic devicde and for his advise on using it and interpreting the test results. Many thanks to Dr. Alan Crivellaro (Università di Padova) as well for devoting his time and expertise to train me in identigying different timber species. Mr. John Addison (Addison Conservation and Design) has also had an important role as he has given me precious insights on the subject of conservation engineering and has agreed to be interviewed for the research. I am grateful to Professor A. MacDonald for joining me during a visit to Pinkie House's roof, for carrying out an initial structural analysis of this roof and for meeting me to discuss his calculations. A special thank you to Dr. Jiri Blaha who has joined me from Prague to visit and survey some Scottish timber roofs and share with me his knowledge on historic carpentry.

I acknowledge Historic Environment Scotland for funding the travels to carry out the surveys and part of the equipment used during the surveys. In particular I thank Mr. Colin Tennant for his feedback, Dr. Alick Leslie for lending me the ultrasonic device and the micro-drilling device, and Dr. Maureen Young for giving me advice on thermography.

I thank COST Action FP1101 and its members for funding my participation to many of their activities and events, such as the training school in Minho University in Guimares (11-14 May 2015), a Short Term Scientific Mission (STSM) at IVALSA Institute in San Michele all'Adige (18-31 May 2015), a meeting of WG1 in Trondheim (18-19 June 2015) and a conference in Wroclaw (8-9 September 2015). This has allowed me to assess the state-of-the-art research on the assessment of historic timber structures. In particular, I thank Dr. Mariapaola Riggio for her guidance during my STSM at IVALSA Institute.

I also thank Mr. Peter Mckeague (HES), Mr. Christopher Fleet (NLS), Dr. Yang Wang and Dr. John Barber (AOC Archaeology) for their help during the development of the ADCRU relational database. I thank Dr. Dimitris Theodossopoulos (Edinburgh University) for inviting me to collaborate in conducting a student workshop on historic timber roofs at Edinburgh University. I thank Dr. Anne Crone (AOC Archaeology) for her support and advice on dendrochronological analysis, Thorsten Hanke (Hanke Bauforschung) for sharing with me his knowledge on Scottish timber roofs, Dr. Anthony Lewis (Glasgow Museums) and Fergus Sutherland (Icosse Heritage Consultants) for their suggestions on archival sources, Dr. Aonghus Mackechnie (HES) for guiding me through Scottish architectural history, Dr. Kate Newland (Stavanger Museum) for her insight on historic Scottish timber trade, and Sonsoles Puntos for helping me with carpentry treatises.

Most of this research is based on visits and surveys to buildings privately owned or in care of HES and NTS; these visits were made possible by the the courtesy of owners, tenants, estate managers, archivists and other professionals who allowed me access, even in areas out of bounds to the public, and provided me with information related to the building, when it was available. A big thank you to all of them and in particular to Dr. Derek Alexander (NTS), Mr. Ronald Alexander, Mr. and Mrs. Barn, Mrs. Jocelyne Cunliffe, Mr. Kinlay Laidlaw (NTS), Mrs. Birgitta Parnell, Mr. Claus Perch and Mr. Chris Prentice (NTS) for their kindness. I would also like to thank those of them who have taken the time to reply to the online questionnaire and Dr. Ashraf Kashif (HES) and Steven Wood (David Narro Associates) who have agreed to be interviewed.

Many thanks to my PhD fellow Clara Gonzalez Manich for being supportive and encouraging all along. She has given me invaluable help, advice and feedback during all of my work. I also thank my other PhD fellow Bowen Qiu and Erasmus trainee Giulia Spigarelli for helping me during the surveys.

Finally, a big thank you to Filippo, without whom this thesis would have never been completed.

Abstract

This thesis researches seventeenth- and eighteenth-century timber roof structures in Scotland, which had been largely forgotten up to now. Previous studies fail in characterizing the extent and nature of historic timber roofs in Scotland, especially post-1650, mainly because of the scarcity of measured surveys. This lack of knowledge, together with the lack of specific standards and training for the assessment of existing timber structures, hinders good conservation practice. Scottish professionals rely mainly on traditional methods and past experience, which makes it difficult for them to reach a confident structural assessment. The result is that many roofs are heavily altered or replaced.

The thesis investigates the extent, nature and condition of seventeenth- and eighteenth-century timber roof structures in Scotland in order to raise awareness about their value and contribute in improving conservation practice. A database of 1500 Scottish buildings of the period has been created and a representative sample of 59 original timber roofs has been surveyed. Archival research has also been carried out. This has allowed tracing the historic development of seventeenth- and eighteenth-century timber roof structures in Scotland and demonstrating that they form a heritage of great extent and quality. For the first time overall structural arrangements, construction methods and details, the species and quality of the timber employed, the role of architects, wrights and patrons in the design process and foreign influences have been comprehensively described and classified. The data gathered during the surveys has also been used to identify typical pathologies and possible causes for each roof structural typology. Moreover, the assessment techniques used during the surveys have been evaluated in terms of effectiveness, reliability, costs and training needed, in order to inform specific training for conservation professionals.

1 Introduction

1.1 Context and Background

This thesis researches the conservation of seventeenth- and eighteenth-century timber roof structures in Scotland. It is part of a wider research on the conservation of Scottish architecture of the period being carried out by the Architectural Design and Conservation Research Unit (ADCRU), at the Architecture Department of the University of Strathclyde (Glasgow). The aim is to recognize the value of this important built heritage in an integrated and comprehensive way, beyond the usual external descriptions, and to contribute in improving current knowledge and conservation practice.

Despite the great extent and quality of seventeenth- and eighteenth-century architecture in Scotland - we have identified more than 1500 buildings of great value so far -, this heritage has not been sufficiently researched. Structural arrangements, construction techniques and materials are only partially known since most buildings of the period have only been researched concerning their external architectural composition, as discussed below.

Scotland is generally not mentioned in books discussing the history of European architecture; even very influential historians like Summerson (1953) consider this country to be characterized by a 'delayed development' until the Union with England in 1707, and state that after this moment Scotland must be treated as 'a provincial extension of the English school'. This lack of recognition is a consequence of the limited research carried out in the field of Scottish architecture, even though in the last thirty years scholars such as Dunbar (1978), Rykwert (1985), Howard (1995), McKean (2001) and Glendinning and MacKechnie (2004) have made significant efforts to raise awareness about the value of Scottish architecture and its distinct contribution in the European context.

These efforts have concentrated mainly on vernacular architecture (Naismith, 1985, Scottish Vernacular Buildings Working Group, 1992), Medieval and Renaissance architecture (Howard, 1995, McKean, 2001) and post-eighteenth-century architecture (McKean et al., 2000, Stamp and Sayer, 1999), leaving the great country houses and stately buildings of seventeenth- and eighteenth-centuries to be further investigated. Some studies of single buildings from this period have been published (Dunbar, 1972, Rowan, 1984), but very few contributions have specifically addressed this part of the Scottish heritage more comprehensively (Gow, 1995, Strachan, 2008).

The importance of many patrons, architects and builders has to be discovered yet, as there are only a few known names to which many of the buildings are attributed due to lack of further evidence. For example, more than fifty buildings are currently attributed to Robert Adam (Rykwert, 1985), only because the period and design style match his own. Only recently the contributions of less known architects like Allan Dreghorn (Lewis, 2015) or John Douglas (Theodossopoulos, 2015), mason-architects like James Smith (González-Longo, 2012) or John Mylne (Harding, 2012) and other less known builders (Lewis, 2006) are being investigated in more detail. Wrights (carpenters in Scotland), in particular, have not been considered worth researching and to date, despite a substantial recent contribution by Newland (2012b), little is known about their relation with architects and their role in the design process.

Moreover, research so far has concentrated mainly on stylistic and architectural features rather than on construction techniques and materials. Contributions to Scottish construction history are in fact very few (Bell, 2004, Gonzalez-Longo and Theodossopoulos, 2012, Jenkins, 2012, Scottish Vernacular Buildings Working Group, 1976, Walker, 2006). No comprehensive research has been published so far on structural aspects of seventeenth- and eighteenth-centuries Scottish architecture: overall structural arrangements and elements still have to be identified, their evolution traced and their condition assessed, in order to encourage their conservation. Some scholars have investigated single structural elements, like timber roofs (Hanke, 2006) or stairs (Simpson, 2007), but the extent and condition of these structures is still uncertain. It is also important to understand if these structures have been designed and built in a vernacular way, and what are the factors that drove their design, such as architectural fashion of the time and availability of materials. The migration of technical knowledge is another crucial aspect: seventeenth- and eighteenth-centuries saw the emergence of professional architects that travelled and studied in Italy, France, and other European countries (Nenadic, 2012). Some foreign influences in Scottish architecture have in fact already been traced (González-Longo, 2012, Howard, 2001, Ottenheym, 2007), but related to architectural design rather than construction techniques and materials.

The development of construction techniques goes hand in hand with the development of architectureas any design change demands for a change in construction methods. This is particularly true for roof structures since the span that a roof structure can achieve necessarily restrains the width of the space that can be built below it. Nevertheless timber roof structures emerge as a neglected topic of research, even because they are often hidden behind decorated ceilings. The result of this lack of knowledge on their extent and nature is that their value is not appreciated and many of the original roofs are replaced with new structures and irredeemably lost.

Some research on the use of timber in Scottish architecture has been published (Apted, 1966, Bell, 2004, Crone and Sproat, 2011, Peddie, 1883) but there has been little focus on its structural role, particularly in roofs. Medieval open roofs have been widely discussed (Crone and Fawcett, 1998, Crone and Gallagher, 2008, Gomme, 2002, Oldriev, 1916, Stell and Baillie, 1993), but roofs hidden behind timber and plaster ceilings, which, according to Hay (1976), Ruddock (1995), Stell (2004) and Hanke (2006), represent the vast majority, have been mostly forgotten. Despite the above mentioned contributions and few more (Crone et al., 2004, Peddie, 1883) we are still unable to say what is the extent and nature of original Scottish timber roofs because the research to date has focused on a restricted chronological and geographical frame and has drawn more on archival documents than on in situ inspections. In particular, very few post-1650 Scottish roofs have been studied making it difficult to assess how structural carpentry has evolved during the important architectural developments of late seventeenth century and eighteenth century. Moreover, little attention has been paid to details such as joints between elements, dressing of the timbers, carpentry marks, and very few seventeenth- and eighteenth-century roofs have been dated with dendrochronology so far. This lack of knowledge makes it difficult to confidently trace a historic development of Scottish roof carpentry.

Even less research has been carried out on the present condition of these structures: very few examples can be found in literature (Murdoch, 2010, Oldriev, 1916, Ruddock, 1995). Research on conservation of Scottish built heritage has been published mostly by Historic Environment Scotland (HES) in the form of technical reports and papers - only few contributions on the assessment of Scottish built heritage have been published by professionals (Gonzalez-Longo, 2008). However, most HES publications focus on upgrading and improvement of historic buildings (Fabian and Dobbie, 2014) - especially regarding energy efficiency (Snow, 2013) -, rather than their condition assessment. Moreover, investigations are either focused on historical and stylistic aspects (Historic Environment Scotland, 2014) or on very technical ones (Baker, 2008), often lacking of a more comprehensive and interdisciplinary approach.

Listings by Historic Environment Scotland mention roof structures very rarely, making it difficult to limit and control interventions carried out on this part of the building. Owners, building managers and professionals taking care of the building maintenance do not always recognize the importance and value of their roof structures, although the integrity of any building largely depends on the protection given by its roof. Consequently inspections and maintenance works are not programmed regularly, accessibility and visibility requirements are often not met and works are poorly documented.

On the other hand, a lack of specific training for conservation professionals makes it difficult for them to reach a confident structural assessment and carry out punctual and effective interventions. The assessment of historic timber structures can be challenging, since the material is organic and has variable properties. Although recent research (Dackermann et al., 2014, Kloiber et al., 2015b, Riggio et al., 2014, Tannert et al., 2014) on the assessment and diagnosis of historic timber structures has made impressive progress, developing many non-destructive and semi-destructive testing methods which can help reducing the assumptions made, professionals in many countries still rely mainly on traditional methods and past experience (Feio and Machado, 2015). This is because the available testing and modelling methods require considerable skills and experience and can be expensive and labour intensive (Machado, 2013). Moreover, many countries do not have the relative regulations and standards (Augelli, 2014) and do not provide the necessary training, as is the case in Scotland. In some cases these challenges have been successfully resolved but these experiences have not been sufficiently analysed, discussed and shared in order to inform other projects. The result is that sometimes the impossibility to reach a confident structural assessment forces engineers to 'stay on the safe side' and carry out unnecessary or over-dimensioned interventions, or completely replace the structure, depriving future generations of part of this important heritage.

1.2 Aims and Objectives

The thesis aims to contribute in improving both current knowledge and conservation practice of seventeenth- and eighteenth-century timber roof structures in Scotland. This aim is pursued by researching about the extent, nature, value and condition of these structures, by assessing current conservation practice and by identifying reliable and effective state-of-the-art methods and tools that can be used for their initial assessment and are accessible to the majority of professionals.

The intent is to demonstrate that seventeenth- and eighteenth-century timber roof structures in Scotland form a heritage of great extent and quality whose study can contribute to the understanding of the history of European carpentry. These roofs are an important and integral part of the buildings they cover, both from a historic and architectural point of view and in structural terms. It is thus imperative to adequately conserve them in order to secure the knowledge of future generations and to ensure long life to the buildings they are part of.

The research also aims to demonstrate that currently these structures are not always adequately conserved. The reason is that their value is seldom recognized but also that professionals who take care of the built heritage are not adequately equipped with the knowledge and skills necessary to deal with historic timber structures. State-of-the-art methodologies and instruments for the in situ assessment of historic timber structures remain to date largely employed in academic research only. The thesis aims to demonstrate that they can be partly implemented by a wider range of users even with a limited knowledge in the field if targeted training is provided. This would certainly improve current conservation practice as it would allow reaching a more confident assessment of the existing structure, which is the fundamental basis to proceed with the design of the necessary alterations, repairs or strengthening interventions.

In order to reach these aims, specific objectives have been pursued:

- Identify seventeenth- and eighteenth-centuries buildings in Scotland and gather all available information on their location, typology, geometry, design, history;
- Understand what types of timber roof structures were used in their original design and later alterations;
- Assess their extent and condition and identify typical pathologies and possible causes;
- Assess current conservation practice of these structures in Scotland (skills, methods, tools, etc), to understand what can be improved;
- Evaluate the reliability and effectiveness of state-of-the-art assessment techniques in this context and identify the knowledge and skills needed to implement them.

1.3 Methodology

A methodology has been devised to pursue the above-mentioned objectives. This introductory section details on the structure of the adopted methodological approach to provide a general context for the extensive discussion on specific methods hosted in chapter 2.

The founding step to this research project consisted in identifying buildings of the period and in gathering the available information on their location, typology, geometry, design, history and condition. While a large amount of information is available in online databases, such as HES (Historic Environment Scotland website - Designations, 2016), RCAHMS (Canmore website - Sites, 2016) and BARR (Buildings at Risk Register website - Buildings, 2016), these resources are not searchable based on any parameter other than the building name and location. It was thus necessary to create a new searchable resource. To do this, the author, in collaboration with another colleague at ADCRU, developed a novel relational database using Microsoft Access, that allows storing, querying and analysing a large amount of data, and ArcGIS software, that allows mapping the data to geographical locations. The database has been fed with information collected from HES, RCAHMS and BARR databases and existing literature on Scottish architecture, including unpublished work (Hanke, 2014, Rock, 2015) (Figure 11).

As expected, a lack of information on timber roof structures emerged and it was therefore necessary to carry out fieldwork on a selected a sample of reference buildings in order to collect first hand data on the roofs' construction techniques, typologies and present condition. The buildings were selected amongst the 1500 identified and included in the database, with the help of a series of queries based on criteria that will be detailed in the next chapter. Briefly, the sample includes buildings of a certain scale designed by architects, because they have been less investigated so far. Amongst these, buildings that represent key moments in Scottish architectural history have been selected. In addition, in order to identify the buildings more likely to retain the original timber roof structure, the availability of information on roof structures and wrights and the preservation of original features have been considered. Finally, buildings were chosen based on accessibility.

To plan the surveys, the owners of 140 selected buildings were contacted. Among them, 80 replied, but some replied too late for a visit to be arranged and some others denied access to their roof space. Eventually, 28 buildings or groups of buildings were surveyed during summer 2014 (Figure 11).

Following the methodologies proposed by Cruz et al. (2015) and Riggio et al. (2014), surveys were preceded by a desk study aimed at gathering all the necessary information on the buildings. Then, a preliminary visual and measured survey was carried out (Figure 11). During these surveys, a series of fixed parameters were recorded in order to compare the structures and draw conclusions from a historical, typological, technological and structural point of view. Namely, these parameters include: roof form and geometry, type of internal structural arrangement, type of connection with the supporting structures, elements' scantlings and section shape, timber dressing, type of joints and fasteners, timber species, roofing material and fasteners, carpentry marks, evidence for reused timber. A preliminary condition survey was also carried out recording if the roof space was in use, the accessibility conditions, the presence of decorative features, unfavourable environmental conditions (poor ventilation, etc), poor maintenance, past alterations and repairs and signs of mechanical damage (deformations, cracks, etc) and material degradation (fungi/insect attack, etc). These initial surveys were carried out using a measurement tape, a laser meter and a digital camera.

Whilst carrying out the surveys, the online catalogue of the Scottish Archive Network (SCAN, 2015), that allows to search all the documents available in Scottish archives, was searched for documents related to the surveyed buildings and wrights of the period (Figure 11). A list of all retrieved documents is included in Appendix E and F. Due to time constraints, the archival research was limited to Glasgow and Edinburgh archives (NLS, NRS, RCAHMS, ECA, EUL, ML) and to some of the building owners' own records. The consulted documents include accounts, estimates, minutes, correspondence, pictures and drawings related to seventeenth- and eighteenth-century wright work. In addition, documents related to St Mary's incorporation of wrights were also consulted. A full list of the consulted documents is included in Appendix G, whilst the transcriptions are included in the surveyed buildings forms (Appendix E and F). Despite being very limited in number, the consulted documents including useful information on roof structures and wrights have allowed to date some roof structures and past interventions. At the same time, these documents provide a basis to start understanding the design process and the role of architects and wrights. Other potentially interesting sources of information have been identified for future research; a list is provided in Appendix D.

The experience and knowledge acquired during the surveys have been used during a Short Term Scientific Mission (STSM) at the IVALSA institute (San Michele all'Adige, Italy) to further develop a structured form produced by the members of COST Action FP1101 to assist the survey and analysis of historic timber roof structures (Riggio et al., 2015a) (Figure 11). The COST Action members had already defined specific objectives and drafted a form using Microscoft Word software. The STSM work focused on reorganizing the contents of the form in both format and structure using Microsoft Access software in order to allow for the analysis of a large amount of data. Classifications of types of roof structures and mechanical damage were also developed and integrated within the form, along with graphics to support the relevant terminology (Figure 11).

The parameters and classifications included in the form were used to guide further surveys carried out in summer 2015. This second survey round considered a sample of buildings chosen based on the previous analysis. In particular, major developments in roof carpentry, leading to buildings with big internal spans, were observed during late seventeenth- century and early eighteenth-century. Therefore, the 2015 selection included buildings of this period with big internal spans. These buildings were identified by analysing plans and sections found in literature and in RCAHMS. In addition, the 2015 selection also considered buildings where access to the roof space had already been granted in 2014. Other criteria such as travel cost and accessibility were considered. Overall, 25 buildings were visited during summer 2015 (Figure 11).

In total, 53 reference buildings or groups of buildings were surveyed. Amongst these, 44 only retained one or more seventeenth- or eighteenth-century roof structure (a few examples date from end sixteenth century) for a total of 59 roof structures surveyed. The surveys were useful to validate the form produced during the STSM and to adjust it to the research purposes. The analysis of the surveys output, together with the information retrieved from archival research, lead to the first identification and dating of different roof structural types of the period, along with a diagnosis of their typical pathologies and possible causes.

In order to understand if these pathologies are adequately addressed by current conservation practice, past alterations and repairs identified during the surveys and in literature were analysed and evaluated. Since past works are often poorly documented and very few examples are published in literature, the assessment of conservation practice on Scottish roofs was complemented by questionnaires and interviews aimed at understanding what are the current approaches of building owners and professionals. An online questionnaire was sent to the owners, users or managers of the surveyed buildings (Figure 11) to understand their approach to the maintenance and documentation of the building. Three conservation engineers were interviewed (Figure 11) to investigate what kind of know-how, skills and approach these professionals exercise when assessing a timber roof structure and how they choose, design and carry out the necessary repair works. Two engineers were selected amongst the most mentioned for repair works in the database, and one was selected because he works for HES, the lead public body taking care of Scottish built heritage. An online research and e-mail exchanges with some course directors was carried out to ascertain what postgraduate and training courses are offered to professionals such as engineers, architects, and craftsmen to acquire specific knowledge about conservation of timber structures.

This work highlighted that current conservation practices in Scotland can be improved by the introduction of specific training for conservation professionals dealing with historic timber structures. In order to understand what the focus of this training should be, more deatailed investigations were carried out in 8 case studies (Figure 11). These investigations were also aimed at learning more about the present condition of the roof structures. The methodology of this further investigation has been devised considering the available resources and the state-of-the-art tools, methods and standards for the assessment of historic timber structures (Figure 11). The timber species and quality have been investigated, along with the environmental conditions of the roof space, hidden parts of the structure and the residual resisting section of the timbers. Further archive research was carried out to find information related to the original construction and later alterations of the roof structures. The structured form was expanded to accommodate the new data.

The case studies were selected amongst the surveyed reference buildings based on criteria of representativeness (roof structure type and date, creating a homogeneous spread amongst the identified types and the two centuries considered), accessibility (geographical location limited to the Scottish central belt, visibility of roof structure and easy access, owner's permission to carry out tests) and availability of other sources of information (archive material and dendrochronological analysis). Buildings with more than one roof structure were preferred. Buildings owned or in care of Historic Environment Scotland were included to understand if the same methodology is applicable to non-privately owned buildings.

The detailed investigations on the case studies allowed an initial assessment of their current condition and, most importantly, they allowed understanding which testing techniques are most reliable and effective in the assessment of these structures. As detailed in chapter 5, the equipment used has been evaluated and compared considering the costs and the knowledge and skills needed for the on-site operation and the interpretation of results.

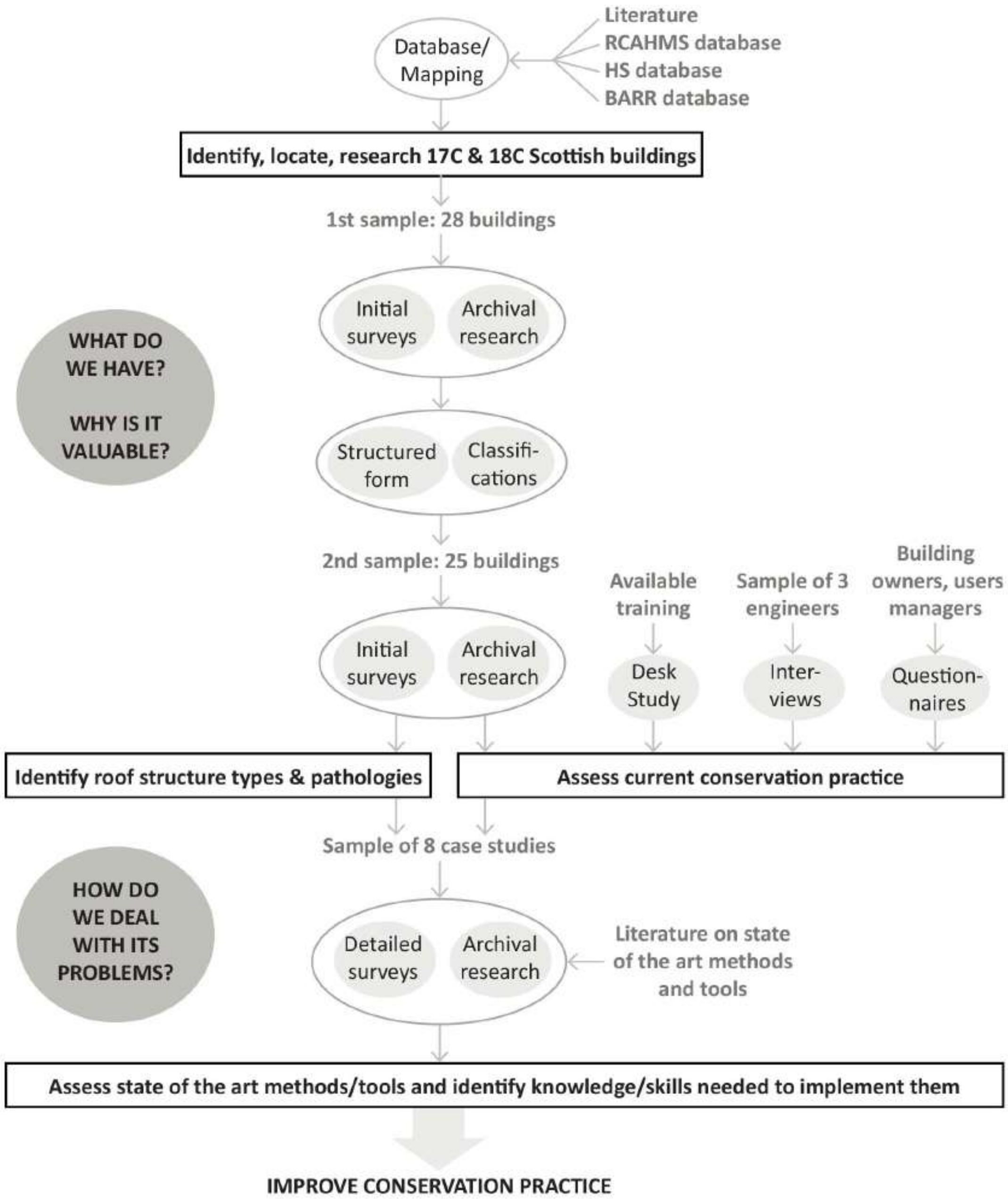


Figure 11: The research methodology employed in this thesis

1.4 Research Limitations

As previously explained, the research investigates a small sample of 53 buildings selected amongst the 1500 identified. Every effort has been taken in selecting the most representative reference buildings and case studies, but it is still a limited sample and future research should focus on widening this sample. We hope the methodology set in the thesis will allow for this work to be continued. The sample of owners, managers, tenants and professionals who have participated in the online questionnaire and have been interviewed is also limited if we consider all the figures involved in conservation projects (craftsmen, contractors, funders, etc).

The research has concentrated on double pitch roofs, the most common, although two shed roofs and two conical structures have been surveyed, because it was difficult to identify the shape of the roofs prior to the visits. Other structural typologies such as flat roofs and steeple roofs have not been included in the research because the considerable number of examples (Hanke, 2006) suggests they deserve to be treated in a separate study. Although there are a few examples of seventeenth- and eighteenth-century crucks (Crone & Mills, 2011) they have not been considered either because they are used in vernacular buildings only.

Time limitations prevented from consulting further archival sources. A complete list of the consulted archival documents is provided in Appendix G, while the information they contain about roof structures and wrights is provided in Appendixes E and F. A list of other sources of information that have not been consulted is provided in Appendix D.

Another important aspect to consider is that the surveys and tests have been carried out mostly by the author alone, only rarely assisted by another PhD student, as noted in the individual case studies. Both the author and the other PhD students had limited previous experience and knowledge in the field. Different results may have been achieved by more experienced people; this however reproduces the intention of the thesis to propose assessment methodologies for a wider range of users, not just specialists as it has been the case until now.

1.5 Structure of the thesis

Apart from this initial chapter, which sets the context, aims and objectives of the research, the thesis consists of 5 chapters: chapter 2 describes the methodology employed during the research; chapter 3 discusses the results of the research in terms of historic development of Scottish timber roofs; chapter 4 describes in detail the case studies; chapter 5 discusses the current conservaton practice of Scottish timber roofs and the results of the research in terms of the assessment of the condition of these roofs; chapter 6 covers the conclusions.

Chapter 2 reviews the available tools, methods and standards at European level for the assessment of historic timber roof structures and then clarifies the methodology used to pursue the research objectives. The sections follow the main steps of the research: the creation of a relational database, the initial survey of 53 reference buildings, the detailed survey of 8 case studies and the creation of a structured form integrated within the database, used to guide the surveys and analyse their results.

Chapters 3 discusses the results of the research in terms of historic development. The architectural context of seventeenth- and eighteenth-century Scotland is set and existing knowledge on timber roof structures of the period is discussed. The results of the research are then used to trace the development of seventeenth- and eighteenth-century timber roof structures in Scotland. Structural arrangements and construction details are discussed within the European context to identify distinct Scottish features and possible foreign influences, discussing the role of architects and wrights in the design process. These aspects are described in detail for each of the 8 case studies in chapter 4. along with the present condition of the structures, whose results are then discussed in chapter 5.

Current conservation practice of Scottish roofs is examined in chapter 5 by looking at the approach of building owners and professionals, affected by the lack of specific standards and training. The findings in terms of present condition and typical pathologies of Scottish roof structures are then presented, discussing the opinion of the interviewed conservation engineers, the results of the visual inspection in the 53 reference buildings and the results of the detailed assessment carried out in the 8 case studies. In the last section the assessment techniques used during the research are evaluated and compared and the skills needed for the initial assessment of timber roof structures are analysed in order to inform the design of specific training for conservation professionals. Chapter 6 summarizes the results of the thesis, giving recommendations for future research.

2 Investigating seventeenth- and eighteenth-century timber roof structures in Scotland: methodology

This chapter reviews the state-of-the-art tools, methods and standards in Europe for the assessment and conservation of historic timber roof structures and then clarifies the methodology used to pursue the research objectives. The review of available tools and methods includes visual inspection, visual strength grading, non-destructive and semi-destructive testing and structural analysis. International and national standards are then reviewed, including Swiss and Italian standards, which are the most complete. Based on this review, a research methodology has been devised, as detailed in the subsequent sections: the creation of a relational database and related mapping of seventeenth- and eighteenth-century Scottish buildings, the measured and condition surveys of a representative sample of timber roofs, the archival research, the detailed investigations in 8 case studies, the establishment of specific classifications and the creation of a structured form integrated within the database, used to collect, report and analyse all the research data.

2.1 Review of the available tools, methods and standards in Europe for the assessment of historic timber roof structures

The decision over what should be conserved of a historic structure and how it should be conserved entails a thorough understanding of its value and present condition. Evaluating existing timber structures is particularly challenging because timber is an organic material: it is heterogeneous and anisotropic and consequently its properties are highly variable; it is vulnerable to biological attack and very sensitive to moisture, thus characterized by large shrinkage and swelling coefficients; its natural features (knots, shakes, etc) can strongly affect the strength and distribution of stresses.

This high variability requires a multidisciplinary approach and a broad knowledge of disciplines spanning from biology to mechanics. The most recent research on the assessment of historic timber structures is reviewed below, looking at methods, tools and standards available, and discussing their principles, purpose, reliability, drawbacks and limitations.

The evaluation of the present condition of existing timber structures involves the identification of the extent of damage, material degradation and natural defects, and the determination of the mechanical properties of wood. All of these aspects influence the behaviour of a timber structure and therefore must be included in the structural anlaysis carried out to evaluate its safety.

It is important to combine results from different sources in order to make the most reliable estimations: the state-of-the-art methodology involves in fact a good coordination between visual inspection, visual strength grading (VSG), non-destructive (NDT) or semi-destructive (SDT) tests carried out in situ and in laboratory, and structural analysis (Cruz et al., 2015, Feio and Machado, 2015). The visual methods and the in situ and laborastory tests are used to gather information about the roof structure that can then be used to carry out a structural analysis and evaluate its safety. It is an iterative process rather than a linear one because the structural analysis must be continuously updated with the information gathered during the surveys (Cruz et al., 2015, Feio and Machado, 2015). A preliminary assessment informs a first structural analysis to identify highly stressed areas that need to be further investigated (Figure 12). Once these investigations are carried out, the structural analysis is updated and used to verify if the structure complies with the ultimate state requirements (Figure 12). If it fails, a more detailed survey (using other tests) must be carried out and the structural analysis updated again (Figure 12).

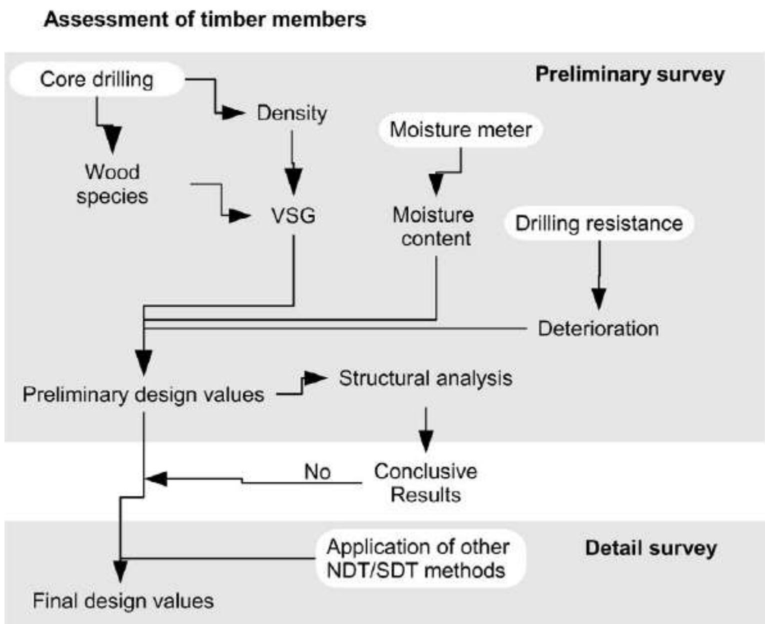


Figure 12: Methodology for the assessment of existing timber structures (Feio and Machado, 2015)

We know the type of data that we need to collect during an inspection and the tools that can be used to collect it, but only recent research has looked into how this data can be reorganized in order to ensure the most reliable assessment. The use of regression models (Machado, 2015), artificial neural network (ANN) models (Feio and Machado, 2015), Bayesian methods (Sousa et al., 2015) and other types of data analysis (Sandak et al., 2015b) is proposed, but these are still under study as many variables are involved. All publications agree that the expert's opinion remains a crucial aspect in the final decision on the structure's level of safety.

We will know discuss in detail the different methods and tools mentioned above: visual inspection, Visual Strength Grading (VSG), non-destructive and semi-destructive testing in-situ and laboratory, structural analysis. Lastly, we will review the standards available for these methods.

2.1.1 Visual Inspection

Visual inspection is the basis of any structural assessment and its most important step. It is fundamental in the process of understanding how the structural system works and what is its overall health condition. The results of the visual inspection form the basis on which the need for further investigations is assessed and planned.

It comprises different levels of in-depth investigations (Cruz et al., 2015, Riggio et al., 2014). A preliminary visual, geometrical and technological survey is aimed at assessing accessibility conditions, identifying the structure typology and details, measuring overall and specific dimensions and identifying materials, loads and environmental conditions. Past and recent alterations and repairs must be recorded as well as any obvious damage and critical areas, in order to determine the need for emergency interventions and set a strategy for further assessments.

A further step comprises a more detailed visual survey aimed at identifying the extent and position of defects (knots, checks, shakes, slope of grain, etc), mechanical damage (cracks, deflections, etc) and material degradation (biological attack or fire damage), even in the supporting structures (walls) (Figure 13). Joints should be subject to a particular detailed survey, considering both their geometry (dimensions and position of fastener, elements' section reduction, etc) and condition, as even surface degradation may have a considerable impact on their performance (Cruz et al., 2015).

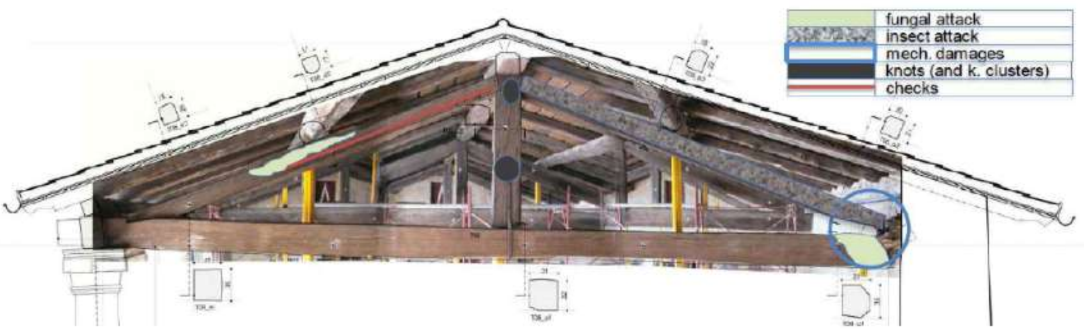


Figure 13: Example of graphics reporting results of visual inspection of a timber truss (Massari et al., 2010)

The assessment of defects, damage and degradation must include a thorough record of their position, extent and type, in order to decide if further investigations are needed. Natural features such as knots, shakes, deviated slope of grain, drying fissures, etc, as described by Tampone (1996), can considerably alter the structure's strength and overall behaviour. Material degradation caused by insects and fungi (Ridout, 2000), corrosion or humidity can reduce the resisting section of timber elements. Mechanical damage is indicative of how the structure is behaving and can allow us understanding what the primary causes of damage are. Different types of cracks, depending on the stresses applied, are discussed by Tampone (2007) (Figure 14).

Figure 14: Failure of a rafter caused by the instability of the strut and favoured by a knot in the rafter and the notch for the joint; the efficient connection of the rafter to the post is the cause of the bending of the post (Tampone, 2007)

2.1.2 Visual Strength Grading

Visual Strength Grading (VSG) can be used to assign strength classes or maximum loads to timber elements, based on the timber species and the natural features and defects assessed visually. Specific standards must be used: Feio and Machado (2015) and Cruz et al. (2015) suggest that if VSG regulations are not available in a specific country, grading rules used elsewhere for the same species can be used; if VSG rules are not available for a specific species, those applicable to species with similar density and modulus of elasticity can be used. The Italian Standard (UNI 11119, 2004) is used by researchers and professionals in many countries as it is the only one specific for grading in-situ historic timber (Feio and Machado, 2015), as we will discuss in section 2.1.6.

Recent guidelines (Cruz et al., 2015) integrate these standards by stressing that strength grading should be carried out in relation to the applied stresses: there is no point in grading a strut, which will only be loaded in compression, for characteristics that can only affect the ability of a member to resist bending. For the same reason, the knots' size allowance should vary depending on their particular position along the section and length of the element. It is proposed to apply different VSG approaches to each type of structural element:

- members subject to bending (ex: purlins): knots are more dangerous in areas of high bending moments and on the tension side; the slope of grain has more severe effects near the supports where shear forces are high; if there is load-sharing the timber mechanical properties should be increased by 10%.
- members in compression only (ex: posts, struts): the effects of defects are negligible.
- members in compression and bending (rafters, collars, posts with braces): defects are more dangerous in the area of maximum moment; this is true for the following two types of members as well.
- members in tension (posts in trusses): defects are critical only close to joints, fissures are not problematic.
- members in tension and bending (tie-beams, collars): all defects can be problematic; allowance must be made for the reduction in section produced by joints.

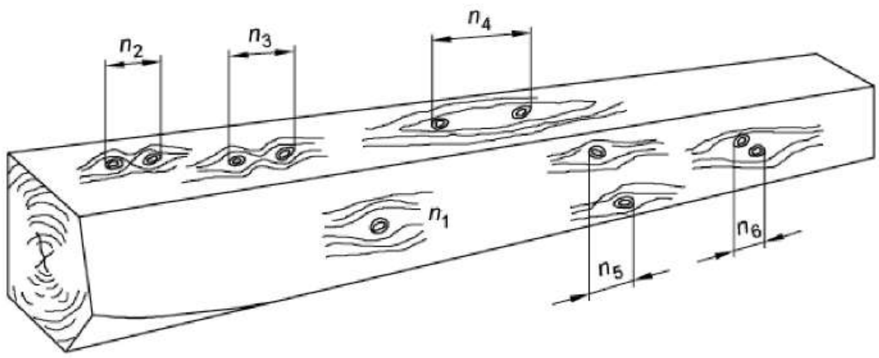


Figure 15: Knots classification according to UNI 11035 (2003): $n_1/n_3/n_5$ = single knots, $n_2/n_4/n_6$ = groups of knots

2.1.3 Non-destructive and semi-destructive testing

Visual methods are very powerful but they can be limited by the subjectivity and low experience of an inspector, reduced accessibility of the timber structure, internal features which cannot be visually assessed (Nowak et al., 2013) and lack of specific criteria in most national standards (Piazza and Riggio, 2008). VSG also requires the timber species identification, which is not always doable (Macchioni 2010). Moreover, the mechanical properties estimated through VSG are generally overly conservative and this can lead to the replacement/demolition of healthy elements (Feio and Machado, 2015). Therefore, even though visual methods must be the first step of any assessment, they are often not sufficient and need to be supported by in situ and laboratory tests.

Destructive tests can give a complete and reliable assessment. However, in the case of historic structures, non-destructive tests (NDT) and semi-destructive tests (SDT) (or minor-destructive, MDT) are preferred since the overall appearance and integrity of the structure is to be preserved. They can be Global Test Methods (GTM), providing large scale analysis, or Local Test Methods (LTM), providing punctual information. The information provided can be qualitative or quantitative.

Results obtained through local methods must be used to make inferences about the same parameters in other parts of the structure. This is clearly a disadvantage considering the high variability of timber. Extensive testing can partly solve the problem, but it is not possible in the case of semi-destructive tests, due to the disruption caused. Global methods would therefore be preferable, but local methods are necessary to obtain information such as the timber species, the moisture content, and the mechanical properties. Unfortunately most of the local methods are also semi-destructive.

Recent publications give a systematic overview of available testing techniques, looking at the equipment used and their applicability and limitations (Table 1). Unfortunately, many techniques have been developed for other materials (as GPR for concrete) or for trees (as Acoustic Tomography), and therefore are not configured for structural timber testing (Dackermann et al., 2014). Different devices doing the same test can give different results, because both the test procedure and the results interpretation require a lot of experience (Hasníková and Kuklík, 2014). There are often accessibility limitations that hinder the use of some bulky devices, such as the Resistance micro-drill (Tannert et al., 2014), while others are not on the market yet (Crespo de Antonio et al., 2016, Kloiber et al., 2015b). This is why NDTs/SDTs remain mainly academic (Machado, 2013), while most professionals rely chiefly on experience, even though this can lead to underestimating the structure's condition and replacing or over strengthening it.

Table 1: existing non-destructive and semi-destructive tests used on timber structures (dynamic/monitoring tests have not been included); regular = global testing methods*, italic = local testing methods; MOE = modulus of elasticity; MOD = modulus of deformability; MOR = modulus of rupture; CS = compressive strength*

TEST	Info obtained	Limitations	References
		NON DESTRUCTIVE	
Thermography	Moist areas, hidden geometry, superficial defects	Qualitative and superficial; better results in heated environments (active thermography)	Riggio et al. (2015b)
Radiography	Internal condition, density	Density estimated; extent and depth of internal features not quantifiable; requires access to both sides; safety issues	Riggio et al. (2014) Lechner and Kliger (2015)
Photogramme try	Geometry, visible condition	Superficial; accuracy depends on devices; requires good illumination	Riggio et al. (2015b) Arce et al. (2016)
Laser scanning	Geometry	Superficial; long post processing; expensive and bulky device	(Bertolini Cestari et al., 2013)

Detector dogs	Internal condition	Early stages of infestation not detected; extent and depth of internal damage not quantifiable; must be trained for each insect species	Zahid et al. (2012)
Microwave reflectometry	Internal condition	Good resolution only in first 20cm of depth; not effective with high moisture contents	Riggio et al. (2016)
Ground Penetrating Radar	Internal condition	Qualitative; extent and nature of internal features not quantifiable; not effective with high moisture contents; requires high expertise to interpret data	Riggio et al. (2014) Riggio et al. (2015b)
Acoustic tests: time of flight, tomography, echo	Internal condition, Dynamic MOE	Resolution depends on wavelength and distance between sources; early decay not detectable; requires species identification and moisture content measurement; requires density to estimate MOE	Dackermann et al. (2014) Llana et al. (2016) Machado et al. (2009)
Sounding with rubber hammer	Internal condition	Reliable only for extended damage; not effective for timbers with big sections	Ross et al. (1999)
Moisture content readings	Moisture content	Punctual in time, unless long-term monitoring in place; requires species identification	Riggio et al. (2014) Kasal and Lear (2010)
Endoscopy	Internal condition, hidden geometry	Needs access (holes or other)	Kloiber et al. (2015a)
Chemical analysis	Type and level of decay	In situ procedure only tells if the wood is affected or not: samples are needed to determine type of fungi	Brozovsky and Zach (2008)
SEMI DESTRUCTIVE			
Microscopic analysis	Wood species	Not always possible to identify specific species	Macchioni (2010)
Infrared spectroscopy	Type and level of decay, wood species, mechanical properties	Superficial; prediction model available for one species only	Sandak et al. (2015a)
Dendrochronology	Wood species, date and provenance	Not always conclusive in terms of dates and provenance; leaves 15mm ⌀ hole	Pignatelli (2010)
Resistance micro-drilling	Internal condition, Resistographic measure, preliminary dendrochronology	Low correlations with material properties; device dimensions reduce applicability; needle often deviates; leaves 3mm ⌀ hole	Tannert et al. (2014) Nowak et al. (2016) Kraler et al. (2012)
Needle Penetration	Internal condition, Density	Superficial; not very reliable for rectangular cross sections; material properties estimated	Tannert et al. (2014)

Hole drilling	Stresses	Device not on the market; results influenced by timber dressing and loading; material properties estimated; leaves hole	Crespo de Antonio et al. (2016)
Screw Withdrawal	Density, Shear strength, CS, MOE, MOR	Superficial; material properties estimated; leaves 3.9mm ⌀ hole	
Hardness test	MOE	Superficial; material properties estimated; leaves 10mm ⌀ hole; requires measurement of moisture content; device not on the market	
Core Drilling	CS parallel to grain, MOE, density	Leaves 10mm ⌀ hole; does not take into account influence of defects; underestimates properties due to misalignment; results not on site	Kloiber et al. (2015b) Tannert et al. (2014)
Tension Micro-specimen	Tensile strength, MOD	Superficial; invasive; high variability of results due to limited dimensions of specimen; does not take into account influence of defects; results not on site	
Pin Pushing	Internal condition, Density, CS	Material properties estimated; device dimensions limit applicability; leaves 2.5mm ⌀ hole; does not take into account influence of defects; requires species identification & moisture content measurement; device not on the market	
Loading Jack	CS parallel to grain, MOD	Leaves 12mm ⌀ hole; does not take into account influence of defects; device not on the market	Kloiber et al. (2015b)
Tension Meso-specimen	Tensile MOE	Superficial; invasive; does not take into account influence of defects; at least 4 samples per element needed; results not on site	

Most tests also have poor correlations with material properties and none of them give a complete description of the strength characteristics, therefore it is preferable to combine more than one technique together (Jasieńko et al., 2013). We will now discuss which tests can be used and combined together to assess the main characteristics of a timber structure: the geometry, the timber species, the environmental conditions, the residual resisting section and the mechanical properties.

2.1.3.1 Geometry

The geometric survey of particularly complex structures can be supported by close-range digital photogrammetry (Riggio et al., 2015b, Luhmann et al., 2014) and terrestrial laser scanning (Park et al., 2007, Kosciuk, 2012, Barber and Mills, 2011). Close-range digital photogrammetry is an optical method that derives the shape and location of an object from photographs of that object. It allows extracting three-dimensional metric models of objects in digital form (coordinates and derived geometric elements) or graphical form (images, drawings, maps) from photographic images taken from different angles: the position and size of objects is calculated using triangulation based on the location a picture was taken and the size of a reference object in the image. It is called "close-range" because the object is at a distance of maximum 300m from the camera.

To reconstruct an object from images it is necessary to describe the light sources, properties of the surface of the object, the medium through which light travels, sensor and camera technology, image processing and further processing. Every image stores all of this information. For every image point, radiometric data (intensity, grey value, colour value) and geometric data (position in image) are obtained throught methods of image interpretation and measurement. The object is modelled from this information and a mathematical transformation between image and object space.

The fundamental mathematical model used by photogrammetry is 'central projecting image' (Figure 16): shape and position of an object are determined by rays joining each image point P' to the corresponding perspective centre O' (placed where the camera is); if the imaging geometry within the camera and the location of the imaging system in object space are known, every image can be defined in 3D object space. While the number of images can be unlimited, a minimum of two images is necessary: the object point can be located in three dimensions by intersecting two corresponding image rays. The accuracy of the restitution depends on the image scale, on the geometry of the acquisition scheme, on the accuracy of the interior and exterior orientation of the camera and on the light source.

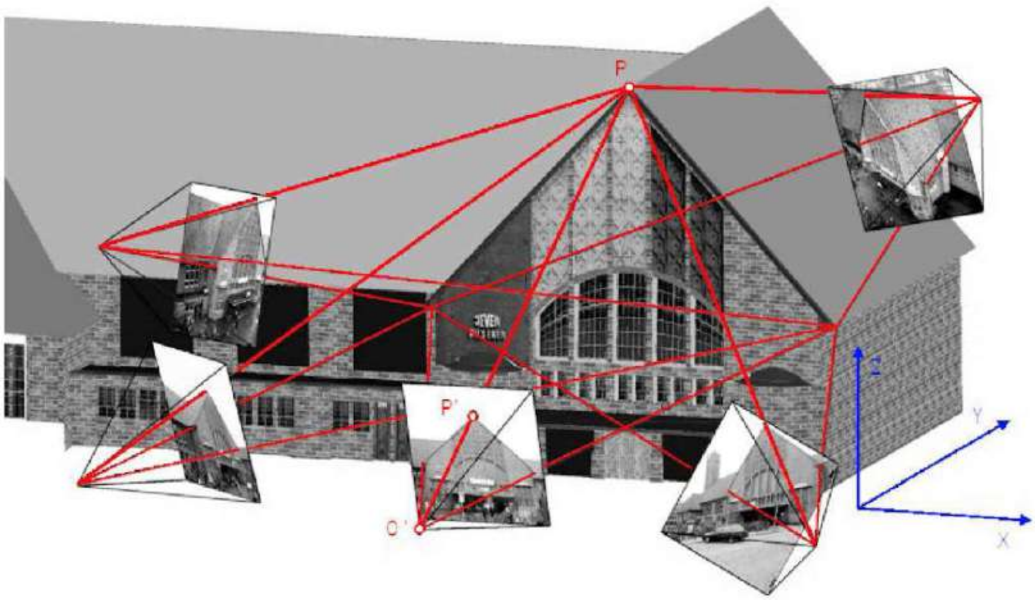


Figure 16: principle of photogrammetric measurement (Luhmann et al., 2014).

Photogrammetry can also be used to support VSG to detect defects, damage and distortions visible on the surface of the object. The photographs taken allow in fact creating a very accurate textural database for the surfaces of the object: this can be used to analyse the superficial extent and position of material features and to extract, by image processing techniques, metric information of defects, damage and distortions.

Terrestrial laser scanning (TLS) has similar results but relies on the principle of pulsed time-of-flight measurement: the distance between the origin of the scanner's own coordinate system and the target is calculated based on the time the laser takes to travel from the instrument to the target and return; the distance is calculated based on the travel speed of the pulse. Scans from different locations are usually required to ensure full coverage of the object. 3D coordinates of points on the object's surface are collected automatically and in a systematic pattern at a high rate (hundreds of thousands of points per second). RGB values can be recorded too.

The result is a dense cloud of measured three-dimensional points. This cloud of points is transformed into a meshed model that must be manually edited. 2D drawings can also be generated by using the point cloud as a base from which features are traced; however, this is not an automatic process and requires skill and experience. The accuracy and loss of original data fidelity during the post-processing of the scans is variable, depending on the distance between the instrument and the measured points (it falls in range of 10^{-4} part of the measuring distance between a few meters and 100m) and the degree of automation of the postprocessing method.

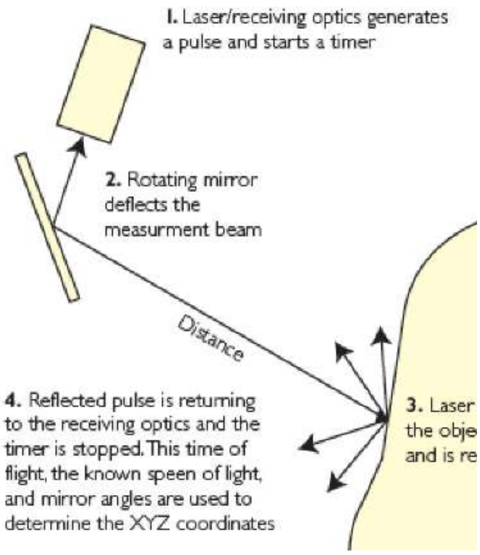


Figure 17: Schematic of time-of-flight laser scanning measurements (Bertolini Cestari et al., 2013, Park et al., 2007, Barber and Mills, 2011)

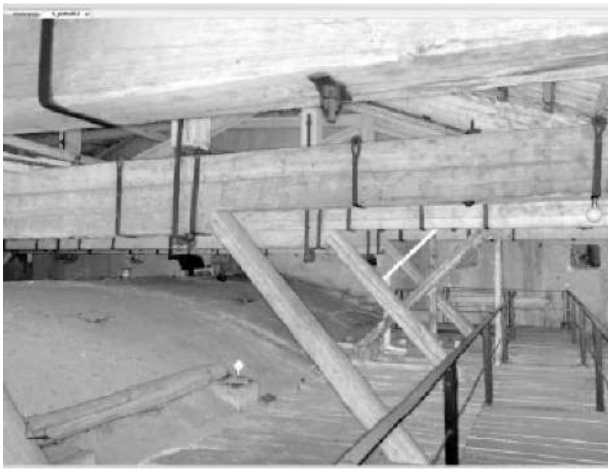


Figure 18: 3D laser scan model of a roof structure (Lamborghini et al., 2015)

Neither close-range photogrammetry nor terrestrial laser scanning are accurate enough for absolute measures, but they can be useful in identifying overall deformations and highlighting asymmetric behaviours of a structure. Photogrammetry has the advantage of being relatively low-cost compared to laser scanning, and the post processing of data acquired is less time consuming. However, TLS is less sensible to light than photogrammetry and does not require the computation for coordinate information upon image acquisition. An example of the use of photogrammetry can be found in Arias et al. (2007). Examples of the use of laser scan can be found in Cescatti et al. (2014), Lamborghini et al. (2015) (Figure 18), Bertolini Cestari et al. (2015). The two techniques can also be combined as in Massari et al. (2010) and Arce et al. (2016).

Infrared thermography (IRT), also called thermal imaging, is a quick non-destructive test that detects infrared radiation emitted by objects, which increases with their temperature: every pixel in the image records a spot temperature (Riggio et al., 2015b, Young, 2014). Therefore it allows visualising and quantifying temperature variations across surfaces, that can be linked to moisture and water infiltrations, thermal bridges, voids, cracks or delamination, areas of heat loss or air leakage. It's a rapid method, non-destructive and non-contact.

IRT cameras for building thermography work with electromagnetic waves with wavelenghts between 8 and 14μm (that do not pass through glass: objects behind glass cannot be assessed). The resolution is usually not as high as that of photographic cameras: it varies from 60x60 pixels to 640x480 pixels. Their thermal sensitivity also varies, providing more or less detail in the resulting thermal image. For useful images to be recorded there needs to be a temperature contrast; it is thus sometimes necessary to wait for the sun to heat the surface to be assessed (outdoors) or to use an artifical heating source such as lamps or heaters (indoors). A certain period of heating is needed before thermal imaging is commenced, in order to allow time for the heat to penetrate the depth required. For the same reasons, windy and/or rainy conditions are not optimal for outdoors assessments.

We will discuss in section 2.1.3.3 the use of IRT to assess environmental conditions and superficial defects/damage. In this section, related to geometry, we are interested in its use for assessing the presence of hidden voids and the geometry of hidden structures: the IRT camera only sees the temperature of surfaces, but it can provide information about the deeper structure where this affects surface temperature. A good example of this application can be found in Cantini et al. (2013), where a vault is analysed through thermography to determine the position of the timber structure above it (Figure 20).

The internal geometry of joints can instead be investigated through x-ray radiography (Riggio et al., 2015b, Riggio et al., 2014, Kasal et al., 2010), resistance micro-drilling and endoscopy (Kloiber et al., 2015a). X-ray radiography was originally developed for medical imaging but it is used for in situ structures since 1960s. It is non-destructive as it uses soft x-rays (electromagnetic waves with wavelength between 10-8m and 10-12m) that are absorbed depending on the material density and thickness. The object to be assessed is placed between the x-ray transmitter and the detector. The test result is a two dimensional x-ray attenuation image, such as the one in Figure 21, showing a wood to wood connection with an internal wood dowel. It is thus useful to detect internal heterogeneities, such as different densities, knots, connectors, material degradation etc.

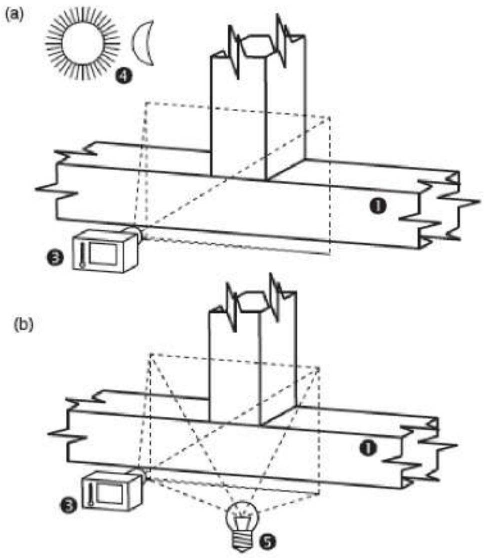


Figure 19: Principle setup for active (a) and passive (b) thermography (Riggio et al., 2015b).

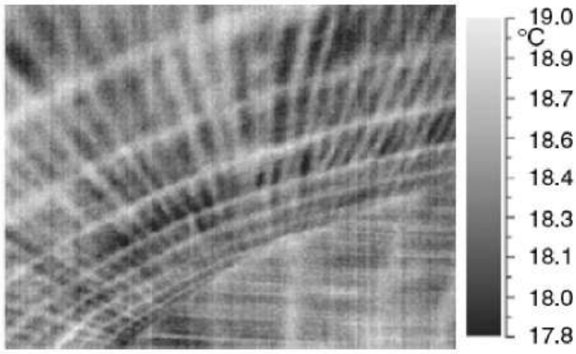


Figure 20: Thermographic image of a vault showing the timber structure behind the plaster (Cantini et al., 2013)

The image sharpness depends on how close the instrument is to the object surface and on energy levels of radiation. Lower energy radiation produces higher quality contrasts, but it is limited in its penetration ability and in he range of densities it can produce on an image. Radiography is not widely used because it has safety issues, it requires access to both sides of the timber element and does not always provide precise information on the extent and depth of internal features.

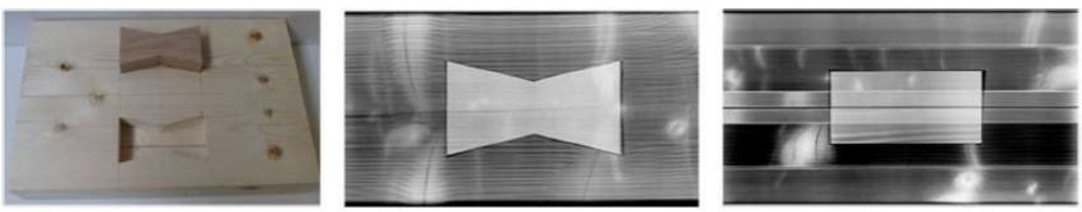


Figure 21: wood to wood connection in softwood with hardwood dowel, and the x-ray radiographies (Riggio et al., 2015b)

Resistance micro-drilling measures relative density profiles of wood by recording the penetration resistance of a thin needle (shaft diameter 1.5mm, tip diameter 3mm) into wood with constant penetration and rotation speed (Tannert et al., 2014, Jasieńko et al., 2013, Nowak et al., 2016, Rinn, 2012). It measures density profiles of wood and thus allows detecting and giving precise information on the extent and position of decay, insect damage, cracks, defects and hidden geometrical features. Points of measurements and drilling angles have to be selected carefully, especially when inspecting joints, to avoid needle deflection. Ideally, the needle should penetrate the tree rings perpendicularly. The drills should be made also based on the desired assessment: for quantitative analysis, drilling patterns at regular intervals are necessary, while for geometry/defects/decay detection, drillings should be made at all locations where there are doubts about the wood internal condition. Each drill results in a density profile where areas of low resistance (drops and low points in the graph) correspond to areas of low density: decay, cavities, cracks (Figure 22). Profiles should be interpreted and evaluated immediately in situ: if a profile cannot be explained, further drillings should be made.

Resistance micro-drilling is certainly one of the most used tests to determine the internal condition of structural timber and joints as it is very reliable and quick. It has been proven to be useful also for preliminary dendrochronological analyses (Kraler et al., 2012). It is however semi-destructive and punctual and there can be accessibility issues caused by the fact that the instrument is heavy and bulky. Examples of use of the resistance micro-drill test to detect internal features in wood can be found in Palaia et al. (2008), Frontini et al. (2015), Bajno et al. (2015), Wang et al. (2013), Massari et al. (2010), Vilches Casals et al. (2015), Riggio et al. (2016).

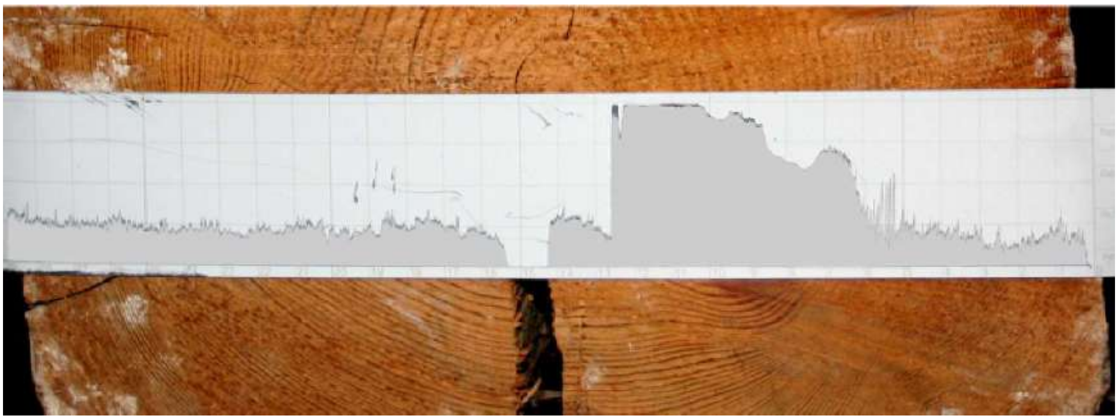


Figure 22: Example of graph resulting from the Resistance micro-drilling test (Nowak et al., 2016)

Local introspective analysis can be performed using endoscopy. The endoscope probe is inserted in small cavities and allows inspecting the condition of wood in inaccessible areas, for example when detached decorative layers hide it. It can be used also to check the presence of appropriate ventilation at beam ends. The inspected area is displayed on a monitor and both pictures and videos can be recorded during the inspection (Riggio et al., 2016). Existing openings can be used to carry out the test, otherwise openings can be expressly made, as in Kloiber et al. (2015a) (Figure 23).

Figure 23: Example of pictures taken with an endoscope inside a borehole in a timber strut (Kloiber et al., 2015a)

2.1.3.2 Timber species

The traditional procedure to identify the timber species is divided in three steps: sampling, macroscopic evaluation and microscopic evaluation (Macchioni, 2010). It is fundamental to carry out a correct sampling in terms of number, representativeness and dimensions of the samples, otherwise the macroscopic and microscopic evaluations can lead to partial or incorrect results. Therefore, the first step is to examine thoroughly the whole structure in order to assess its homogeneity in terms of species, looking at colour, vein, texture, and determine the need for sampling (Macchioni, 2010).

The macroscopic and microscopic evaluations use comparative techniques: characteristic aesthetical and anatomical features are identified in the three sections of a sample - transversal, radial, tangential - and compared with standards in a scientific atlas of wood species (Nardi Berti et al., 2006). The macroscopic evaluation can be carried out with a magnifying glass. A list of macroscopic features is provided by Crivellaro et al. (2016) (Figure 24). Unfortunately it rarely allows to a confident identification, especially in case of softwood. Thus it is often necessary to proceed with the microscopic evaluation by means of optical or electronic microscopes. Microscopic features are provided by Nardi Berti et al. (2006) (Figure 25). In some cases it is still necessary to terminate the identification at a level higher than the species within the botanic taxonomy.

Alternatively, radiography and tomography are used, especially for wooden artefacts such as paintings, where sampling is not feasible (Van den Bulcke et al., 2009). Automated imagine recognition techniques are used in the wood industry to analyse a great amount of samples more quickly (Hang-jun et al., 2013, Shuaiqi et al., 2015).

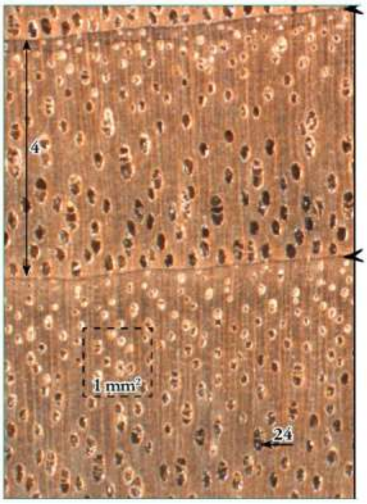


Figure 24: Example of identification of macroscopic features in the transversal section of a sample of Alder (alnus sp.); 4=semi-porous annual ring, 17=between 6 and 20 vessels per mm^2, 24=tyloses (Crivellaro et al., 2016)

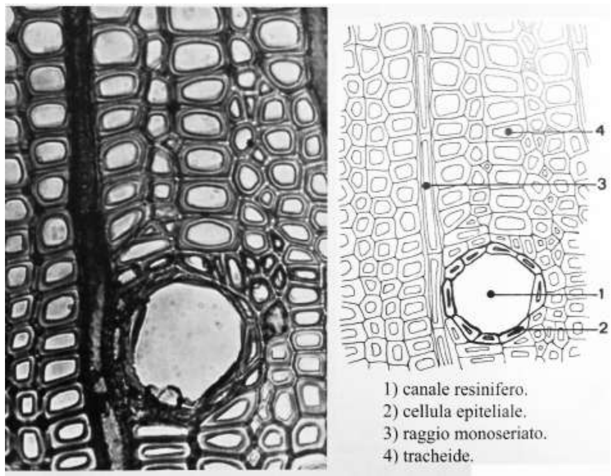


Figure 25: Example of identification of microscopic features in the transversal section of a sample of Douglas fir (pseudotsuga douglasii) (Nardi Berti et al., 2006); 1=resin canal, 2=epithelial cell, 3=uniseriate ray, 4=tracheid

2.1.3.3 Environmental conditions

As previously mentioned, timber is vulnerable to biological attack and it is very sensitive to moisture. The presence of biological attack strongly depends on the environmental conditions in which the structure is. Thermometers, hygrometers and thermal cameras can be useful in measuring the air temperature and relative humidity, the wood moisture content and in detecting humid areas.

Wood moisture content (MC) represents the proportion of water to the proportion of wood material [%]. The only direct method for determining MC in timber is to measure the quantity of water in a wood sample or the weight of the sample when oven-dry; it is however semi-destructive and time consuming. The alternative is to estimate MC in situ by means of indirect methods that use the relationships between MC and other measurable physical–chemical properties of wood: hand-held electric moisture meters using the resistance, capacitance or hygrometric method (Kasal and Lear, 2010, Riggio et al., 2014). The meters can be pin-less, taking measurements on the surface, or with pins, taking measurements at different depths, which is preferable although semi-destructive (Figure 26). Measurements must be calibrated based on wood temperature and species.

MC readings are necessary to carry out a correct VSG and to calibrate the results from NDTs/SDTs, but also to understand if there are favourable conditions for biotic attack. Environmental conditions can be quite variable, with daily and yearly changes. The best way to assess them is through long-term monitoring. However, even punctual measurements should remain inside a certain range in order to avoid biotic attack: air temperature should remain between 15° and 21° and the relative humidity between 45% and 65% (Ridout, 2000). MC should never be too far from the equilibrium moisture content, calculated based on the air temperature and relative humidity (Figure 28), and it should always remain between 8% and 18% (Ridout, 2000). Only few specialized insects can survive moisture contents beneath 18%: beetles (that can survive up to 12%, a few up to 8%) and termites (in warmer regions). Fungi generally will not appear under 20% moisture content (Ridout, 2000).

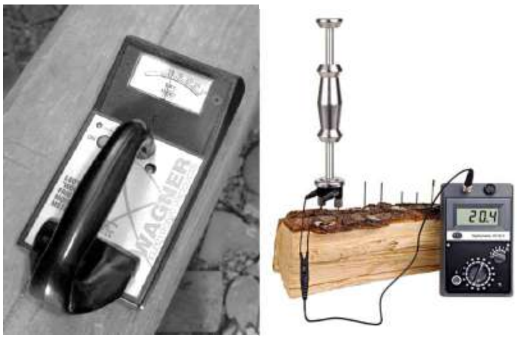


Figure 26: Example of moisture meter without pins on the left and with pins on the right

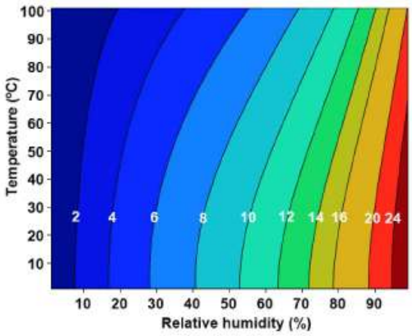


Figure 27: Equilibrium moisture content based on the air temperature and relative humidity (Ross, 2010)

Infrared thermography can be useful in spotting thermal bridges or areas with high humidity, caused by water ingress problems (Figure 28), as in Rodríguez Liñán et al. (2015), Morales-Conde et al. (2013), Riggio et al. (2016). It can also be used as support for VSG as in Colla and Gabrielli (2015) (Figure 29), especially if the timber surface is not visible (e.g. it is painted). Knots, shrinkage cracks and other fissures appear as colder features, or warmer if they are passing-through cracks. Results are however limited to the surface and can be affected by surface roughness/porosity and by environmental conditions (wind, temperature, etc). As previously discussed, active thermography in heated environments is in fact far more efficient than passive thermography in unheated environments (Riggio et al., 2015b).

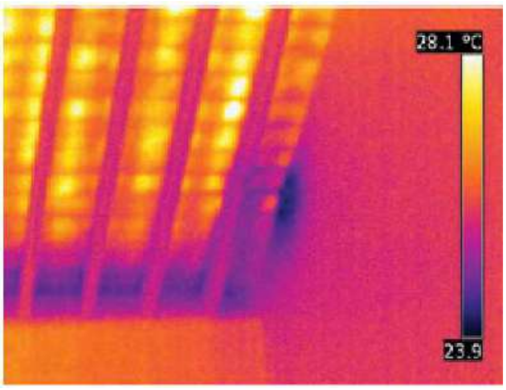


Figure 28: damp areas identified in thermographic imaging (Rodríguez Liñán et al., 2015)

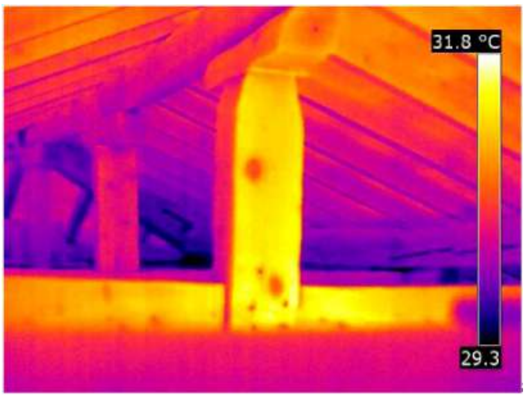


Figure 29: Thermographic image showing knots in a timber roof structure (Colla and Gabrielli, 2015)

2.1.3.4 *Residual resisting cross section*

Historic timber structures may show significant variation in the cross section geometry along the same element, as a result of both construction methods and deterioration. 3D laser scanning and digital photogrammtery can be useful to measure the cross section from outside, as discussed in section 2.1.3.1, but a reliable assessment of the internal condition of wood is fundamental to be able to estimate the overall dimensions correctly. Acoustic tests, resistance micro-drilling, x-ray radiography, detector dogs, ground penetrating radar (GPR), endoscopy, needle penetration and pin pushing can all provide information on the internal condition of timber elements, including natural defects, damage and material degradation (Table 1). Non-destructive methods (acoustic tests, x-ray radiography, detector dogs, GPR, endoscopy) are often used as screening tests to decide where to use SDTs.

Acoustic tests and resistance micro-drilling are the most used tests for this purpose. Resistance micro-drilling has already been discussed in section 2.1.3.1. Acoustic tests are of various types, ranging from the simple sounding with a rubber hammer, to time-of-flight methods, tomography and ultrasonic echo (Dackermann et al., 2014, Ross and Hunt, 2000, RILEM, 2010). The traditional method of sounding with a blunt object (typically a rubber hammer) is widely used to detect interior deterioration. Based on the tonal quality of the sounds resulting from the strike, large interior voids or decay can be identified. However, the test is highly subjective and high expertise is required to hear differences in the sounding because conditions other than decay can contribute to variations in the sound quality. Moreover, the test does not provide any quantitative information and is not effective for early or intermediate stages of decay nor for timber with big sections. An example of its use can be found in Frontini et al. (2015).

In order to address the drawbacks of traditional sounding various non-destructive testing methods have been developed. One of the most common and simplest is to measure the time-of-flight of sound waves, also called stress waves. Stress waves are induced by striking the specimen with an impact device instrumented with a sensor that sends a start signal to a timer. Another sensor, placed on the other side of the specimen, records the arrival of the propagating stress waves and sends a stop signal to the timer. This allows measuring the time needed for stress waves to travel accross the specimen. The velocity of the waves (V) is then calculated based on this time (T) and the distance (d) between the sensors:

$$V = \frac{d}{T}$$

Acoustic waves are of elastic type, hence they provide indications about the elastic properties of a material: their velocity of propagation is a function of Young Modulus of Elasticity (E), material density (p) and Poisson coefficient (v). The wave velocity increases proportionally with the increase of the elastic modulus:

$$Vp = \sqrt{\frac{E}{p}\frac{1-v}{(1+v)(1-2v)}}$$

This means that waves with higher velocity identify denser, sound material, while slower waves identify degraded material, characterised by voids, cracks or decay. Wave velocity is also related to frequency (f) and wavelength (λ):

$$V = f \times \lambda$$

Wavelength (λ) is inversely proportional to frequency. High-frequency waves (ultrasonic) have shorter wavelengths: they detect smaller defects and thus have a higher resolution, but they are attenuated more quickly and thus cannot penetrate thick specimen or low density degraded material. Instead, low-frequency waves (sonic) with longer wavelenghts can cross thick specimen and degraded material, but are characterized by a lower resolution. The resolution of sonic signals equals to about one third of the wavelenght: the smallest detectable defect is greater than one third of the wavelength.

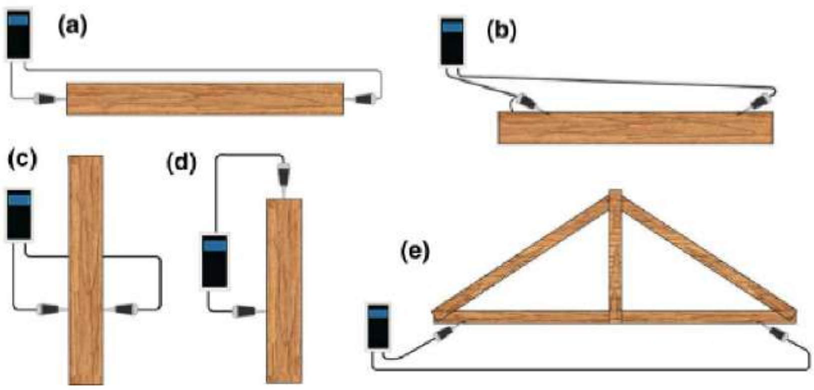


Figure 30: time-of-flight measurements in structural timber using different wave propoagation modes: direct longitudinal (a), indirect longitudinal (b and e), transverse (c), semi-direct (d) (Dackermann et al., 2014)

The velocity of stress waves is also affected by the moisture content and temperature (high MC causes an increase in propagation time while high temperature causes an increase in velocity) and by wood anatomy. Velocity is higher in grain longitudinal direction, where there are few or no boundaries to cross, and lower in grain transverse direction, where waves encounter numerous cell walls. For most structural members fibers of the wood align more or less with the longitudinal axis of the member. The test can be carried out in both directions and various modes (Figure 34:). For sound wood, longitudinal stress wave velocities generally range between 3500 and 5000 m/s, depending on the timber species, while transverse stress waves fall in the range of 1000-1500 m/s. Reference velocities for various species can be found in literature (Dackermann et al., 2014) and compared with the measured velocity to assess the internal conditions of the timber specimen. The relative decrease ($\Delta Vrel$) between the reference velocity ($Vref$) and the measured one ($Vmes$) indicates the amount of decay between the two sensors:

$$\Delta Vrel = \frac{Vref - Vmes}{Vref} \times 100$$

Sonic and ultrasonic tomography uses the same method (time-of-flight) but with more sensors distributed on the surface of the specimen allowing to obtain cross-sectional or three dimensional imaging of the object (Figure 31). The number of sensors is nearly unlimited, allowing to adapt the resolution to case by case requirements. The wave propagation time, recorded for each pair of sensors, and the coordinates of the points where the sensors are placed, are the input data for the tomographic analysis. As shown in Figure 31, the received signal provides a projection of the object's internal conditions: the coloured lines in the 2D-tomogram indicate apparent stress-wave speed between sensor positions - green lines indicate intact and mechanically connected parts while red lines show areas where the waves traveled around an anomaly.

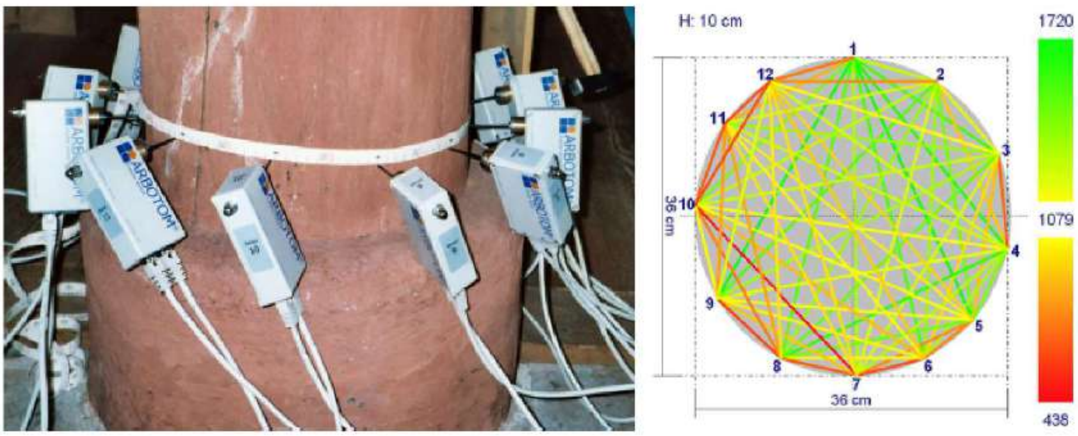


Figure 31: sensor chain for cross-sectional tomography (left) and 2D-tomogram of the timber post (right) (Dackermann et al., 2014)

After correcting the results for timber anisotropy (by relating the sonic pulse velocity in a generic direction inside the timber element to the pulse velocity in radial direction) iterative or direct inversion algorithms can be used for tomographic reconstruction: the result is a velocity map to which the timber section perimeter can be overalapped to ease interpretation (Figure 32). In the example in Figure 32 it appears that the average velocity through the section is low, below 1000 m/s, and only in limited areas, particularly at the centre and top, the recorded velocities seem to indicate sound material (Colla, 2015).

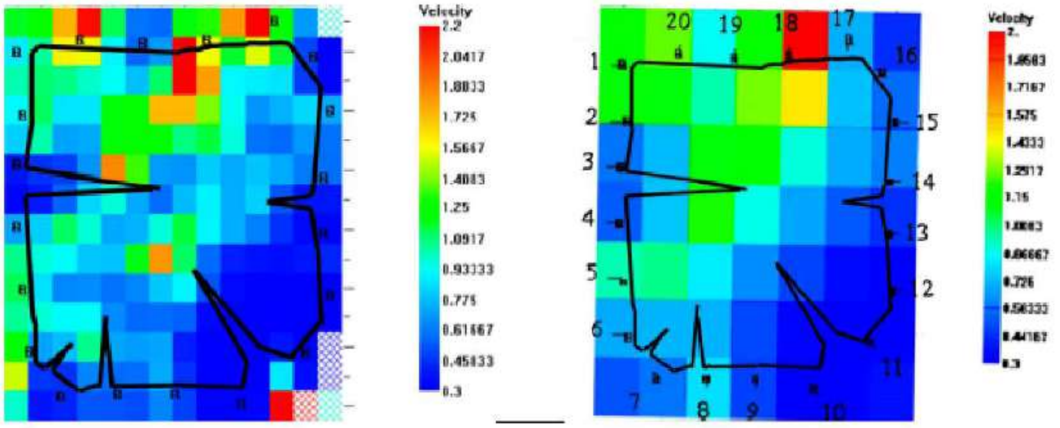


Figure 32: velocity model (14x14 pixels) of a timber section, corrected for material anisotropy, obtained from 5 iterations of straight type and 6 iterations of curved type; signal velocity legend from 300 to 2200 m/s (left) - velocity model (7x7 pixels) of the same timber section after 5 straight iterations and 5 curved iterations; signal velocity legend from 300 to 2000 m/s (Colla, 2015)

Tomography is time consuming and requires high expertise, but the resolution is much improved compared to simple time-of-flight methods. As in simple time-of-gflight methods, access to both sides of the specimen is required. The ultrasonic echo technique, on the contrary, can be carried out with one face of the specimen accessible only. It is in fact based on the reflection of ultrasonic stress waves on material inhomogeneities, such as the back surface of the investigated object (called back wall - this allows assessing the thickness of the object) or other interfaces such as a damaged area. During the measurement, a sensor placed on the object's surface emits a sonic wave which passess through the object and is reflected by the back wall. Any irregularity in the wooden structure changes the structure of the reflected signal, called back-wall echo.

Results of the ultrasonic echo technique are usually presented as A-scans (Figure 33 right) and B-scans (Figure 33 left). A-scans show the transmission time and intensity of the pulse, while B-scans are cross sections of the investigated object obtained by composing various A-scans recorded with a defined distance. B-scans enable to identify changes in signal structure along the measured axis: in Figure 33, for example, the back wall at 9.5cm and the knot at 4.5cm are clearly detected in the B-scan on the left. Other detailed tests need to be carried out in areas with no or an unexpectedly early echo from the back wall, because this can be a sign of damage. With the ultrasonic echo tenchique only it is in fact difficult to locate the exact position of damage within the specimen and to distinguish between one large irregularity and a cluster of small ones.

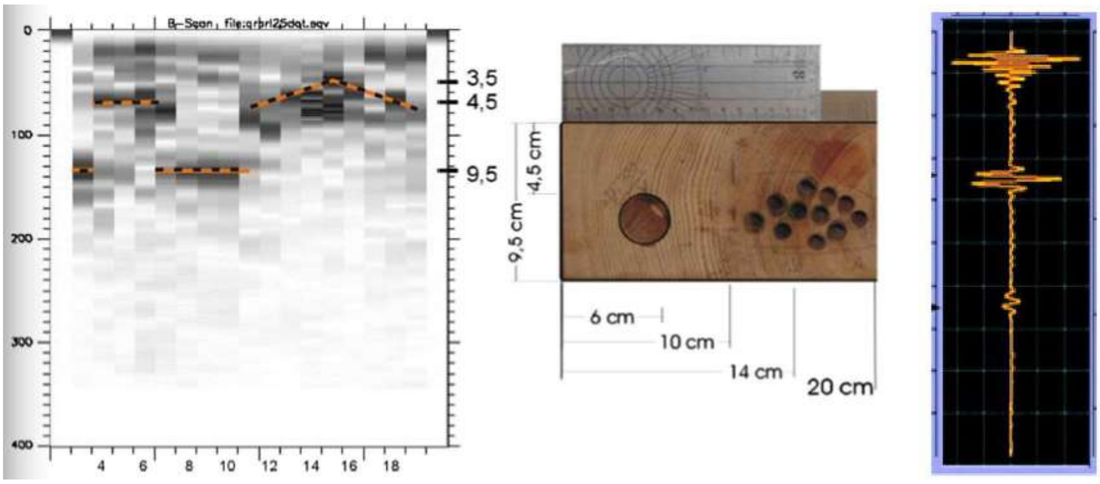


Figure 33: Example of elements investigated with the ultrasonic echo technique: in the centre a section of the investigated element (Dackermann et al., 2014), on the left an A-scan (Dackermann et al., 2014) and on the right a B-scan (RILEM, 2010)

In conclusion, acoustic tests are appealing because they are non-destructive. However, they cannot detect early decay and they require the identification of the species and the measurement of the moisture content to calibrate their results. Examples of use of acoustic tests can be found in Rodríguez Liñán et al. (2015), Cescatti et al. (2014), Morales Conde et al. (2015), Palaia et al. (2008), Colla and Gabrielli (2015), Bajno et al. (2015), Brozovsky and Zach (2008), Wang et al. (2013). Acoustic tomography is preferable as it is a global method, but it can be limited by attenuation or low resolution and the test set-up is time-consuming. Examples of use of tomography can be found in Imposa et al. (2014), Colla (2015), Riggio et al. (2015b) and Riggio et al. (2016).

X-ray radiography and endoscopy can also be useful to assess the residual resisting section, as already discussed in section 2.1.3.1. A very traditional technique uses detector dogs to detect insect infestation: they are very effective but only for the insect species they have been trained to identify (Zahid et al., 2012).

GPR is an electromagnetic (EM) technique based on the propagation and reflection of very short pulses (<10ns) inside the investigated object (RILEM, 2010, Riggio et al., 2014). An antenna in contact with the surface of the tested object moves along survey lines and emits EM signals into the object. These signals are reflected by interfaces between material layers with different dielectric properties. Measurements can be performed in reflection mode (one antenna used for both transmission and rececption of the signals) or transmission mode (investigated object placed between two antennas).

The propagation velocity and attenuation of EM waves are directly related to the permittivity of dielectric materials such as wood:

$$v = \frac{c}{\sqrt{\varepsilon}}$$

c is the propagation velocity of EM waves in free space, ε is the material dielectric constant or permittivity. The permittivity of wood depends on several parameters: moisture content, density, temperature, fiber direction and applied frequency.

Data recorded by GPR is visualized in real-time bi-dimensional images called radargrams: on the horizontal axis there is the distance covered by the antenna and on the vertical axis the signal reflection time. The vertical axis can be converted to depth (d) by knowing or estimating the dielectric constant of the materials or by knowing the thickness of the investigated element:

$$d = vt/2$$

v is the wave propagation velocity and *t* is the measured reflection time. By analysing the position and amplitude of the reflections inner defects and features can be detected. In the radargram in Figure 34, especially after applying a ground removal filtering (bottom radargram), metal carpentry and inclusions are clearly visible, as well as knots; the reflection of the rear side of the beam is also visible as a continuous line (b) parallel to the surface reflection line (a) (Colla and Gabrielli, 2015).

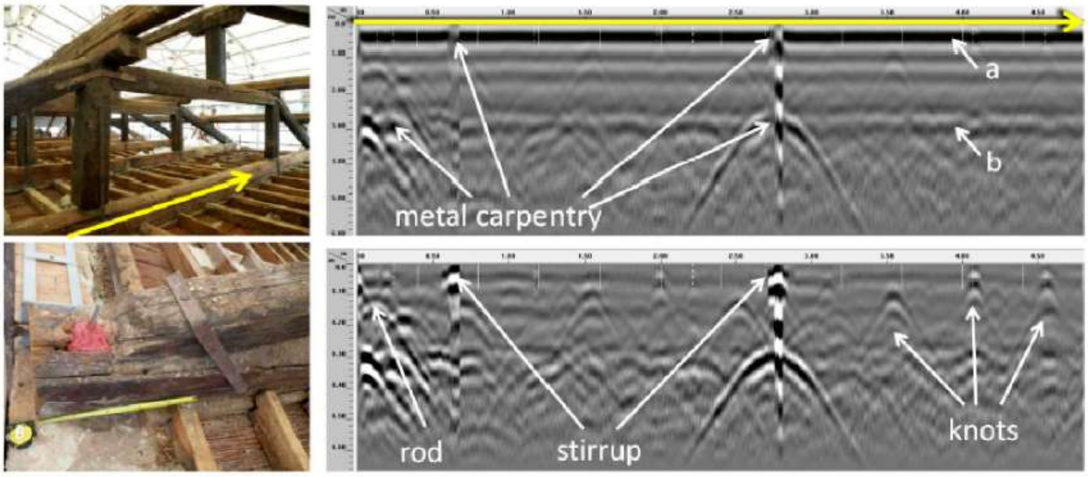


Figure 34: GPR test carried out on a timber tie-beam in reflection mode: survey line on th elatera face of the tie-beam (top left in yellow), detail of the metal elements near the beam head (bottom left), raw and post-processed radargrams (right, top and bottom) (Colla and Gabrielli, 2015)

The advantage of GPR is its ability to investigate a large surface within relatively short time. The application of GPR to timber structures is still limited, however, because GPR signals are affected by several paramenters (moisture content, salinity, material density) and thus it requires high expertise to collect data and to post-process and interpret the results. An example of its use for timber elements can be found in Colla and Gabrielli (2015).

The needle penetration test measures the penetration depth of a pin shaped striker into a wood specimen resulting from a defined impact loading on the striker (Tannert et al., 2014, Kloiber et al., 2014b). The depth of penetration of the striker is an indication of the wood's resistance: the shallower the indentation, the higher the resistance. Thus it determines the condition of a wood member at or near the surface, allowing detecting superficial degraded/damaged areas. The results are primarily related to wood density, wood species, moisture content and ring orientation. The device with the brand name "Pilodyn" is widely used for this test, becoming a synonym for such test (Figure 35). Examples of its use can be found in Imposa et al. (2014), Palaia et al. (2008), Brozovsky and Zach (2008), Massari et al. (2010) and Branco et al. (2010).

Compared to needle penetration, the pin pushing test allows assessing the condition of the investigated object at various depths, as it is based on the recording of a force applied to a pin gradually pushed into wood (up to 11cm depth) in relation to the measured distance of pin displacement (Kloiber et al., 2015b). The device can be fixed to the investigated element with a fabric strap and the pin is pushed into the material by a rack and pinion gear driven by two opposite manual cranck for both hands (Figure 36).

The output is a graph of the applied pin pushing force (Figure 37) which can be used to establish the mechanical resistance of wood: the peaks of the graph correspond to a higher force and thus a higher wood resistance, while the lower values of force indicate a lower resistance. The resistance depends on the wood species, density and moisture content, thus the test results should be interpreted considering these parameters. Moreover, the test is accurate only when the pin penetrates in the radial direction, perpendicular to the grain. Disadvantages of the test are that it is semi-destructive, local and that the developed device is not on the market yet.

Figure 35: Pilodyn device: the penetration depth of the striker can be read directly on the scale attached on its side (Tannert et al., 2014)

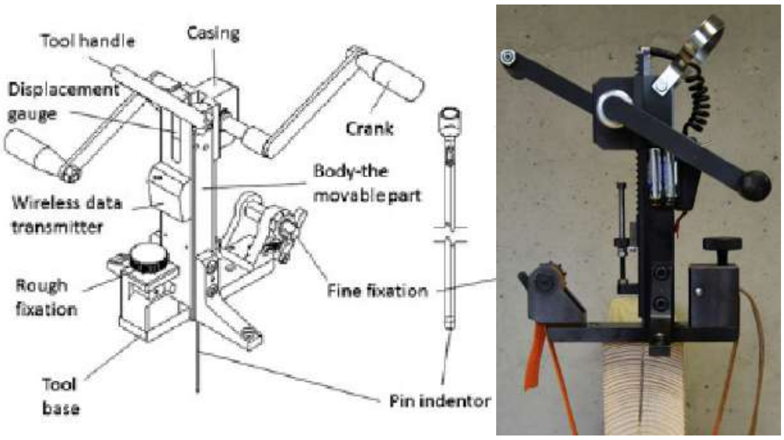


Figure 36: The device developed for the pin pushing test (Kloiber et al., 2015b)

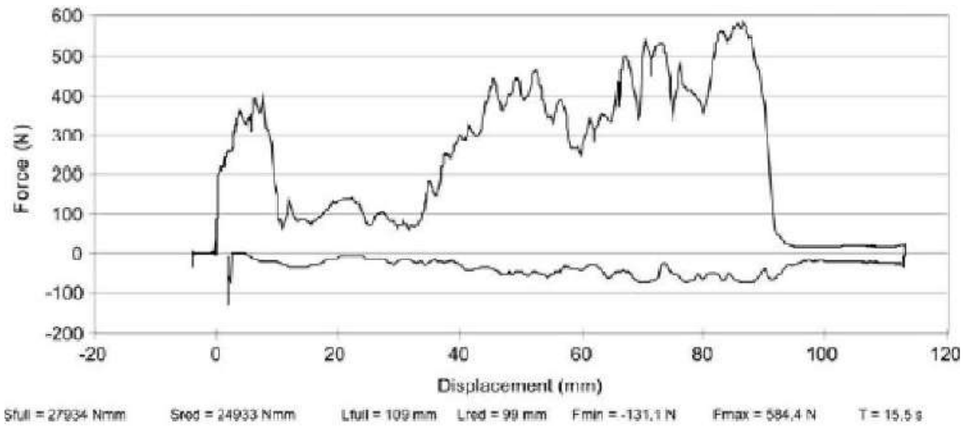


Figure 37: The output graph of the pin pushing test: the x axis is the depth to which the pin was pushed, the y axis is the force needed for pushing (Kloiber et al., 2015b)

The future of timber diagnosis could be image recognition: researchers are developing the integration of high resolution images of wood texture (obtained through digital photogrammetry) and non-destructive imaging of internal defects (obtained through ultrasonic tomography), to understand how external and internal features are correlated and if external ones can help interpreting the internal ones (Riggio et al., 2013). Unfortunately, an in situ test procedure has not been developed yet.

2.1.3.5 Mechanical properties

Mechanical properties are often estimated based on the timber species, but they can vary a lot from one piece of timber to the other, even if of the same species, because timber is anysotropic and heterogeneous. VSG helps taking into account the defects of timber, but it is generally overly conservative. That is why NDTs and SDTS are used to support VSG results.

Density, bending strength and modulus of elasticity are three main characteristics of timber from which other important parameters can be derived based on of empirical relations. Some tests can measure them directly: tension micro- and meso-specimens, core drilling, loading jack (Table 1). Other tests can only estimate these parameters through correlations with their output parameters. Unfortunately correlations are often poor, variable and not reliable, mostly due to the natural variability of timber properties, but also because of the test conditions (Feio and Machado, 2015).

Tension micro-specimens are used to measure tensile strength (which is very close to bending strength) of timber elements by testing small samples taken from its surface (Tannert et al., 2014, RILEM, 2010, Kloiber et al., 2015b). Triangular micro-specimen (5/8mm reduced to 8/12mm^2 in the central part) or meso-specimen (15x15x25mm reduced to 10x5mm^2 in the central part) are extracted with a circular or jig saw on the element's surface in order to have their length parallel to the grain. A careful choice of sampling place is fundamental in order to avoid defects and degraded areas.

Wooden blocks are glued to both ends of the samples in order to be able to insert the samples in simple grips and load them in a common testing device (Figure 38). The tensile strength and the modulus of deformability are measured to calculate the modulus of elasticity. The test is unfortunately semi-destructive and its results are related to the superficial layer of the element in that particular area where the sample was extracted. Moreover, the limited dimensions of the specimen cause high variability of results (Kloiber et al., 2015b). The interpretation of the results carried out on small wood samples can in fact be problematic (Lechner, 2013). An example of its use can be found in Kloiber et al. (2010).

Core drilling is also a local, semi-destructive test: cores of small diameters of about 5mm (at least 20mm long) are extracted from timber elements and tested in a compression device (Figure 39) (Kloiber et al., 2015b, Kasal, 2010). It allows evaluating the compressive strength and modulus of elasticity. Manual or electrical driven drills are used for core extraction. The resulting holes (10mm diameter) are smaller than most knots found in timber and do not compromise the element's overall strength. The samples must be extracted from healthy, undamaged wood in the radial direction.

The loading jack test (Kloiber et al., 2015b, Kloiber et al., 2014a) is particularly interesting compared to the others as it is the only that can be carried out in-situ. The device measures the compression behavior of clear wood zones of timber members as they are loaded by a miniature loading jack inserted into a pre-drilled hole of 12mm diameter. Simmetrically arranged grips/jaws are pushed apart inside the hole to get as close as possible to pure compression-loading mode in a laboratory (Figure 40). The test can be repeated at different depths up to 115mm. Unfortunately, it is again a local semi-destructive test and the device is not on the market yet. An example of its use can be found in Kloiber et al. (2015c).

Figure 38: Tensile test of a triangular bar (Kloiber et al., 2015b)

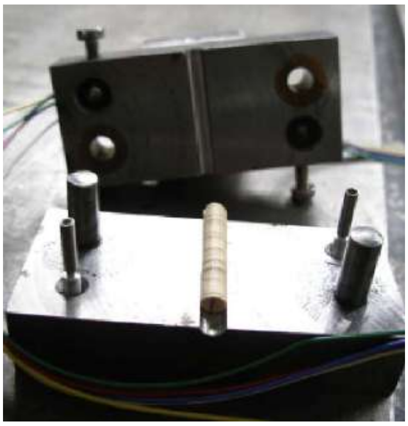


Figure 39: Compression device to test radial cores (Kloiber et al., 2015b)

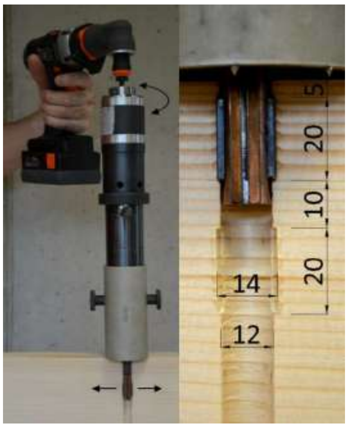


Figure 40: The loading jack device (Kloiber et al., 2015c)

Destructive tests on samples give the most reliable results. Even though they are necessarily invasive, one sample can sometimes be used to obtain more than one parameter, maximising its value: samples from core drilling can be used, for example, to identify the species (Macchioni 2010), to carry out mechanical tests to determine the compressive strength, modulus of elasticity and density (Kloiber et al., 2015b), to measure the moisture content (Kasal and Lear, 2010), to evaluate the type and level of decay (Kasal, 2010) and to determine the felling date and provenance through dendrochronological analysis (Pignatelli 2010). Unfortunately all this information is related only to the specific point in the timber element where the core has been extracted; more cores can be collected but only up to a limited number since they are dirsuptive (Kasal, 2010).

Some in situ semi-destructive tests are less invasive and still reliable: the hole drilling, the hardness test, the pin pushing, the loading jack, the needle penetration and the screw withdrawal (Table 1). Unfortunately, the first four devices are not on the market yet (Crespo de Antonio et al., 2016, Kloiber et al., 2015b). The pin pushing, loading jack and needle penetration have already been discussed. While the results of the first two tests have good correlations with wood density and compression strength parallel to the grain (Kloiber et al., 2015b), needle penetration is widely used as it is not invasive, very quick and easy to use, but the correlations with density of its results have been found to be quite poor (Íñiguez-González et al., 2015).

Hole drilling was born to measure residual stresses in technological metallic devices and was later used for isotropic materilas only; a recent study (Crespo de Antonio et al., 2016) shows its potential for in situ timber structures. A rosette of three strain gauges is glued around the area where the stresses want to be measured (Figure 41). One gauge is parallel to the fibre direction, another one is perpendicular to the fiber direction and the last one is on the bisector. This area must be on the bottom face of a timber element under bending, where the maximum tensile stresses are. A small hole is then drilled in the area inside the gauges to relief the stresses, allowing measuring strains around the hole. The results of this first attempt to use the technique on in situ timber structures are promising, but the technique's reliability will be clear only once other studies are made.

The hardness test proposed measures the resistance to plastic deformation due to a constant load (Tannert et al., 2014, Kloiber et al., 2015b). A variable load is used to produce a given depth of impression on the lateral surface of wood, orthogonal to the grain direction. The test device is a mechanical or electric actuator equipped with a load cell, eventually electronic, and a displacement transducer, all attached to the investigated timber element with collars (Figure 42). The instrument has a 10mm diameter steel hemispherical bit as indenting device. The instrument measures the load force *R* required to embed 5mm the indenting device into wood. A correction factor δ is used to correlate *R* with the elastic modulus parallel to the fiber direction $E_{0,mean}$ in order to take into account the presence of defects:

$$E_{0,mean} = \delta \text{ x A x } R^{0,5}$$

A is a coefficient that depends on the timber species, the value of the applied force and the wood moisture content. Several factors influence the hardness measurement of wood, such as anisotropy, heterogeneity, moisture content, surface orientation of wood and the shape and size of the object applying the force. Nevertheless the test has been successfully used since the 80s; an example of its use can be found in (Tomasi et al., 2008).

The screw withdrawal test is used to estimate wood density, modulus of elasticity and modulus of rupture (Tannert et al., 2014, Kloiber et al., 2015b). Two devices are available for this test: one is a screw-extraction-force tool where the load cell measures pull out loads of screws; the other is a clamp type tool that mounts a load cell in the clamp (Figure 43). Commercially available wood screws can be used as probes; they should be long enough for the entire depth of wooden objects. The probes are pulled out of pre-drilled lead holes. Coaxial multiple-withdrawal testing can be used to obtain axially distributed withdrawal resistances. The relationship between withdrawal resistance (*P*) and wood density (*D*) is:

$$D = a\ x\ P + b$$

The regression constants *a* and *b* are obtained from a database. The relationship between the withdrawal resistance (*P*) and compression strength (*C*) is:

$$C = c\ x\ P + d$$

The regression constants *c* and *d* are obtained from a database. The relationship between the withdrawal resistance (*P*) and dyinamic modulus of elasticity *(MOE*) is:

$$MOE = e\ x\ D\ x\ v^2 + f$$

D is average density obtained from the withdrawal test, *v* is the stress wave speed determined by stress wave timers and *e* and *f* are regression constants obtained from a database. The relationship between the withdrawal resistance (*P*) and modulus of rupture *(MOR*) is:

$$MOR = g\ x\ P\ x\ v^2 + h$$

v is the stress wave speed determined by stress wave timers and *g* and *h* are regression constants obtained from a database. The test is semi-destructive and local, but most of all it is difficult to compare results with other studies since the probes are not standardized. The results are also affected by moisture content, size, and the presence of sap wood and heart wood.

Figure 41: A rosette of three gauges placed around the drilled hole to measure bending stresses (Crespo de Antonio et al., 2016)

Figure 42:The test device used for the hardness test (Kloiber et al., 2015b)

Figure 43: The device used for screw withdrawal (Kloiber et al., 2015b)

There have also been efforts to correlate results obtained through resistance micro-driling with results from destructive tests measuring mechanical properties of timber. The resistance measure (*RM*) is correlated to density, strength and modulus of elasticity through relative resistance (*RA*) and drilling depth (*H*):

$$RM = \frac{\int_0^H RA\ x\ dh}{H}$$

Many studies show that the correlations between *RM* and timber mechanical propertires are however quite poor and the fact that there are many different devices available on the market requires separate calibration for each device (Jasieńko et al., 2013, Nowak et al., 2016). The main goal of resistance micro-drilling is therefore not the assessment of timber mechanical properties but the verififcation of results obtained from other non-destructive tests. Examples of use of *RM* to estimate timber mechanical properties can be found in Cescatti et al. (2014), Morales-Conde et al. (2013) and Kloiber et al. (2015a).

Time-of-flight acoustic tests are the most used in situ to estimate the mechanical properties of timber because they have the advantage of being completely non-destructive. The dynamic modulus of elasticity (MOE_d) can be estimated by correlating the stress wave velocity (*V*) and the timber density (*ρ*):

$$MOE_d = V^2 x\ \rho$$

They are the only non-destructive test that can be used for this purpose, even though recent research is looking into using thermography (Carpentier et al., 2015) and radiography (Lechner and Kliger, 2015) to determine wood density. The results of time-of-flight acoustic tests require however a calibration based on the timber species and the moisture content, and the density is needed to estimate the Modulus of Elasticity (Dackermann et al., 2014). Usually, tabulated values for various species are used to estimate density, since its direct measurement cannot be carried out non-destructively. Moreover, correlations have been found to be variable, even because they are often obtained with tests on small defect-free samples that do not represent adequately the in situ timber's complexity (Rodríguez Liñán et al., 2015). The influence of operational conditions seems to be critical as well (Feio and Machado, 2015). Examples of the use of time-of-flght acoustic tests for the assessment of timber mechanical properties can be found in Rodríguez Liñán et al. (2015), Cescatti et al. (2014), Morales-Conde et al. (2013), Morales Conde et al. (2015), Bajno et al. (2015), Vilches Casals et al. (2015).

2.1.4 Structural Analysis

All the information gathered through visual assessment methods and tests are used to carry out a structural analysis in order to evaluate the level of safety of the structure. Structural analysis of historic structures is a challenging task because it involves many uncertainties, such as load history, boundary conditions, etc. This is particularly true for timber structures where it is difficult to estimate the geometry of the resisting section, the material's mechanical properties, the strength of joints, and the behaviour of spatial structures. It must be kept in mind that historic timber structures are generally more flexible than those designed today, so it is not appropriate to apply modern service limit states to them. Moreover, they are often very robust: more than one load path must be considered, because decay in one member might just transfer stresses on a neighbouring member. It is thus suggested to use an iterative procedure with subsequently increased complexity, where structural analys is continuously updated with the information gathered during the surveys (Cruz et al., 2015, Holzer, 2016). The important parameters for structural analysis are the dimensions and shape of the elements' resisting cross section, the mechanical properties and the behaviour of joints.

As previously discussed, the measurement of the elements' resisting cross section and its subsequent modelling can be difficult and time consuming. A study was carried out by Lourenço et al. (2013) to understand if using average values of the cross section dimensions provides adequate levels of safety. Four different roof structures were considered and modelled with the real sections, average sections, minimum sections and average section ±10% variation. It was concluded that using a probabilistic model with mean cross sections equal to the results from inspection and a coefficient of variation of 10% results in reasonable estimates of safety. It was also found that assuming all deteriorated timber as non-resistant leads to erroneous results – a remaining capacity factor for the residual cross section area of 10% provides more consistent results (Lourenço et al., 2013). The shape of the resisting section is generally approximated to round (Lourenço et al., 2013) or rectangular (Pompejano et al., 2015), although no study has been carried out to assess the influence of this parameter.

Mechanical properties assessed through VSG and NDTs/SDTs are often higher than expected; it is thus suggested to use a partial material factor γ_M>1,0 (Cruz et al., 2015). The results from VSG are often preferred because they are more conservative and keep into consideration the defects of timber (Rodríguez Liñán et al., 2015).

The connections between elements are often the weakest point of the structure (Branco et al., 2010, Holzer, 2016). Most traditional carpentry joints are only able to partially transfer moments, compression and shear forces and they are only minimally able to transfer tensile forces (Jasienko et al., 2014). This is true especially if the fasteners are decayed or have failed. Moreover, the weakening of the cross section of the elements caused by the joints' indentations is rarely taken into consideration. According to Cruz et al. (2015), only if suitable data is available for the joints' moment-rotation capacity their contribution to the overall structural performance may be taken into account instead of assuming them as pinned joints; in any case no allowance should be made for the capacity of timber pegs. Holzer (2016) agrees on the fact that complex modelling of joints should be implemented only when strictly necessary and in any case in a second step of the analysis.

In case of spatial load-bearing systems numerical analysis with 3-dimensional models is necessary (Cruz et al., 2015). The presence of sarking boards connecting all the frames together and to the gable walls transforms Scottish roofs into veritable 3D structure (similar to an upside-down boat). Numerical analysis is thus necessary to consider the sarking’s contribution. There are not many published examples of structures with sarking boards, and the few that have been investigated with a structural analysis have not always considered the contribution of the sarking (Pompejano et al., 2015). In the case of Valentino’s Castle in Turin (Italy) the structure was modelled at first without the sarking, and it was not verified. Then the contribution of the sarking was added, in the form of an equivalent flat shell of the same stiffness with equivalent thickness equal to 7cm, and the structure was verified (Bertolini Cestari et al., 2015) (Figure 45). This further proves the sarking’s contribution to the overall structural performance.

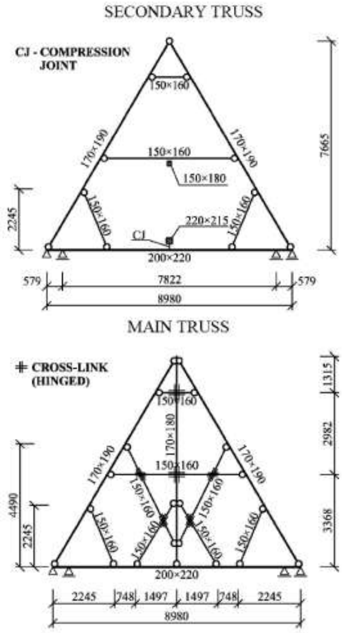


Figure 44: Non-linear joints modeled by Gocal et al. (2015)

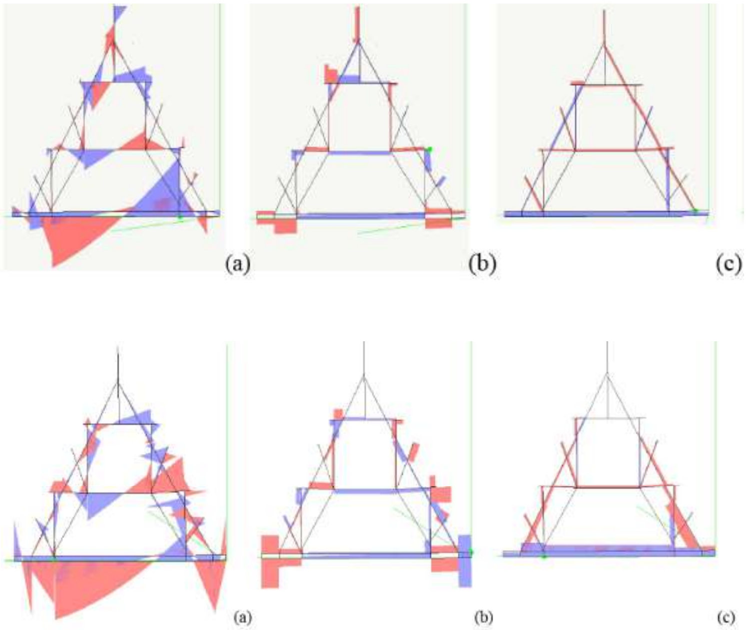


Figure 45: Example of stresses in a truss considering the contribution of the planking (above) and disregarding it (below); a) bending moment, b) shear force, c) axial force in a truss (Bertolini Cestari et al., 2015)

2.1.5 Standards

Standards allow professionals to carry out assessments more confidently and provide them with more reliable results. An overview of standards for the in situ assessment of timber structures is given by Macchioni et al. (2010) and Augelli (2014).

The Eurocode program by CEN up to now lacks of adequate tools. The only international standards which partly address the conservation of historic timber structures are ISO 13822 (2001) and EN 16069 (2012). The first applies to timber only partially since it relates to all building materials and its principal aims are structural safety and economy, not conservation. The latter is not specific for timber either, as it gives guidelines on how to carry out an initial survey of any artefact belonging to the built cultural heritage.

At a national level, Italy has the most complete series of standards related to the conservation of historic timber structures: UNI 11161 (2005) and UNI 11138 (2004) establish criteria and requirements for the assessment and interventions on historic timber structures, UNI 11119 (2004) is related to the condition assessment and Visual Strength Grading of single timbers elements, UNI 11118 (2004) gives guidelines for the species identification, UNI 11141 (2004) for dendrochronological analysis and UNI 11130 (2004) and UNI 11035 (2003) define the specific terminology. These standards have been developed by the Work Group 20 'Wood and wood based products' of the Technical Committee UNI-NORMAL, created in 1996 in Italy, following an agreement between the Ministry of Culture and the Italian Standardisation body (UNI) (Macchioni and Piazza, 2006). The need for specific standards related to historic timber structures sparked from the safety needs of many public historic buildings and many bad restoration examples. Fourty experts from different entities (universities, private companies, professionals, public administrations, etc.) were involved in the activity of Work Group 20, organized through the institution of ad hoc groups working on the development of a common terminology and a common standard.

The Italian standards are used today by professionals and researchers in Italy (Bertolini et al., 2010, Macchioni et al., 2011, Massari et al., 2010) and other European countries such as Portugal (Lourenço et al., 2013, Sousa et al., 2015, Sousa et al., 2013), Belgium (Schueremans, 2009), Greece (Bertolini Cestari et al., 2007). In fact, they have been developed as standards valid on a national level but suitable for proposal on a European level.

UNI 11138 (2004) is of great importance as it allows controlling the quality of interventions on wooden artefacts by establishing criteria for the assessment, design and implementation of interventions on historic load-bearing timber structures. It specifically describes the need to evaluate the present condition of the timber structure in order to understand its real structural behaviour and its role within the building. A process of survey and analysis is prescribed, which includes a geometrical characterization, decay, damage and defects characterization and a full report on the current situation comprising thematic detail drawings.

According to UNI 11161 (2005) the assessment of historic timber structures must include:

- the description of the present state: historical documentation, written description and graphical/photographic documentation of the structure and its present condition, including classification and quantification of damage and decay;
- the diagnosis of the single elements: the dating, the identification of the timber species, existing and future thermo-hygrometric conditions and moisture content of wood, condition diagnosis of all wood components, and classification and quantification of potential decay.

UNI 11119 (2004) specifies how to proceed with the detailed survey of each wooden element, evaluating its original characteristics and any modifications occurred during its service life. To conduct the inspection correctly, the object must be accessible, clean and visible; otherwise the lack of full access must be recorded and alternative investigations conducted. The assessment must include the identification of the wood species, the wood moisture content, the class of biological risk (EN 335-2, 2006, EN 335, 2013), the geometry, the position and extension of any defects, decay and damage and of critical areas. All these characteristics are then used to grade the entire wood member and, if necessary, each critical area separately; if an alteration occurs due to mechanical damage or localized biological decay, only the efficient section must be considered. Each grade corresponds to maximum values of stresses that can be applied. The standard also specifies what information should be included in the report.

Other countries have standards for visual strength grading of timber: EN 1912 (2007) gives guidance on existing grading standards and the species to which they are normally applied. UNI 11119 (2004) is however the only standard for grading in situ historic timber.

Switzerland published in 2011 a new series of standards (SIA 269/5, 2009), comprehensively described by Brühwiler et al. (2012) and Kohler and Steiger (2011). The part on wood is based mainly on UNI 11119 (2004). Following the Swiss example, Scotland could provide itself with a set of standards for historic timber structures based on the Italian ones. This would ensure that professionals follow a standardized procedure during the assessment and the design and implementation of interventions.

The above mentioned standards, together with recommendations given by ICOMOS (1999b), emphasize the importance of surveying thoroughly timber structures before any intervention, and give guidelines on what should be recorded. They do not however explain how to graphically report the survey and how to represent damage and decay in an accurate and codified way. As underlined by Augelli (2014), there is the need for a codified representation mode for timber structures, such as the one available for masonry (UNI 11182, 2006), to allow for clarity and understanding amongst the different professionals involved in the conservation of timber structures.

2.2 A novel database of seventeenth- and eighteenth-century buildings in Scotland

The following sections describe the methodology used in this thesis to investigate Scottish timber roofs, which has been devised based on the state-of-the-art tools, methods and standards reviewed in the previous section. It includes the creation of a database and related mapping, archival research, preliminary geometrical, technological and condition surveys in 53 buildings and detailed investigations in 8 case studies. A structured form has also been developed to collect, report and analyse all the research data.

2.2.1 Data acquisition

To assess the extent, nature and condition of seventeenth- and eighteenth-century Scottish timber roofs, the first step was to identify Scottish buildings of the period and gather all available information on their location, typology, geometry, design, history and condition. This information has been collected from the available literature and from online databases providing descriptions and locations of buildings listed or scheduled by HES (Historic Environment Scotland website - Designations, 2016), drawings/pictures/historical records of buildings surveyed by RCAHMS (Canmore website - Sites, 2016) and a description of the condition of historic buildings in disrepair (Buildings at Risk Register website - Buildings, 2016).

Unfortunately these descriptions, pictures and drawings do not always include a record of the inside of the buildings and very rarely mention construction techniques and structural aspects. Moreover, although they store and provide a great amount of information, they are not searchable: it is not possible to search buildings based on the construction date, or based on the name of a person who designed/built/transformed them (architect/mason/wright/patron), or any other parameter different from the building name and location. It is therefore not possible to assess the extent of seventeenth- and eighteenth-century Scottish buildings with these tools alone.

This is why it has been necessary to create a new relational database and related mapping of seventeenth- and eighteenth-century Scottish buildings able to store, manage, search and analyse a great amount of data. The database has been developed with Microsoft Access and ArcGIS. The data, collected from the above mentioned databases and from the available literature, is stored in Access, while ArcGIS is used to plot results of searches and queries.

This tool has been used to locate seventeenth- and eighteenth-century Scottish buildings and record their history, identifying the different types of interventions carried out (alterations, repairs, extensions, etc), the corresponding dates and the people involved in each intervention (commissioners, architects, masons, etc). All the available information on the structural and typological aspects as well as the present condition of the buildings has been recorded. The dates of birth and death, provenance, apprenticeship, and any other information about patrons, architects, masons, etc, has been included as well. Drawings, pictures and other documents are stored through external links. About 1500 buildings have been identified so far, but the database is continuously populated and expanded by the members of ADCRU.

Metadata has been included through qualifiers, in order to be able to keep a record of the 'quality' of data. For intervention dates, for example, a qualifier has been introduced to be able to distinguish between an intervention which is reported to have been carried out in the last quarter of the seventeenth century, and one reported to have been carried out between 1675 and 1700: they have the same start and end dates (1675-1700) but the former has '25' as qualifier and the latter '1', because the date range is precise only in the second case.

All data has been referenced to literature, the HES/RCHAMS/BARR databases or other websites, or personal comments of scholars, professionals and building owners. Discrepancies between references have been reported too, when present.

2.2.2 Selection of reference buildings

A sample of 53 reference buildings has been researched and surveyed in order to collect first hand data to integrate the database. These reference buildings have been selected with the help of a series of queries run in the database, based on certain criteria aimed at identifying the buildings more likely to retain the original roof structures and, amongst these, the most representative of the architecture of the period and those for which more sources of information were available.

It was decided to focus on stately buildings designed by architects, since they have been less researched so far, as previously discussed: public buildings, stately homes and outstanding town houses. The selection process implemented amongst these buildings can be summarized in 4 phases (phase 2 and 3 ran parallel):

1) At the time when the first selection was made, in spring 2014, 1240 buildings were included in the database - the following criteria were used in this first phase:

- All the demolished, never built and ruinous buildings were discarded;
- Other buildings were discarded because the whole building, or a big part of it, was rebuilt after 1800;
- Buildings with flat roofs were discarded as well, since it was decided not to include this structural typology in the study;
- A further shortlist was created by selecting buildings that had a major intervention during seventeenth or eighteenth centuries and no major alteration/restoration after 1800.

2) The first phase ended with 450 buildings; a further selection was made by including buildings:

- whose timber roof is mentioned in literature or in the HS/RCAHMS/BARR databases;
- whose timber roof structure is visible in drawings held at the RCAHMS archives;
- that still retain the original plaster ceilings, and so probably the above original structure too;
- whose records report the name of the wrights that worked there;

- that represent key moments in Scottish architectural history, due to innovative ideas/techniques/forms that have been used in their design and construction;
- in which dendrochronological analysis has been carried out, so that information on timber species and felling dates is available;
- owned by HES or the National Trust for Scotland (NTS), easier to access.

3) In the meantime, the surveyors/archaeologists/architects working for NTS and HES were contacted to ask for information on buildings in their care. In some cases they were able to say straight away if the original roof structure is still in place and if it is accessible. They also suggested other buildings that had not been included in the shortlist resulting from phase 1.

4) Phase 2 and 3 ended with a shortlist of around 100 buildings. The owners were contacted to ask for information and accessibility. When the contacts were not found, a letter was sent by post. When someone replied and a visit was agreed, other buildings in the same area were selected (picking from the list resulting from phase 1), in order to optimize the trip time and expenses.

Among the contacted owners, 80 replied. Some replied too late for a visit to be arranged (the winter season does not provide optimal environmental conditions to carry out surveys) and some denied access to their roof space for various reasons: lack of interest, attic spaces used for activities that could not be interrupted, presence of bats, no knowledge of how to access the roof structure, etc. Eventually, 28 buildings or groups of buildings (such as Stirling Castle) were visited during summer 2014.

In order to widen the sample, a second selection of buildings was made in 2015 based on criteria of proximity (Glasgow and Edinburgh) and accessibility and based on the findings of the surveys carried out the year before: late seventeenth- and early eighteenth-century buildings showed innovations in roof carpentry, especially those with big internal spans. Therefore plans and sections found in literature and online (Canmore website - Sites, 2016) were analysed to find buildings of this period with wide internal spans. At the time when this second selection was made, 1500 buildings were included in the database.

A total of 49 building owners were contacted and 25 visits were arranged for summer 2015. Thereafter 53 reference buildings or groups of buildings were surveyed in total (Figure 46, Figure 47). The roof structure of one of these buildings was not visible nor accessible as it was hidden behind plaster and no hatches were available. Moreover, during the survey of 8 of the buildings it became apparent that the roof structures were not the original ones and dated to post-1800: this was established by looking at their arrangements and details (discussed in chapter 3). The survey of these structures was not carried out in detail.

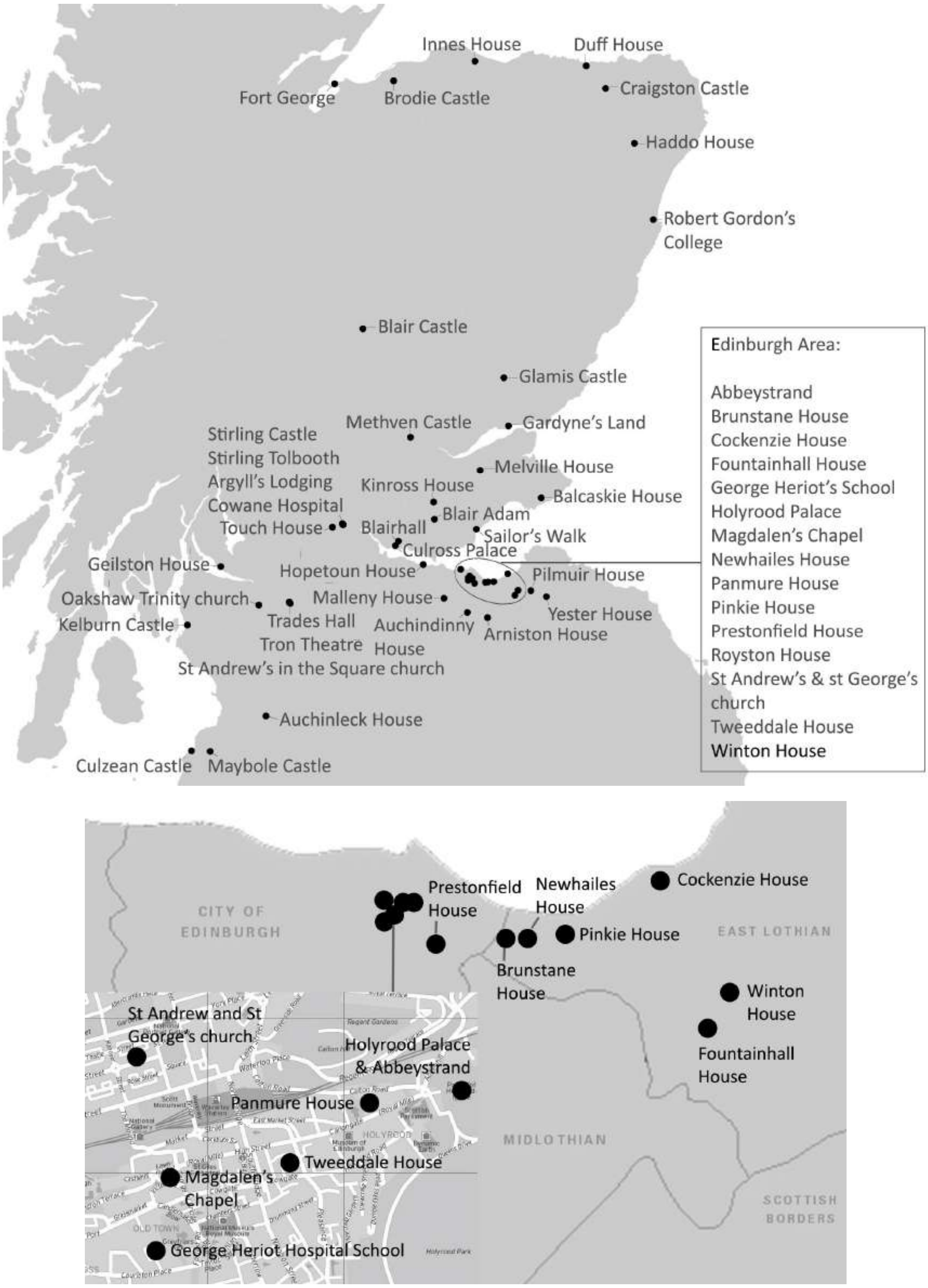


Figure 46: Names and locations of the 53 reference buildings surveyed - adapted from Serafini and Gonzalez Longo (2016) - with a zoom on the Edinburgh area

The final sample of surveyed buildings retaining seventeenth- and eighteenth-century roof structures (a few examples date to end sixteenth century) is of 44 (Figure 47). Some of these buildings have more than one roof structure, either because they are groups of buildings (as Stirling Castle) or because their roof structures are structurally independent or correspond to different construction phases, as in Touch House (Figure 48). Thus we surveyed a total of 59 roof structures (Figure 47).

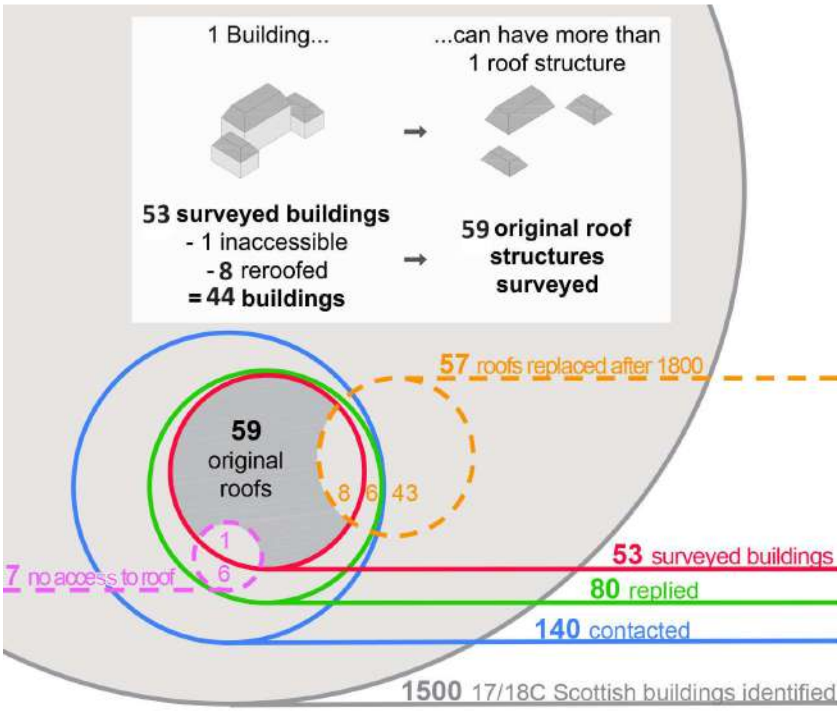


Figure 47: The selection process of the reference buildings surveyed and the results of the surveys in terms of number of original roof structures found - adapted from Serafini and Gonzalez Longo (2016)

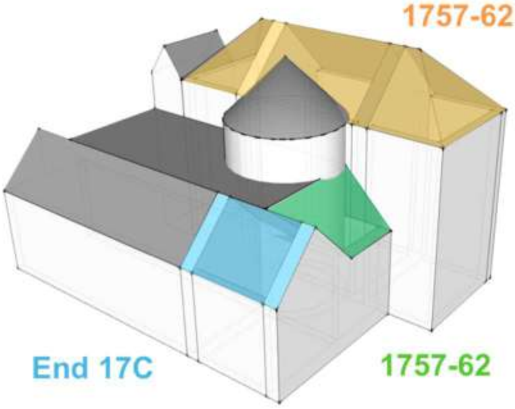


Figure 48: A model of Touch House seen from North-West showing the three roof structures surveyed

Only three of the surveyed roofs had already been researched and published: Stirling Castle (Hanke, 2008), Methven Castle (Murdoch, 2010) and Magdalen Chapel (Ross and Brown, 1916). The dendrochronological analysis of the roof timbers in Gardyne's Land, Duff House and Fort George is reported in unpublished reports (Crone, 2001, Crone, 2008a, Crone and Mills, 2008) as well as the surveys of the roofs of Geilston House, Sailor's Walk, Panmure House and Brodie Castle Stables (Addyman, 2000, Addyman, 2011, Addyman et al., 2006, Lelong et al., 1998).

2.3 Preliminary surveys carried out in 53 buildings

2.3.1 Data collection

A preliminary survey has been carried out in the selected 53 reference buildings to identify the geometry, construction techniques and typologies of roofs and to start assessing their present condition. A desk survey was carried out at first to gather all available information related to the building, also through e-mail or phone contact with the owners, tenants, managers or professionals taking care of the buildings. The second step was a half-day or one day visit to the building to carry out in situ geometrical, technological and condition surveys. Archival research was carried for some of the surveyed buildings, based on availability and accessibility of documents. The collected data is reported through texts, drawings and photographs included in Appendix E.

2.3.1.1 Geometrical and technological survey

As suggested by Riggio et al. (2014) and Cruz et al. (2015) a preliminary geometrical and technological survey was carried out to identify the roof structural typology and its construction details and to measure its overall dimensions. A tape meter, a laser meter and a digital camera were used. In order to be able to compare the structures and draw conclusions from a historical, typological, technological and structural point of view, a series of fixed parameters were recorded:

- roof form (gabled, hipped, dome, etc);
- roof geometry (maximum span, height, pitch, length, etc);
- internal structural arrangement (common rafter roof, purlin roof, etc);
- connections with the supporting structure (wall-plates, rafter feet, etc);
- elements' scantlings and section shape (square, renctangular, etc);
- timber dressing (hand-axed, hand-sawn, etc);
- joint types (mortice and tenon, lapped, etc) and fasteners (metal nails, wooden pegs, etc);
- timber species (macroscopic analysis);
- roofing material (slates, lead, etc) and its fasteners (nails, pegs, etc);
- carpentry marks;
- evidence for reused timber (redundant joints, etc);

The dimensions shown in the final drawings in Appendix E (span, height, length, scantlings, etc) result from the average of a minimum of two measurements (Figure 49). The pitch has been deduced based on the span and height. When the plan or internal structure were more complicated further measurements were taken. The geometry of joints was not measured at this stage.

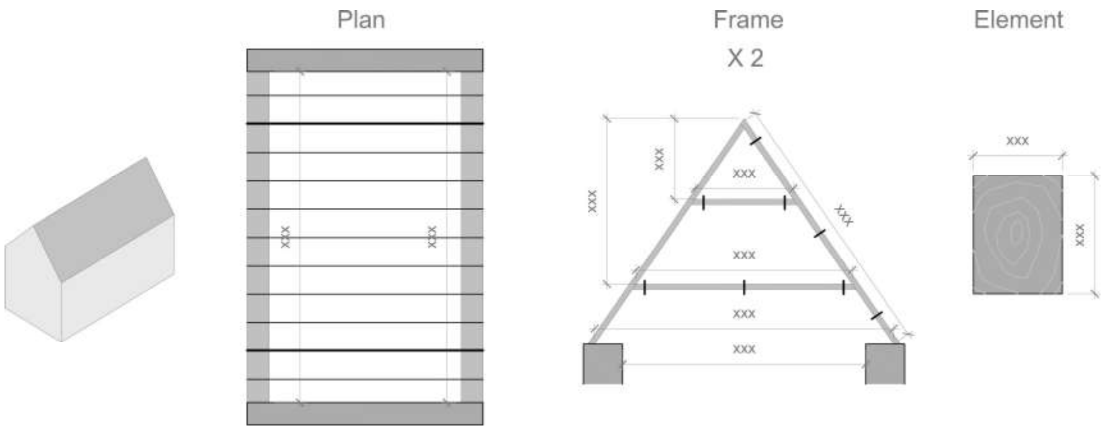


Figure 49: Diagram of measurements taken during the preliminary surveys in a typical common rafter roof

2.3.1.2 Condition survey

The preliminary survey was also aimed at assessing accessibility and identifying any obvious damage and critical areas (Cruz et al., 2015, Riggio et al., 2014). It included in fact the recording of:

- the use of the roof space, e.g. if it is partly occupied by attic rooms;
- accessibility conditions: which parts of the structure are visible, which are accessible and measurable, is the roof space well lit and easily accessible, etc;
- the presence of decorative features which might restrict repair interventions;
- the presence of unfavourable environmental conditions (poor ventilation, presence of pigeons/wasps/bats, etc) and/or poor maintenance;
- past or recent alterations and repairs;
- signs of mechanical damage (deformations, cracks, etc) and material degradation (fungi/insect attack, etc).

The extent and position of damage, degradation and defects were not documented at this stage.

2.3.1.3 Archival research

Archives were searched for information on the surveyed buildings and on wrights of the period. Documents were found through the SCAN online catalogue (Scottish Archive Network, 2016). A list of the archival documents available for the surveyed buildings is provided in each building form in Appendix E. Due to time constraints, only documents found in archives in Glasgow and Edinburgh or in the buildings themselves were consulted: pictures, drawings, accounts, estimates, minutes, correspondence and registers held at National Records of Scotland (NRS), National Library of Scotland (NLS), the Royal Commission on Ancient and Historical Monuments of Scotland (RCAHMS), Edinburgh University Library (EUL), Edinburgh City Archives (ECA), Mitchell Library (ML), George

Heriot Hospital, Glasgow Trades Hall, Touch House, Tweeddale House. A full list of the consulted documents is provided in Appendix G.

The number of consulted documents including useful information on roof structures and wrights is limited but it has nevertheless been of aid to the research. Some drawings and photographs in RCAHMS and NLS showed roof structures (Appendix A) and were thus useful to select buildings to visit and integrate the sample of surveyed roofs. Other documents were useful to date the roof structure, as in Stirling Castle (NLS MS1646 Z.02/18b, 1719, NRS GD124/15/471, 1707), George Heriot Hospital (NRS GD421/5/2, 1633-42), Glasgow Trades Hall (ML T-TH 1/1/7, 1787-98), Touch House (TCH letter to Mr Seton, 1751, TCH account by Paterson, 1757, TCH account by Deas & Co, 1757-8), Tweeddale House (NLS MS14665/64, 1750-6, NLS MS14551/115, 1750, NLS MS14551/126, 1753). In other cases drawings were useful to identify and date past interventions, as in George Heriot Hospital (GH reports, 1997), Glasgow Trades Hall (TDH 1/899, 1856, ML Shanks 152/T6, 1955), Pinkie House (RCAHMS LOR/M/17/5, 1953, HES report by Adams, 1954), Touch House (RCAHMS LOR/T/1/5, 1928), Tweeddale House (NLS MS14680, 1779-82, TWH drawings/pictures, 1980s), Yester House (NLS MS14551/109, 1742-49). Documents related to St Mary's Chapel Incorporation (ECA SL 34/4/1, 1706-74, ECA SL34/4/2, 1706-1774, NLS ACC 70/56, 1711-33, ECA SL 34/1/7, 1740-55) and others discussed in section 3.3.4 were used to start understanding the timber procurement, the design process and the role of architects, wrights and patrons.

Future research should focus on carrying out a more thorough archival research. In fact, we have already identified other potentially interesting archive material, not consulted due to time constraints; a list is provided in Appendix D.

2.3.2 Identification and dating of different types of roof structures

We have grouped the surveyed roof structures in four main types, based on their design and structural arrangements: purlin roofs and three types of rafter roofs - common rafter roofs (or simple frames), complex frames, and trussed roofs (Figure 50). 3D trusses form a subgroup of trussed roofs and composite roofs are composed of more than one type of structure.

In purlin roofs the rafters, devoid of any load-bearing function, rest on purlins, which are the real supporting elements. The purlins span from one gable wall to the other; in one example only (Touch House) they are also supported by vertical/slanted timber elements. Rafters generally have notches in correspondence with purlins; in Touch House only they are morticed in the purlins and therefore composed of two separate timber elements.

Common rafter roofs (or simple frames) are composed of closely spaced rafter couples joined at the apex and connected transversally by one or more collars and longitudinally by the sarking boards.

There is no structural hierarchy amongst the rafters: they are all load-bearing. The vast majority of these roofs supports a simple pitched gabled roof, but some have intersections and some others support hipped, M or shed roofs.

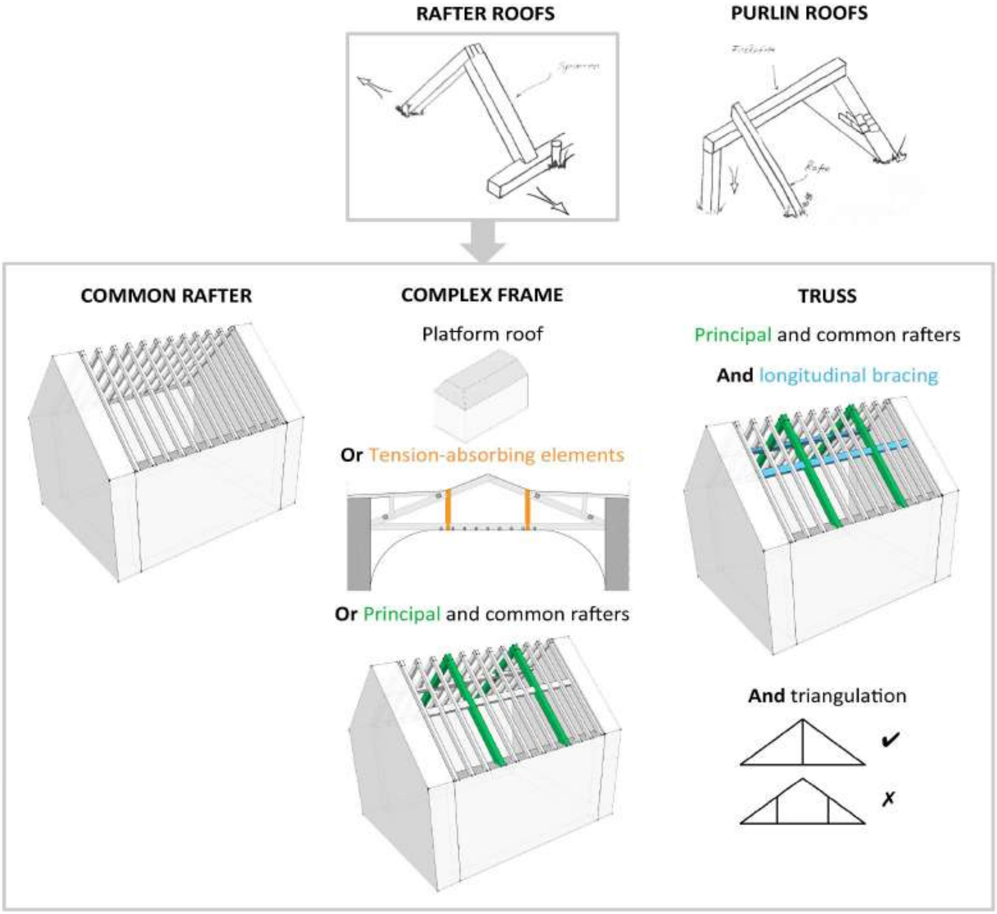


Figure 50: Diagram showing the classification in structural types established for the surveyed roof structures

Complex frames are similar to simple frames but they are characterized by one or more of these three features: platform arrangements, tension-absorbing elements, subdivision in primary (load-bearing) and secondary (non load-bearing) rafters. These features are important because they change the structural behaviour of common rafter roofs: the platform eliminates the joint at the rafter apex and places a horizontal element in its place, posing deflection and joint-opening issues; tension-absorbing elements reveal awareness of the fact that timber can work in tension and that ties can be used to counteract deflection in other elements; the subdivision in primary and secondary rafters allows to concentrate loads only in certain areas of the supporting masonry.

The structures we have included in the group of trussed roofs strongly differ from roof structures used in Scotland previously and their design suggests foreign influences, as we will discuss in chapter 3. They all employ principal and common rafters, butt-purlins and triangulation, although not always effective. Butt-purlins are morticed in the rafters, rather than vice versa, thus they only provide longitudinal rigidity to the structure (Figure 85, Figure 86). The 3D trusses sub-group includes trusses that develop spatially: Culzean Castle and St Andrew and St George's church employ radial trusses, whilst Glasgow Tron church employs trusses in both directions, transversally and longitudinally.

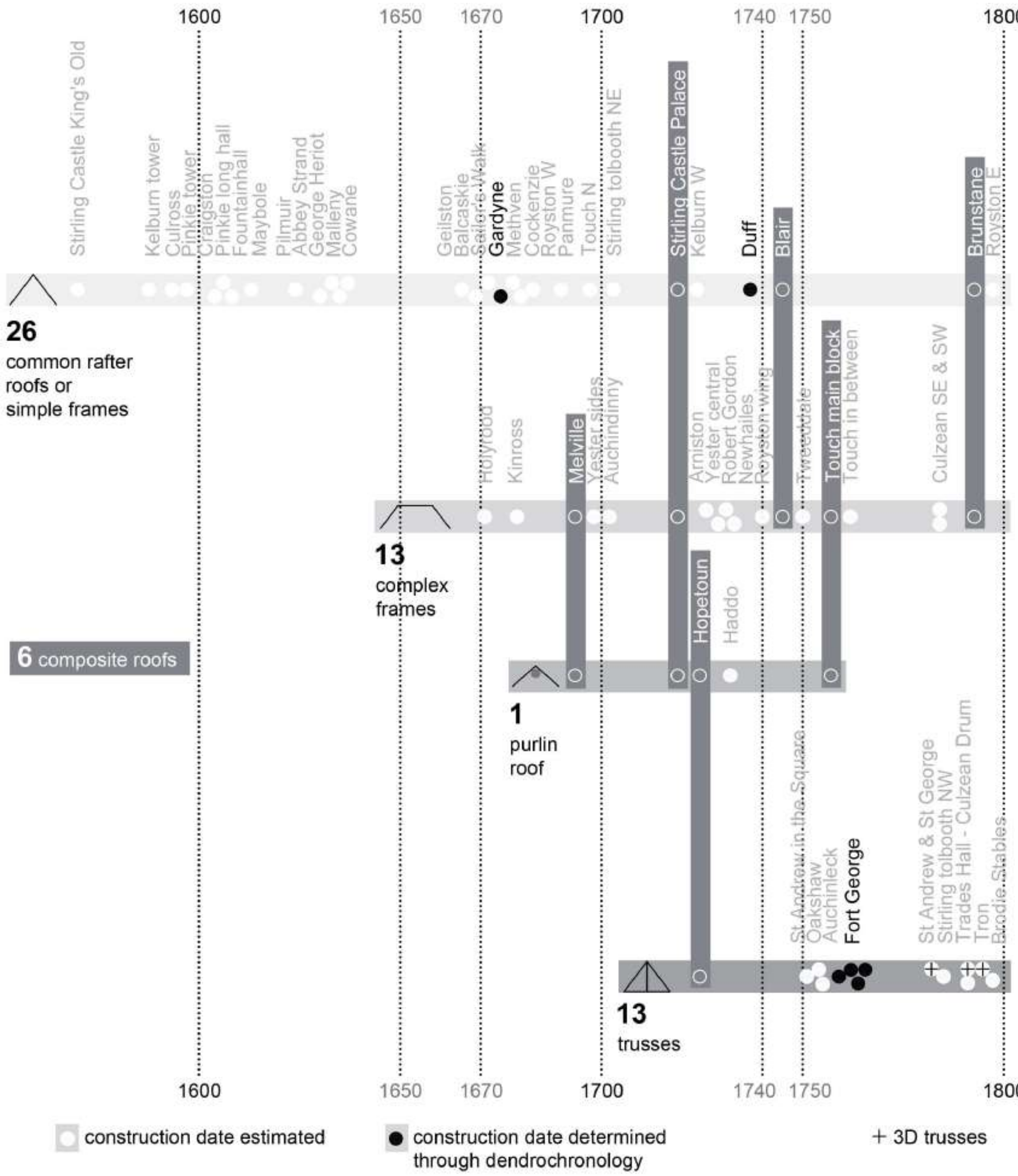


Figure 51: Timeline showing the chronological distribution of the 59 roof structures surveyed classified in different structure types: common rafter roofs, complex frames, purlin roofs, trusses (top to bottom) and composite roofs (in dark grey); the construction dates have either been estimated (white circles) or determined through dendrochronology by previous research (black circles)

Figure 51 shows how the different structure types are distributed chronologically. Unfortunately, the construction date of the roof structures is certain only in a few cases, where dendrochronological analysis has been carried out: Gardyne's Land (1675-90), Duff House (1737), Fort George (1747-69).

All the other construction dates have been estimated based on the buildings' construction history and the comparison with the other surveyed roof structures.

Extensive archival research and in situ investigations are required to properly date a building; in the case of 6 of our buildings this has not been done yet so their construction date has been estimated by scholars based on stylistic features. Moreover, the roof construction date does not always match the building construction date, because sometimes roofs are replaced at a later date. Most of the surveyed roof structures have been considered to be contemporary to the building construction, but 7 of them have been considered to be of later date: their dating has been estimated based on other reported intervention dates or by comparison with other roof structures. Table 2 reports the structure type, dating and method of dating of the 59 roof structures surveyed.

Table 2: The structure type, dating and method of dating of the 59 roof structures surveyed

Building name and roof location	Roof structure type	Roof date	Dating of original roof construction (not considering later alterations) based on: Dendro chronol ogy	Building construction date		Building other date reported	Comparis on with other roofs
				reported	estimated		
Abbey Strand	SF	1630			x		
Arniston House	CF	1726-55		x			
Auchindinny House	CF	1702-7		x			
Auchinleck House	T	1755-62		x			
Balcaskie House	SF	1668-74		x			
Blair Castle	C (SF+CF)	1745				x	
Brodie Castle Stables	T	end 18C					x
Brunstane House	C (SF+CF)	end 18C				x	
Cockenzie House	SF	1680-3		x			
Cowane's Hospital	SF	1637-48		x			
Craigston Castle	SF	1604-7		x			
Culross Palace	SF	1597-1611		x			
Culzean Castle South-East	CF	1784-92		x			
Culzean Castle South-West	CF	1784-92		x			
Culzean Castle Drum Tower	3D T	after 1791				x	
Duff House	SF	1737	x				
Edinburgh Panmure House	SF	1690			x		
Edinburgh St Andrew's and St George's Church	3D T	1782-4		x			
Fountainhall House	SF	early 17C			x		
Gardyne's Land	SF	1675-90	x				

Geilston House	SF	1666		x			
George Fort Staff block	T	1762-4	x				
George Fort Museum	T	1764	x				
George Fort Chapel	T	1763	x				
George Fort Store	T	1759-61	x				
George Heriot's Hospital	SF	1633-7		x			
Glasgow St Andrew's in The Square Church	T	1751-3		x			
Glasgow Trades Hall	T	1791-4		x			
Glasgow Tron Church	3D T	1793-4		x			
Haddo House	P	1732-6		x			
Holyrood Palace	CF	1671-8		x			
Hopetoun House	C (P+T)	1721-48				x	
Kelburn Castle tower	SF	1581		x			
Kelburn Castle West wing	SF	1722		x			
Kinross House	CF	1679-93		x			
Malleny House	SF	1635		x			
Maybole Castle	SF	early 17C			x		
Melville House	C (CF+P)	1697-1703		x			
Methven Castle	SF	1678-81		x			
Newhailes House	CF	1733-51		x			
Oakshaw Trinity Church	T	1754-6		x			
Pilmuir House	SF	1624		x			
Pinkie House tower	SF	end 16C			x		
Pinkie House long hall	SF	1613		x			
Robert Gordon's College	CF	1731-2		x			
Royston House West	SF	1683-96		x			
Royston House wing	CF	1740-1		x			
Royston House East	SF	end 18C					x
Sailor's Walk	SF	1670s			x		
Stirling Castle Palace	C (SF +CF+P)	after 1719					x
Stirling Castle The King's Old Buildings	SF	1557		x			
Stirling Tolbooth North-East	SF	1703-5		x			
Stirling Tolbooth North-West	T	1785				x	
Touch House main block	C (P+CF)	1757-62		x			
Touch house in between	CF	1757-62		x			
Touch House North range	SF	end 17C					x
Tweeddale House	CF	1750-6				x	
Yester House central	CF	1729-48				x	
Yester House sides	CF	1699-1728		x			

2.3.3 Selection of case studies

Further investigations have been carried out in 8 case studies selected amongst the surveyed roof structures according to the following criteria:

- Type: based on the number of surveyed examples per group, more simple frames were selected, followed by complex frames and trusses, and lastly by purlin roofs and composite roofs (Figure 51);
- Date: based on the chronological distribution, more examples from eighteenth century (cell highlighted in grey in Table 3) were selected, because there are more structure types during the eighteenth century rather than during the seventeenth century (Figure 51);
- Location: restricted to the Scottish central belt (Glasgow, Edinburgh, Stirling), in order to be able to easily revisit the buildings if necessary;
- Availability of other sources of information (archive material - A in Table 3 - and dendrochronological analysis - D in Table 3);
- Accessibility: structure visible in most of its parts and roof space well lit and easily accessible in order to be able to bring in and around the assessment equipment (roofs with problems in accessibility are in grey in Table 3);
- Complexity: buildings with more than one roof structure whose typology and/or construction date is different (in bold in Table 3), so that with one visit more than one roof structure can be tested;
- Ownership: buildings owned or in care of HES or NTS (underlined in Table 3), to test if the methodology is applicable to non-privately owned buildings.
- Permission: owner's permission to carry out tests (roofs with problems in permission are in grey in Table 3).

The following buildings were selected (Table 3, Figure 52):

- Cockenzie House (1680-3) with a simple frame;
- Holyrood Palace (1671-8) with a complex frame;
- Newhailes House (1733-52) with a complex frame;
- Pinkie House (1613) with a simple frame;
- Stirling Castle Palace (after 1719) with a composite roof structure (simple frame, complex frame and purlin roof);
- Touch House with a simple frame (end seventeenth century) and a composite roof structure (complex frame and purlin roof, 1757-62);
- St Andrew's in the Square church (1751-3) with a trussed roof;
- St Andrew's and St George's church (1782-4) with a 3D trussed roof.

Table 3: The selection of the case studies (framed in black) amongst the surveyed roofs

SIMPLE FRAMES	COMPLEX FRAMES	TRUSSES	PURLIN ROOFS	COMPOSITE ROOFS
Abbey Strand	Arniston House A	Edinburgh St Andrew's And St George's Church	**Touch House main block** A	Brunstane House
Cockenzie House A	*Auchindinny House*	Glasgow St Andrew's In The Square Church A	**Touch House in between** A	Hopetoun House A
Cowane's Hospital A	Holyrood Palace A	Glasgow Trades Hall A		**Stirling Castle Palace** A
Edinburgh Panmure House	Newhailes House A	*Glasgow Tron Church*		
Geilston House	**Royston House wing**	Oakshaw Trinity Church		
George Heriot's Hospital School A	*Tweeddale House* A	***Stirling Tolbooth***		
Malleny House	***Yester House*** *A*			
Pilmuir House	***Yester House*** *A*			
Pinkie House long hall A				
Pinkie House tower A				
Royston House West				
Royston House East				
Stirling Castle The King's Old Buildings *A*				
Stirling Tolbooth				
Touch House North A				

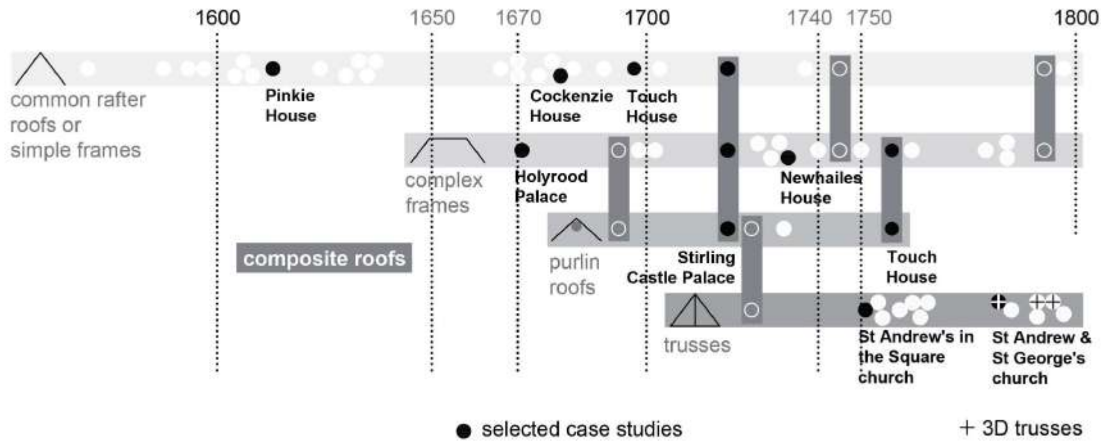


Figure 52: Timeline showing the chronological distribution of the selected case studies amongst the 59 roof structures surveyed

2.4 Condition surveys and material Investigations carried out in the case studies

2.4.1 Selection of assessment techniques

In the selected case studies in-depth surveys and investigations have been carried out to learn more about their construction and present condition. Specific objectives, identified after surveying the 53 reference buildings, have been pursued:

1. Identify the timber species and quality, to understand if different species were used for different structures and if the timber trade influenced the development of different structure types or vice versa;
2. Assess the environmental conditions of the roof spaces to understand their influence on the roof condition;
3. Find strategies to assess the geometry and condition of invisible/inaccessible parts of the structure, such as the connection with the lateral walls;
4. Compare different tests to assess internal damage and material degradation in order to estimate the residual resisting section of the timber elements;
5. Identify the skills involved in the assessment and compare tests based on their cost, training needs and reliability of results, to discuss which could be introduced to professionals through specific training.

As discussed in section 2.1.4.5, many testing devices used to assess the mechanical properties of timber are not on the market yet and those that are require a calibration through laboratory testing that could not be carried out in the time-frame available. This is why this aspect has not been investigated.

A series of assessment techniques have been selected to investigate the above-mentioned aspects, considering the available equipment in Scotland (highlighted in light grey in Table 4) and the state-of-the-art research on the assessment of existing structural timber, discussed in section 2.1. Criteria of cost, reliability of results and expertise required to operate the equipment and interpret the results have been considered, as discussed below.

There is only one way to assess the timber species and quality and to measure the air temperature/relative humidity and the wood moisture content in situ, as discussed in section 2.1. Data loggers can be used for long-term monitoring of environmental conditions, but they are quite expensive, which is why they have not been used (Table 4). On the contrary, different tests can help assessing parts of the structure hidden behind timber or plaster: thermography, endoscopy and Ground Penetrating Radar (GPR) (Table 4). The first two have been preferred because they require less expertise in the interpretation of results and because they are less expensive (Kloiber et al., 2015a, Riggio et al., 2015b). Moreover, thermography can also be useful in identifying moist areas and as support to VSG (Colla and Gabrielli, 2015). Many tests are available even for the assessment of the internal condition of timber (Table 4). However, the needle penetration test gives only superficial results, detector dogs need to be trained for every specific insect species and cannot detect early stages of decay, radiography involves safety issues, GPR requires high expertise and is not effective when there are high moisture contents, just as microwave reflectometry. Therefore acoustic tests have been preferred. Despite being expensive and semi-destructive the resistance micro-drilling has also been selected because it is very reliable and quick: it is the one that gives more precise information on the extent and position of internal features, allowing a reliable estimation of the residual resisting section and a verification of the results from other tests.

Table 4: The selection of assessment techniques to investigate specific aspects: only devices available on the market have been included; light grey = available in Scotland or virtually cost-less. The selected techniques are framed in black.

1. material		**2. environmental conditions**		**3. invisible structure**	**4. internal condition**
timber species	timber quality	air	moisture content		
macroscopic analysis	Visual Strength Grading (VSG)	thermometer	hygrometer	thermography	detector dogs
microscopic analysis	monitoring			endoscopy	microwave reflectometry
				Ground Penetrating Radar (GPR)	Ground Penetrating Radar (GPR)
					acoustic tests
					micro-drill
					needle penetration
					radiography

The testing equipment used is summarized in table 5:.

- a chisel and a hammer to collect samples, hand lenses (x10/20 magnification) to analyse the samples macroscopically and a light transmission microscope (James Swift model MP3502) to analyse the samples microscopically;
- an air thermometer to measure the air temperature and relative humidity and a hygrometer (GANN Hydromette RTU 600) to measure the wood moisture content;
- a thermal camera (FLIR E4) to spot humid areas and assess hidden parts of the structure together with a snake camera (Northvision NC-Z04N);

- a rubber hammer, a portable ultrasonic device (Proceq Pundit PL-200) and a micro-drilling device (IML RESI F-400) to assess the internal condition of timber and estimate the residual resisting section of the elements.

A device for acoustic tomography (ARBOTOM) was also available but it was decided not to use it as it is very bulky and heavy and therefore difficult to operate alone.

Table 5: The testing equipment used in the detailed investigations of the case studies

identification of the timber species	measurement of environmental conditions	assessment of hidden parts of the structure	assessment of internal condition of timber
chisel, hammer	thermal camera (FLIR E4)		rubber hammer
			
hand lenses (x10/20 magnification)	air thermometer	snake camera (Northvision NC-Z04N)	ultrasonic device (Proceq Pundit PL-200)
			
light transmission microscope (James Swift model MP3502)	hygrometer (GANN Hydromette RTU 600)		micro-drilling device (IML RESI F-400)
			

2.4.2 Assessment methodology

Since some tests require to be calibrated based on parameters obtained from other tests, the assessment has been carried out according to a defined sequence, explained in Figure 53. The timber species and the air temperature/relative humidity are needed to calibrate the wood moisture content measurements when they are taken (Riggio et al., 2014). Therefore the hygrometer could only be used after the species had been identified and the air temperature/relative humidity measured. The macroscopic analysis of the timber species can be carried out in situ (Macchioni, 2010), thus, when it was sufficient to confidently identify the timber species, phase 1, 2 and 3 were carried out on the same day. However, the collection of samples and their microscopic analysis was often necessary; in this case phases 1, 2 and 3 were carried out in sequence. This has happened during the first assessments, when the macroscopic analysis could not be carried out with sufficient confidence yet. The timber species and the wood moisture content are necessary to calibrate the results of the ultrasonic device only during the post-processing (Dackermann et al., 2014); therefore the ultrasonic test could be carried during phase 1 as well. In practice this has never happened due to lack of time. The micro-drilling device, which is semi-destructive, has always been used at the very end, after all the data from the other tests had been analysed, in order to identify the critical areas to test and minimize the disruption to the structure.

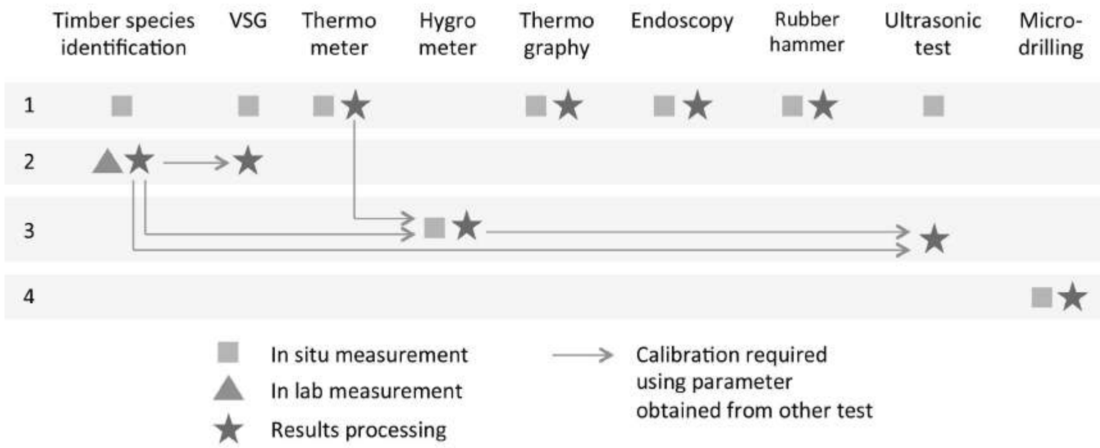


Figure 53: Assessment phases resulting from the need to calibrate some tests with parameters obtained from other tests

The tests have been carried out at specific locations. The number of elements composing the roof structures of the selected case studies is high, especially in the case of simple and complex frames. The complex frame in Holyrood Palace, for example, is composed of around 600 elements. It was therefore not feasible to carry out during an initial assessment VSG and testing of all the elements, as required by UNI 11119 (2004). As previously discussed, most of these roof structures are not composed of primary and secondary rafters and frames, therefore it was not possible to select the elements to test based on their structural importance. Hence the decision to choose a certain number of frames in each roof structure as a representative sample. A similar procedure has been applied by Podestà et al. (2013). These frames have been called ‘reference frames' and chosen based on their position: the first and last as close as possible to the gable walls or the extremities of the roof, and the others distributed at regular intervals (Figure 54). In some case studies additional critical elements (affected by material degradation, mechanical damage or significant strength affecting defects) have been identified during the detailed visual inspection and measured/tested together with the elements composing the reference frames.

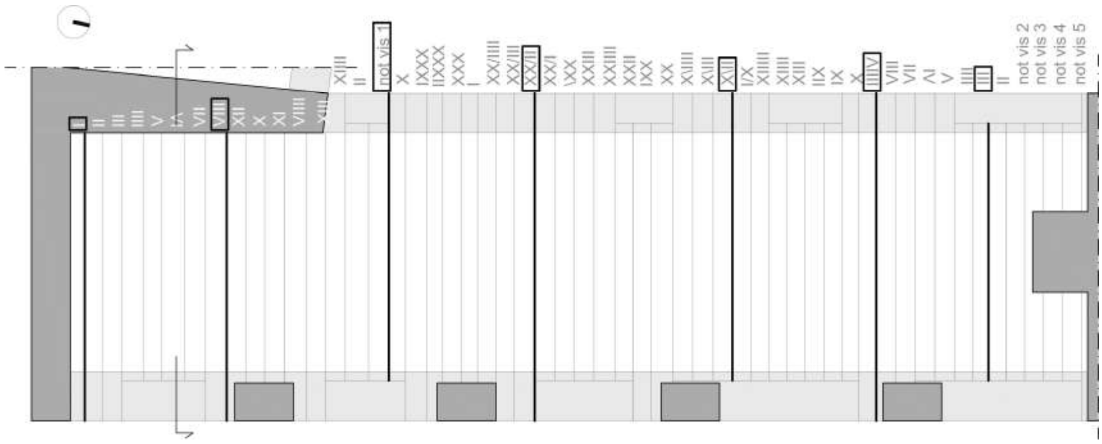


Figure 54: The plan of the roof above Pinkie Houses' long hall with the reference frames highlighted in black

The assessment has been divided in 2 parts:

PART I, to assess the timber species and quality, to measure the environmental conditions and to find ways to assess the geometry and condition of invisible/inaccessible parts of the structure:

1. Macroscopic and microscopic timber species identification (Figure 55);
2. Measurement of the air temperature and relative humidity (Figure 55);
3. Use of a thermal camera to spot humid areas and study the geometry of hidden structures;
4. Use of a snake camera to study the geometry and condition of hidden structures;
5. VSG of all elements of a sample of reference frames to assess the timber quality (Figure 56);
6. Moisture content readings of all elements of a sample of reference frames (Figure 56).

PART II, to assess the internal condition of timbers and estimate their residual resisting section:

7. Detailed mapping of visible pathologies to identify critical elements (affected by material degradation, mechanical damage or significant strength affecting defects) (Figure 55, (Figure 56);
8. Moisture content readings of critical elements identified;
9. Sounding with rubber hammer in the same points where the moisture content has been measured;
10. Ultrasonic test in the same points where the rubber hammer has been used (Figure 56);
11. Micro-drilling test where a high moisture content (>18%) has been measured, where visible material degradation has been identified, where the ultrasonic device has recorded a low velocity or an unstable signal (Figure 56).

Part I has been carried out in all eight case studies, while Part II has been carried out in four roof structures: the simple frame above the painted gallery in Pinkie House, the complex frame above the

North range of Holyrood Palace, the simple frame above the South-West range of Stirling Castle Palace and the complex frame above the North-East range of Stirling Castle Palace. These roof structures have been chosen because they represent well the two most numerous structure types (simple frames and complex frames), they have very good accessibility and their owners were interested in proceeding with further investigations. Table 6 summarizes the tests carried out in the case studies.

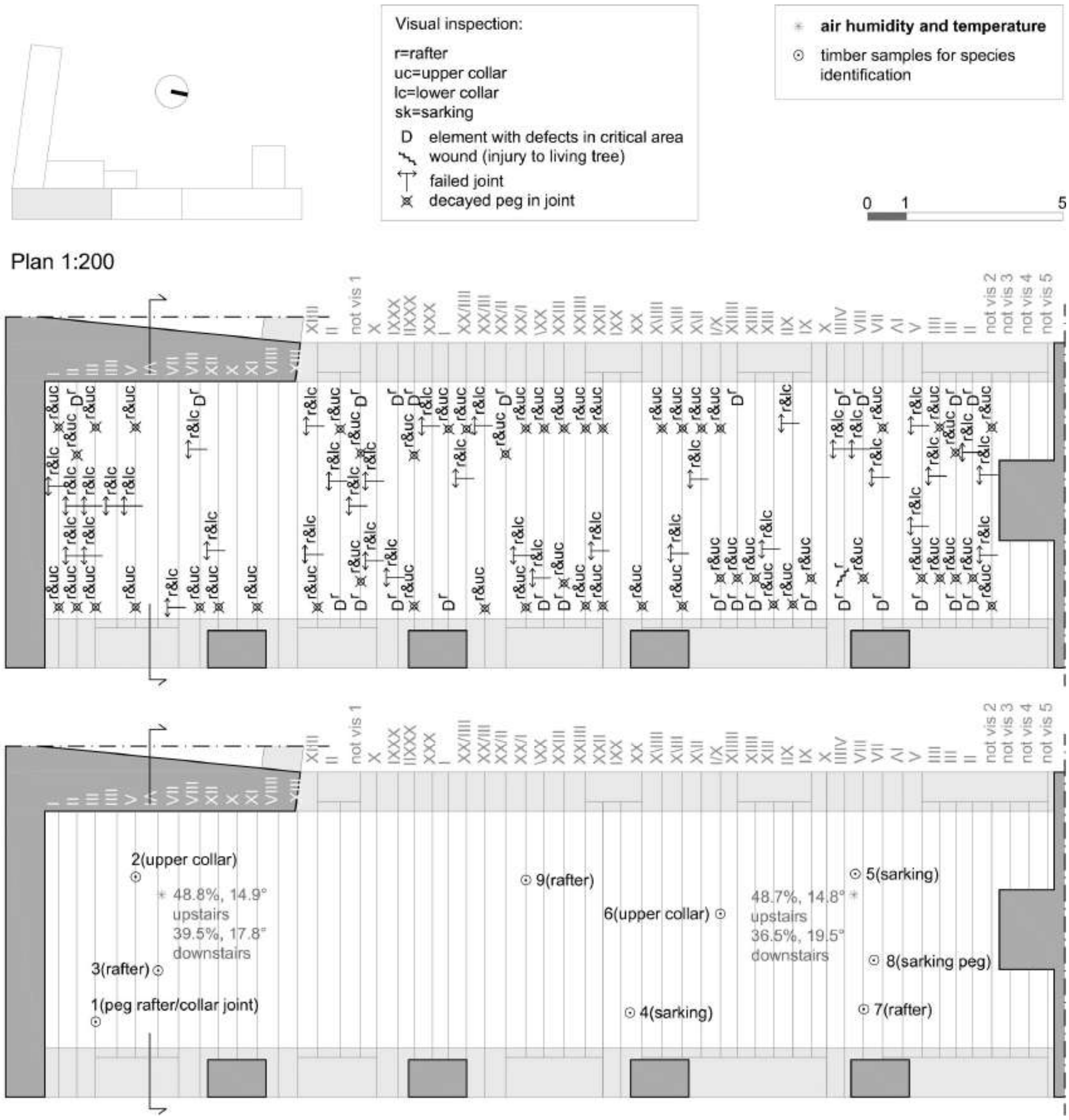


Figure 55: the plan of the roof of Pinkie Houses' long hall with the results of the detailed visual inspection and of the air temperature and relative humidity measurements, and the location of the sampling for the timber species identification

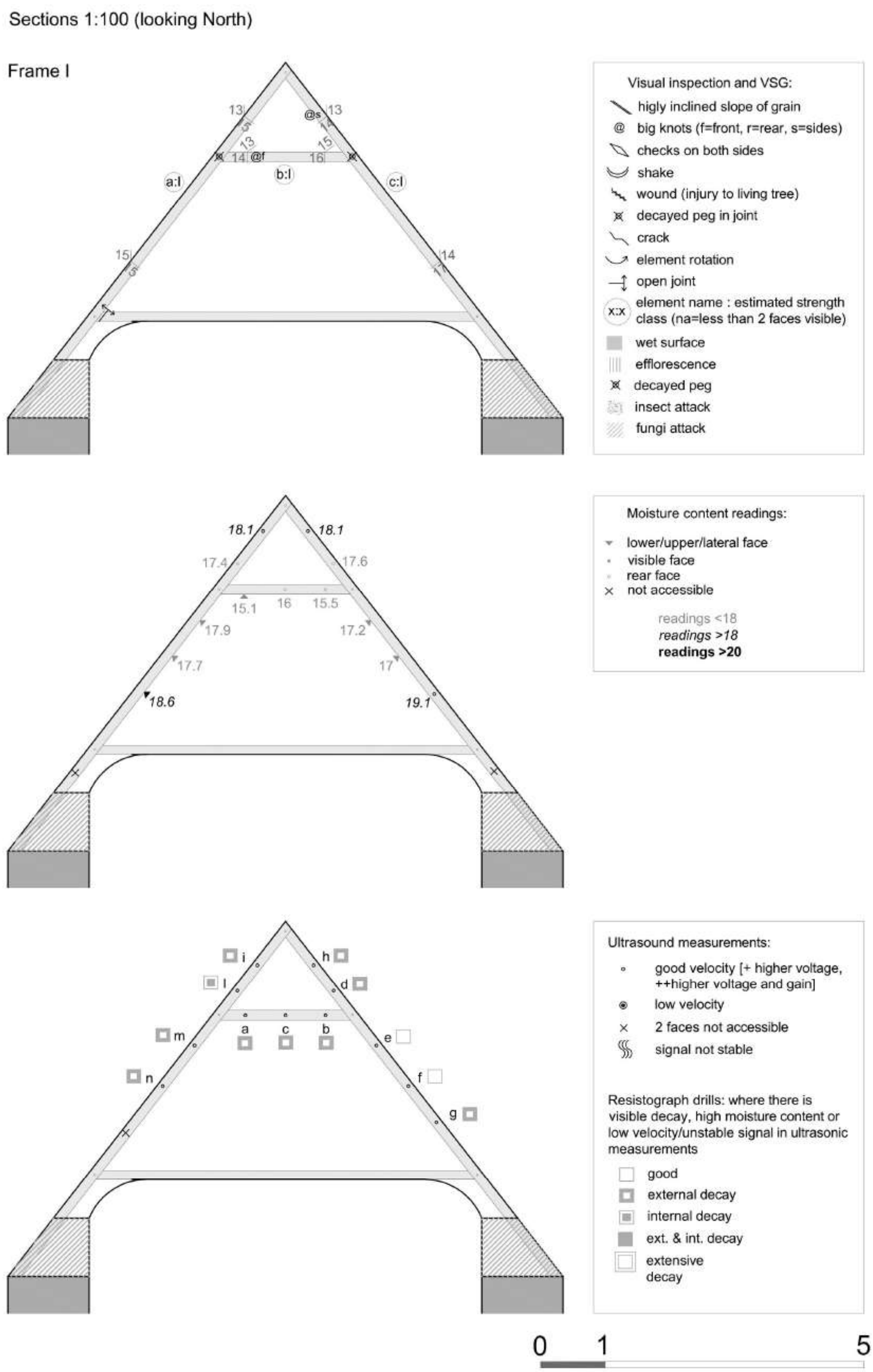


Figure 56: The results of the assessment of one of the reference frames of the roof above Pinkie Houses' long hall; the lower collars could not been assessed because they are hidden underneath insulation sheets

Table 6: A summary of the tests carried out in the case studies

	Timber Species Identif.	Air Temp. Humid.	Thermal camera - snake camera	Visual Strength Grading	Moisture Content Readings	Detailed Visual insp.	Rubber hammer	Ultrasonic test	Micro-drill
St Andrew's & St george's church	x	x	x	1 truss	1 truss	1 truss			
St Andrew's in the Square church	x	x	x	1 truss	1 truss	1 truss			
Cockenzie House	x	x	x	12 frames	11 frames	1 section of roof			
Holyrood Palace	x	x	x	3 frames	3 frames & critical elements	all roof	3 frames & critical elements	78 points	78 points
Newhailes House	x	x	x	2 frames	2 frames	2 frames			
Pinkie House above long hall	x	x	x	7 frames	7 frames	all roof	7 frames*	25 points	25 points
Stirling Castle Palace NE Range	x	x	x	3 frames	3 frames & critical elements	all roof	3 frames & critical elements	45 points	45 points
Stirling Castle Palace SW Range	x	x	x	3 frames	3 frames & critical elements	all roof	3 frames & critical elements	32 points	32 points
Stirling Castle Palace NW Corner	x	x	x	all primary elements					
Stirling Castle Palace W Range	x	x	x	3 frames					
Stirling Castle King's Old Buildings	x	x	x						
Touch House North range	x	x	x	4 frames	4 frames	4 frames			
Touch House main block	x	x	x	all primary elements	all primary elements	all primary elements			

* no critical elements identified

Holyrood Palace and Stirling Castle are in the care of HES and have been chosen to prove that the methodology is applicable even to not privately owned buildings. Scheduled Monument Consents were approved to carry out tests in both buildings. However, the need for permissions provoked delays, which have to be taken in consideration when programming testing campaigns.

2.4.3 Tests procedure and interpretation of results

2.4.3.1 Macroscopic and microscopic identification of the timber species

The timber species has been identified following procedures and suggestions in Macchioni (2010) and Nardi Berti et al. (2006) and personal training given by Alan Crivellaro (University of Padova).

The whole structure has been assessed visually in order to decide where to take samples. At least one sample has been collected from each structural element type (rafter, collar, etc) (Figure 55). When possible, the sample has been collected where loose splinters were readily available, in order to minimize the disruption to the structure.

The samples have been analysed through comparative techniques macroscopically in situ with hand lenses (Figure 57) and later in the laboratory with a light transmission microscope (Figure 58). Some pegs securing the joints between elements have been identified macroscopically only, to avoid collecting samples and disrupting the overall appearance and functioning of the elements.

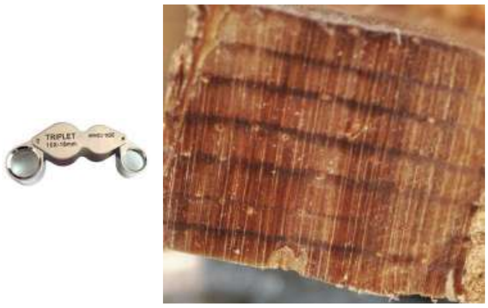


Figure 57: Hand lenses used for the macroscopic identification of the timber species (left) and a sample of pinus sylvestris taken from Cockenzie House (right)

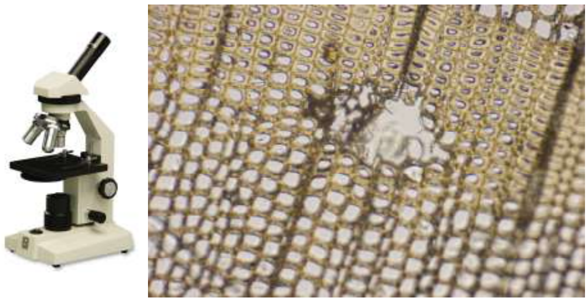


Figure 58: The light transmission microscope used for the microscopic identification of the timber species (left) and the same sample as in Figure 57 (right)

2.4.3.2 Environmental Conditions

An air thermometer has been used to measure the air temperature and relative humidity. It has been left for 15 minutes in the measurement location to allow it to get used to the environment before reading the measurement. When the roof space was big, 2 or 3 measurements have been taken in different areas and then averaged (Figure 55). The readings have been analysed considering that the air relative humidity should remain between 45% and 65% and the air temperature between 15° and 21° in order to avoid optimal conditions for biotic attack (Ridout, 2000).

The hygrometer GANN Hydromette RTU 600 has been used to measure the wood moisture content (Figure *59*). It has been operated according to RILEM guidelines (Riggio et al., 2014) and to the manufacturer's instructions. Insulated pins have been used and the measurements have been calibrated according to the air temperature and timber species. The readings have been analysed considering that the wood moisture content should never be too far from the equilibrium moisture content (Figure 27), and should always remain between 8% and 18% (Ridout, 2000).

2.4.3.3 Thermography and endoscopy

The thermal camera FLIR E4 has been used according to the manufacturer's instructions and to personal suggestions given by Maureen Young, an HES conservation scientist. It has been used both in the roof spaces and in the rooms underneath to spot humid areas and to assess the geometry of the structure hidden behind the plaster/timber panelling (Figure 60).

The USB snake camera Northvision NC-Z04N has been used to assess the condition of the connection with the wall-head, by inserting the probe in the space in-between the rafters. In Cockenzie House the probe was also inserted through three small holes opened in the panelling in the attic rooms.

Figure 59: The hygormeter GANN Hydromette RTU 600 used during the surveys (left) and a picture of the author while taking measurements with it (right)

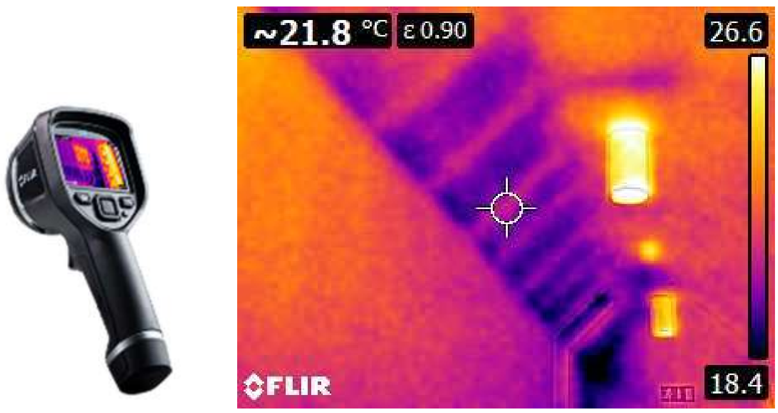


Figure 60: The FLIR E4 thermal camera used during the surveys (left) and a thermographic image taken in the attic rooms of Stirling Castle Palace (right)

2.4.3.4 *Visual Strength Grading*

Visual Strength Grading (VSG) has been carried out on all elements of the reference frames according to the Italian Standard UNI 11119 (2004) and recent guidelines (Cruz et al., 2015). An extract of the Italian Standard, showing the maximum values for each of the parameters considered as 'strength affecting' in order for the timber element to correspond to strength class I, II or III, is reported in Table 7; Table 8 shows the maximum stresses corresponding to each strength class for *Pinus Sylvestris*, the species found in all of the assessed case studies.

As suggested by Cruz et al. (2015), we have evaluated the importance of defects in relation to the applied stresses and we have not taken into consideration wane nor vertical drying fissures because they are not actually 'strength affecting' parameters: wane reduces the negative effect of knots and slope of grain and drying fissures are dangerous only when they very deep and on the sides of an element, reducing the height of its resisting section. On the contrary, the position of the pith has been recorded as it is a strength affecting defect (Tampone, 1996).

Accessibility and visibility issues sometimes hindered from grading the timber elements. When three out of four faces were visible the timbers were graded but the limitation was reported in the results.

Table 7: The maximum values allowed for each of the strength affecting parameters corresponding to strength classes I, II, III (UNI 11119, 2004)

Strength affecting parameters		**Strength Classes**		
		I	**II**	**III**
wane		≤1/8	≤1/5	≤1/3
various defects/frost fissures/shakes		absent	absent	limited
single knots		≤1/5 ≤50mm	≤1/3 ≤70mm	≤1/2
groups of knots		≤2/5	≤2/3	≤3/4
slope of grain [%]	radial	≤1/14 (~7%)	≤1/8 (~12%)	≤1/5 (~20%)
	tangential	≤1/10 (~10%)	≤1/5 (~20%)	≤1/3 (~33%)
checks/drying fissures		not passing through		

Table 8: Maximum stresses [N/mm^2] for Pinus Sylvestris at 12% moisture content (UNI 11119, 2004)

Strength Classes	**Compression parallel to grain**	**Compression Perpendicular to grain**	**Bending**	**Tension parallel to grain**	**Shear parallel to grain**	**Modulus of Elasticity**
I	11	2	12	11	1	13000
II	9	2	10	9	0.9	12000
III	7	2	8	6	0.8	11000

2.4.3.5 Acoustic tests

Timber sounding and a time-of-flight method have been used to assess the internal condition of timbers. A rubber hammer has been used as a first screening test, according to personal suggestions by Alan Crivellaro (University of Padova). The centre of each element has been struck to understand if the element is loaded and to identify extensive damage. The elements have also been struck at regular intervals all along their length to identify internal material degradation.

The ultrasonic device has been used according to RILEM guidelines (Dackermann et al., 2014) and to the manufacturer's instructions (Figure 61). Direct transversal measurements have been taken to assess the internal conditions of timber elements. Longitudinal measurements, which can be used to estimate the timber mechanical properties, have not been carried out because the correlations with strength/stiffness are not always high (Feio and Machado, 2015) and they require the input of density. Moreover they have been found to be very difficult to carry out in-situ: the signal was often too unstable for the ultrasonic device to record automatically a measurement.

Figure 61: The ultrasonic device Proceq Pundit PL-200 used during the surveys (left), PhD student Bowen Qiu using it during the surveys in Stirling Castle Palace (centre) while the author applys the transducers to the timber (right)

The use of sonic stress waves (below 20 KHz) rather than ultrasonic waves (above 20 KHz) is recommended by RILEM (Dackermann et al., 2014) for timbers with a depth greater than 89mm, such as the ones found in the analysed roof structures. This is because higher frequency waves have shorter wavelengths that are able to detect more subtle interior defects, but cannot travel long distances due to greater attenuation. Nevertheless, many studies have used ultrasonic devices to test timbers of bigger sizes (Cescatti et al., 2014, Morales Conde et al., 2015, Rodríguez Liñán et al., 2015), therefore we have decided to use 54 KHz standard transducers.

At first, we coupled the transducers to the timber with gel and a thin sheet of latex, but the irregular surface of the timbers caused the measurements to be unstable. Thus visco-elastic silicone polymer putty (silly putty) was eventually chosen as coupling agent, as it can adapt well to the surface but, unlike gel, it is stiff enough to resist the pressure (suggested by Dr Daniel Ridley-Ellis, Napier University).

The Voltage and Gain have been left to the default values (200Vpp and 100 respectively) unless the signal was unstable: in this case the Voltage was gradually increased, and then the Gain as well, up to the maximum level. Nevertheless, in some cases it was still impossible to take a measurement. Five measurements have been taken in each measurement point and averaged. The distance between the transducers was manually measured and input into the ultrasonic device, which then automatically calculated the velocity.

The measurement of the time of flight calculated automatically by the ultrasonic device is often not accurate, due to the noise underlying each measurement. In order to remove this noise, the signal has been manually processed in the following way (Table 9):

- The arithmetic mean and standard deviation of the signals in the last part of the graph, where only the noise remains (highlighted in grey Figure 62), have been calculated;
- an upper and lower threshold have been calculated according to the following formula: $AM \pm 5 \text{ x } SD$ [µs] (AM = arithmetic mean; SD = standard deviation; factor 5 was chosen because the thresholds calculated with factor 3 produced invalid results);
- the first signal greater than the upper threshold and lower than the lower threshold have been identified, the resulting time of flight being the lowest between the two;
- the five measurements have then been averaged.

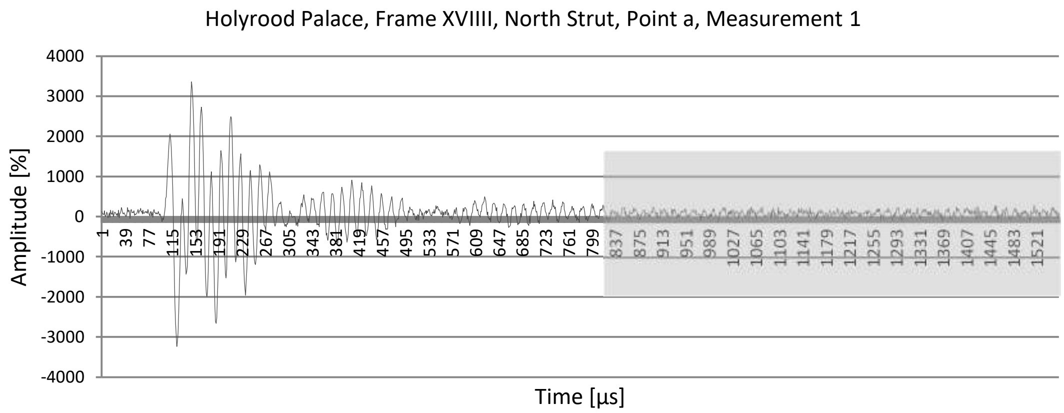


Figure 62: Signal curve of an ultrasonic measurement taken in Holyrood Palace; the last part of the graph, where only the noise remains, is highlighted in grey (only about 1/10 of the graph is here shown due to space limit). The time of flight has been calculated here to be 101 (Table 9)

Table 9: Calculation of the time of flight of the ultrasonic measurement shown in Figure 62

Distance [m]	Arithmetic mean of noise [µs]	Standard Deviation of noise [µs]	Upper threshold (A+5SD) [µs]	Lower threshold (A-5SD) [µs]	First Less Than [µs]	First Greater than [µs]	**Time of flight [µs]**	Arithmetic mean [µs]
0.1	89.43	61.52	397.03	-218.17	114	101	**101**	101.6
	90.04	62.45	402.30	-222.23	114	102	**102**	
	90.03	61.00	395.05	-214.99	114	101	**101**	
	90.02	60.67	393.35	-213.31	114	101	**101**	
	90.55	62.58	403.47	-222.37	115	103	**103**	

The velocity has been calculated according to the following formula (Table 10):

$$\mathrm{V} = \frac{\mathrm{d}}{\mathrm{TOF}}\ [\mathrm{m/s}]$$

(V = velocity; d = distance between the transducers; TOF = time of flight)

The velocity has then been corrected according to the grain orientation and the moisture content (Table 10). The relative angle between the impact direction and the grain orientation influences the speed of sonic waves (Dackermann et al., 2014): the slowest wave is for an impact of 45° orientation to the annual growth rings; the fastest is for radial excitation and is about 30% faster than with 45° orientated rings; the tangential is about halfway between the radial and the 45°. Therefore the result of the ultrasonic measurement needs to be manually increased with adjustment factors of 1.3 in case of an impact of 45° orientation to the annual growth rings and 1.15 in case of an impact tangential to the annual growth rings. The example measurement in Table 10 has been taken with an impact of 45°, hence the velocity has been increased by 1.3.

The moisture content also influences the speed of sonic waves. Its influence is different for each timber species. We have adjusted the velocity based on the measured moisture content (Table 10) using an equation developed for *Pinus Sylvestris* by Rodríguez Liñán et al. (2015) to refer all ultrasonic measurements perpendicular to the grain to the same moisture content (12%):

$$\mathrm{V}_{12} = 15.89\ (\mathrm{H}_{\mathrm{x}} - 12) + \mathrm{V}_{\mathrm{x}}\ [\mathrm{m/s}]$$

(V12 = ultrasonic velocity perpendicular to the grain with a moisture content of 12%; Hx = moisture content different from 12%; Vx = ultrasonic velocity perpendicular to the grain with an Hx moisture content)

The Ultrasonic velocity should be corrected also according to the time lag dependent on the device and the timber species and knottiness (Llana et al., 2016). Unfortunately correlations for the used device, the Proceq Pundit PL-200, are not available yet.

Table 10: Calculation and correction of the ultrasonic wave velocity of the time of flight calculated in Table 9

Distance [m]	Time of flight [µs]	Velocity [m/s]	Velocity corrected according to direction [m/s]	Moisture Content [%]	**Velocity corrected according to moisture content [m/s]**
0.1	101.6	985	1280	15.7	**1340**

The ultrasonic test measures the time-of-flight of sound waves travelling through wood. Sound waves propagate quickly through dense, solid materials; on the contrary they are attenuated and diverted by voids, cracks, or decay, because they must find a path around these defects and this results in increased transmission times. Therefore, the internal conditions of timber can be evaluated by comparing the measured wave velocities with reference velocities for sound wood. Two different reference velocities have been found for *Pinus Sylvestris*: 1470 m/s in Dackermann et al. (2014) and 1200 m/s in Rodríguez Liñán et al. (2015). The relative velocity decrease has been calculated for both reference velocities according to the following equation (Dackermann et al., 2014) (Table 11):

$$\Delta V = \frac{V_{ref} - V_{mes}}{V_{ref}} 100 \, [\%]$$

(ΔV = relative decrease of the wave velocity; V_{ref} = reference wave velocity; V_{mes} = measured wave velocity)

The relative velocity decrease has been analysed considering the relationship proposed by Dackermann et al. (2014):

- up to 10% decrease = no decay;
- 10/20% decrease = 10% decayed area;
- 20/30% decrease = 20% decayed area;
- 30/40% decrease = 30% decayed area;
- 40/50% decrease = 40% decayed area;
- >50% decrease = >50% decayed area.

The density loss has been estimated according to the equation developed by Rodríguez Liñán et al. (2015) for ultrasonic measurements perpendicular to the grain (Table 11):

$$\Delta d = 53.257 - 0.0396 \, V \, [\%]$$

(Δd = density loss; V = ultrasonic velocity perpendicular to the grain)

According to Rodríguez Liñán et al. (2015), timber is deteriorated when the density loss is > 30% (wave velocity < 600 m/s).

Table 11: Relative wave velocity decrease calculated by comparing the velocity calculated in Table 10 with reference velocities and estimation of density loss

Location	Visible Decay	Moisture Content [%]	Velocity [m/s]	Relative Velocity Decrease [%]		**Density Loss [%]**
				Reference 1470 m/s	Reference 1200 m/s	
Holyrood Palace Frame XVIIII North Strut Point a	no	15.7	1340	8.9	-11.5	**0.3**

In conclusion, areas with possible internal damage/decay have been identified where the ultrasonic device has measured waves with a low velocity (>10% decrease compared to the reference velocity 1470 m/s, as suggested by Rodríguez Liñán et al. (2015)) and where it has not been possible to take measurements because the signal was not stable enough.

2.4.3.6 Micro-drilling test

The ultrasonic waves test has been designed for concrete structures and its application to timber structures is quite recent. Some research has been carried out providing us with correlations, correction factors, and reference velocities, as discussed above, but these results are based mostly on laboratory tests carried out on clear wood samples, which do not reflect the complexity of in-situ timber and do not consider the limits and difficulties of in situ measurements.

The resistance micro-drilling test is on the contrary very reliable, but it is minor-destructive as it leaves a 3mm diameter hole through the section of the timber element. If the ultrasonic test, which is completely non-destructive, could be used as 'screening test' to decide where to use the micro-drilling device, as is currently done in tree health inspection, this would considerably reduce the amount of drills needed and therefore the damage to the structure. In order to understand if the ultrasonic device used gives reliable results for the analysed timber roof structures, the micro-drilling device has been used as 'verification' test: micro-drills have been carried out not only where the ultrasonic device has identified possible internal damage/decay, but also in other areas (Figure 56): where a high (>18%) moisture content has been measured and where visible external decay has been identified during the visual inspection.

The micro-drilling device IML RESI-F400 has been used according to RILEM guidelines (Tannert et al., 2014) and to the manufacturer's instructions. Although there have been efforts to correlate results obtained through micro-drilling with strength/stiffness of timber, correlations have been found to be quite variable and not always reliable (Nowak et al., 2016). The drilling graphs have therefore been evaluated only qualitatively, looking at areas with decreased velocity which can correspond to internal decay/damage (Tannert et al., 2014). Areas with zero resistance have been highlighted in red and areas with decreased resistance have been highlighted in yellow (Figure 63: in grey is the part of the graph outside the timber element). Areas with very high resistance, corresponding to knots, have been highlighted in green.

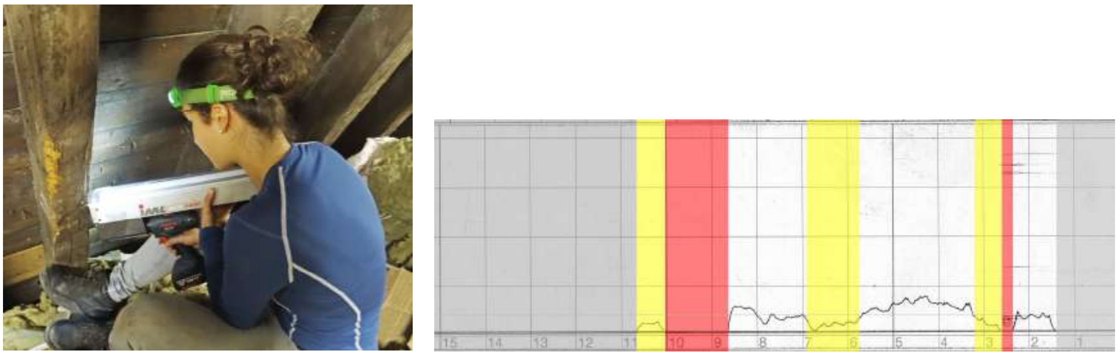


Figure 63: The micro-drilling device IML RESI-F400 used during the surveys (left) and an example of micro-drill graph from Holyrood Palace - North range, frame 43, North strut, point b (right)

2.5 A novel structured digital form to support the survey and data analysis

The data collected during the historical and archival research and the surveys has been reported in a structured form integrated within the database. The form has been produced in collaboration with COST Action FP1101 (Serafini et al., 2016) (Appendix I) and then further developed and adapted by the author to meet the purposes of this research. It has been useful to guide the surveys and to produce consistent results, but also to analyse the data.

2.5.1 Approach

Structured forms have been used since 1980s for vulnerability surveys and post-event damage recognition surveys. The form by Benedetti and Petrini (1984) was developed to assess the seismic vulnerability of masonry buildings in Italy. More recent research has produced different types of forms to assess seismic damage (Baggio et al., 2007), to assess causes of failures in 20th century timber roof structures (Frese and Blaß, 2011, Hansson, 2011, Toratti, 2011) and to assess the seismic vulnerability of traditional Italian timber roof structures (Parisi et al., 2013). In all of these studies the first step is a visual examination of the structures according to a codified procedure: a series of characteristics that determine or influence the specific aspect studied are identified and then a classification criteria is defined to be able to compare different cases, identify urgent interventions and make a plan for risk reduction in the territory.

The form developed by Toratti (2011) has a two-fold purpose: help the experts in the assessment, making them aware of the relevant questions that need answers; produce consistent results that can be analysed in order to draw conclusions on typical damage and related causes. The form developed by Task Group 1 (TG1) of Working Group 1 (WG1) of COST Action FP1101 (Riggio et al., 2015a), has the same purpose but focused on timber roof structures, not addressed so far. Starting from this work, the author created a structured form using Microsoft Access during a two-week Short Term Scientific Mission (STSM) in May 2015 at CNR IVALSA Institute in San Michele All'Adige (Italy), under the suprvision of Dr. Mariapaola Riggio (Serafini et al., 2016). Prior to the STSM work, TG1 had already identified a series of objectives that the form should fulfil (Riggio et al., 2015a):

- Allow collecting a significant amount of data reporting typical damage/vulnerabilities;
- Define structural types (considering the European built asset) and a damage taxonomy to provide a consistent approach to the evaluation of structural damage;
- Distinguish between material degradation and mechanical damage;
- Support multi-level analysis (visual inspection, in-situ tests, lab-tests, etc.).

The form was however in word format, which did not allow for the analysis of a big amount of data and was not suitable for quick inspections, due to the considerable amount of pages involved. Moreover, a tree-like organisation (system, unit, element, connection) had been implemented but structure types and damage taxonomy for each level had not been clearly identified. The inclusion of VSG regulations had to be defined too, and graphics were needed to support the relevant terminology. Most importantly the form needed to be validated by applying it to real case studies.

The STSM work focused on the reorganisation of the contents of the TG1 form in both format and structure using Microsoft Access software in order to integrate it with the database of seventeenth- and eighteenth-century Scottish buildings. After the STSM, the form was validated by using it during the surveys of summer 2015, in order to identify typical damage and vulnerabilities in Scottish roof structures. This validation work brought to a semplification and adaptation of the form to the specific purposes of the research, as explained below. The filled forms can be found in Appendix E.

2.5.2 Content

The form aims at assisting the professional during inspections in recording and organising all the information needed, pointing out critical aspects that need special attention, and during the analysis of data from several inspections allowing to draw conclusions regarding construction history and typical damage and causes. The tree-like organisation of the TG1 form has been retained and enriched with a classification of types of structures and damage for each level (Figure 64). Each building can have one or more roofs (systems), composed of a primary and a secondary structure;

each of these can be composed of units (groups of elements repeated with the same arrangement), elements and connections between elements.

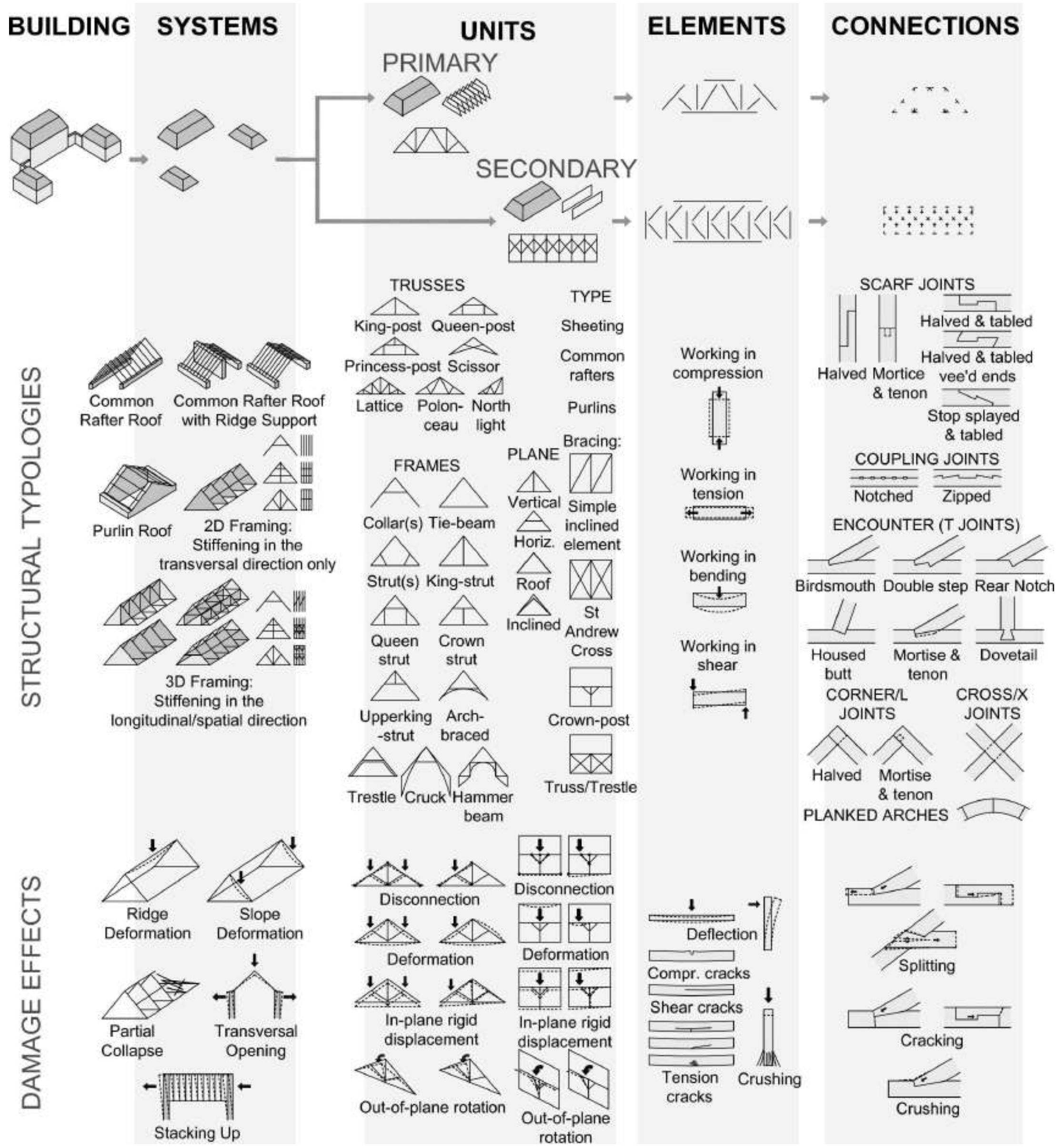


Figure 64: The tree like organization of the structured form, with a classification of structural typologies and damage effects identified for each level: building, system, unit, element, connection (Serafini et al., 2016)

Structural types have been grouped into families according to their structural behaviour rather than their geometrical arrangement. The structural behaviour has been assessed based on previous research (Lohrum and King, 2006, Szabó and Kulin, 2005, Tampone, 1996) and discussions with the members of TG1. Clearly, not all local variations have been considered.

The form is divided in three main sections: the first is related to the building, the second is related to the preliminary survey and the third to the detailed survey of the eight case studies.

2.5.2.1 *The building*

General information on the building's name, location, property and protection status, original and current use, geometrical aspects, interventions and literature/archival references are recorded in the first section of the form (Figure 67). X and Y coordinates and the geo-referencing system have been included in order to be able to plot the results. The property can be private, public or belong to the church. The protection status can be 'UNESCO' (part of a World Heritage site), 'National' and 'Regional'. The HES listing and RCAHMS ID (now incorporated in HES) are specified. Geometrical aspects include the number of floors above ground level and if the building is freestanding or not. All information found related to the building history and the people involved are included in the 'interventions' tab. The partial or complete transcription of the consulted archival documents is included at the end when available.

2.5.2.2 *Geometry, technology and condition of the roof structure*

The second section of the form starts with plans and sections of the building (1:1000) and the roof (1:500, 1:100) (Figure 68), then specific geometrical and typological information is reported (Figure 69), such as:

- Geometry (Figure 65), maximum span, height, pitch and length;
- Type and dimensions of primary and secondary structures (Figure 64);
- Type of connection with the supporting walls (Figure 66);
- Roof construction period and its method of identification (reported, estimated or assessed through dendrochronology);
- Roofing material (slates, lead, clay tiles, stone slabs, wooden shingles, copper plates, thatch) and its fixing method (metal nails, wooden pegs);
- Elements' section shape (square, rectangular, with wanes, round, trapezoid), the timber dressing (rustic: hand axed, rustic: hand sawn, civil: machine sawn) and average scantlings of the primary elements;
- Types of joints (Figure 64) and fasteners (timber pegs/dowels/wedges/keys, metal nails/bolts/straps);
- Timber species and its method of identification (macroscopic analysis, microscopic analysis, dendrochronological analysis);
- Carpentry marks;
- Signs of reused timbers such as redundant joints.

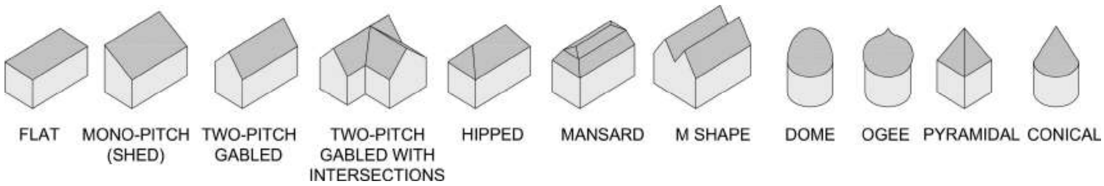


Figure 65: The classification of roof geometries included in the structured form

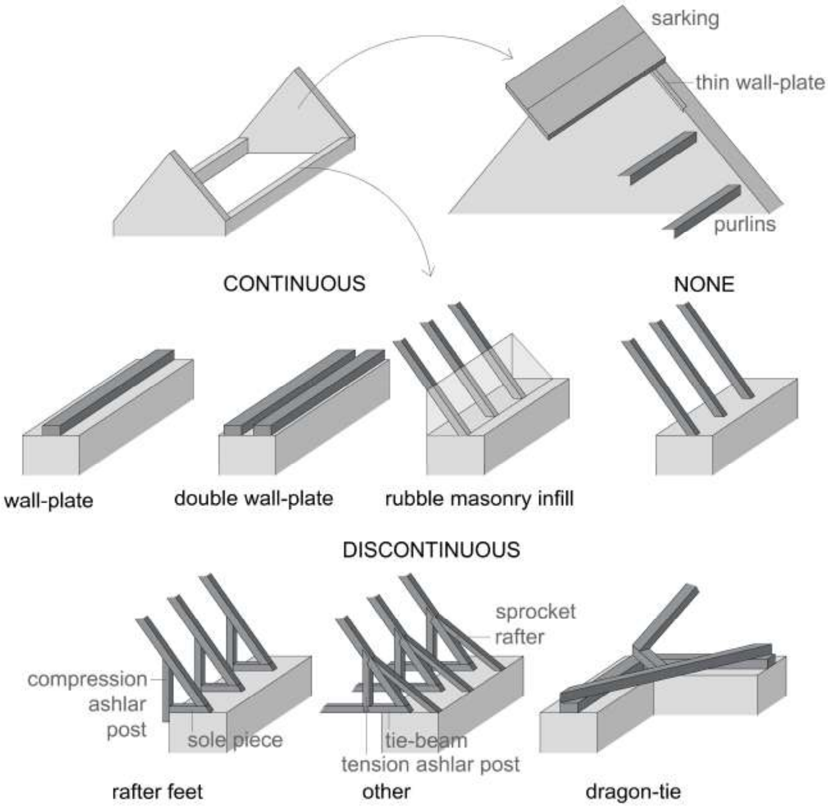


Figure 66: The different types of connections with the supporting walls included in the structured form

The roof description can include a comment on the fact that the original structural concept is different from the present behaviour: e.g. a unit might have been designed as a king-post truss but it is estimated to be behaving as a king-post frame, because of poor design, poor construction, etc.

GLASGOW ST ANDREW'S IN THE SQUARE CHURCH

Location GLASGOW, CITY OF GLASGOW (GLASGOW, CITY OF)

X coordinate 259698 Y coordinate 664681

Geogr. Referencing System BRITISH NATIONAL GRID

Property status CHURCH

Rcahms ID 44237

HS Listing A

Original Use Religious

Current Use Religious

Freestanding ✔ N. of floors above ground level 1 Location link I:\Arch\AD Building picture link I:\Arch\ADCRU\1718cent s

INTERVENTIONS

Intervention type:	From:	To:	Description:	Reference:
CONSTRUCTION	1740	1757	ROOF STRUCTURE BUILT BETWEEN 1751 AND 1753	RENWICK 1911

People involved:

Last Name	First Name	Role	Attributed
DREGHORN	ALLAN	DESIGNER	☐
NAISMITH	MUNGO	MASON	☐
CLAYTON	THOMAS	PLASTERER	☐
ROBERTSON	JOHN	WRIGHT	☐
CROSS	JAMES	MASON	☐
LAWSON	GAVIN	MASON	☐
CATION	DAVID	MASON	☐
WILSON	JOHN	WRIGHT	☐
FLEMING	WILLIAM	WRIGHT	☐

Intervention type:	From:	To:	Description:	Reference:
ALTERATION	1874		INTERIORS	HS

People involved:

Intervention type:	From:	To:	Description:	Reference:
ALTERATION	1906			RCHAMS

People involved:

Intervention type:	From:	To:	Description:	Reference:
ALTERATION	1921		INTERIORS	HS

People involved:

Intervention type:	From:	To:	Description:	Reference:
CONSERVRESTOR	1980	1989	NO RECORDS - CHURCH ARCHITECT THINKS IT INVOLVED CARBON FIBRE RODS AND RESIN INJECTION BY RBR SCOTLAND LTD	CHURCH ACHITECT

People involved:

LITERATURE REFERENCES

Author	Year	Unpubl.	Title	Pages
GLENDINNING M. & MACKECHNIE A.	2004	☐	SCOTTISH ARCHITECTURE	118
RENWICK R. (ED.)	1911	☐	EXTRACTS FROM THE RECORDS OF THE BURGH OF GLASGOW WITH AND OTHER DOCUMENTS VOL. VI A.D. 1739-59	
WILLIAMSON E. & RICHES A.	1990	☐	THE BUILDINGS OF SCOTLAND COLLECTION: GLASGOW	

Suggestions for further research

Anna Serafini PhD thesis - Supervisors: Cristina Gonzalez Longo and Andrew Agapiou, Architecture department, University of Strathclyde

Figure 67: First section of the structured form: information related to the building (this example shows St Andrew's in the Square church)

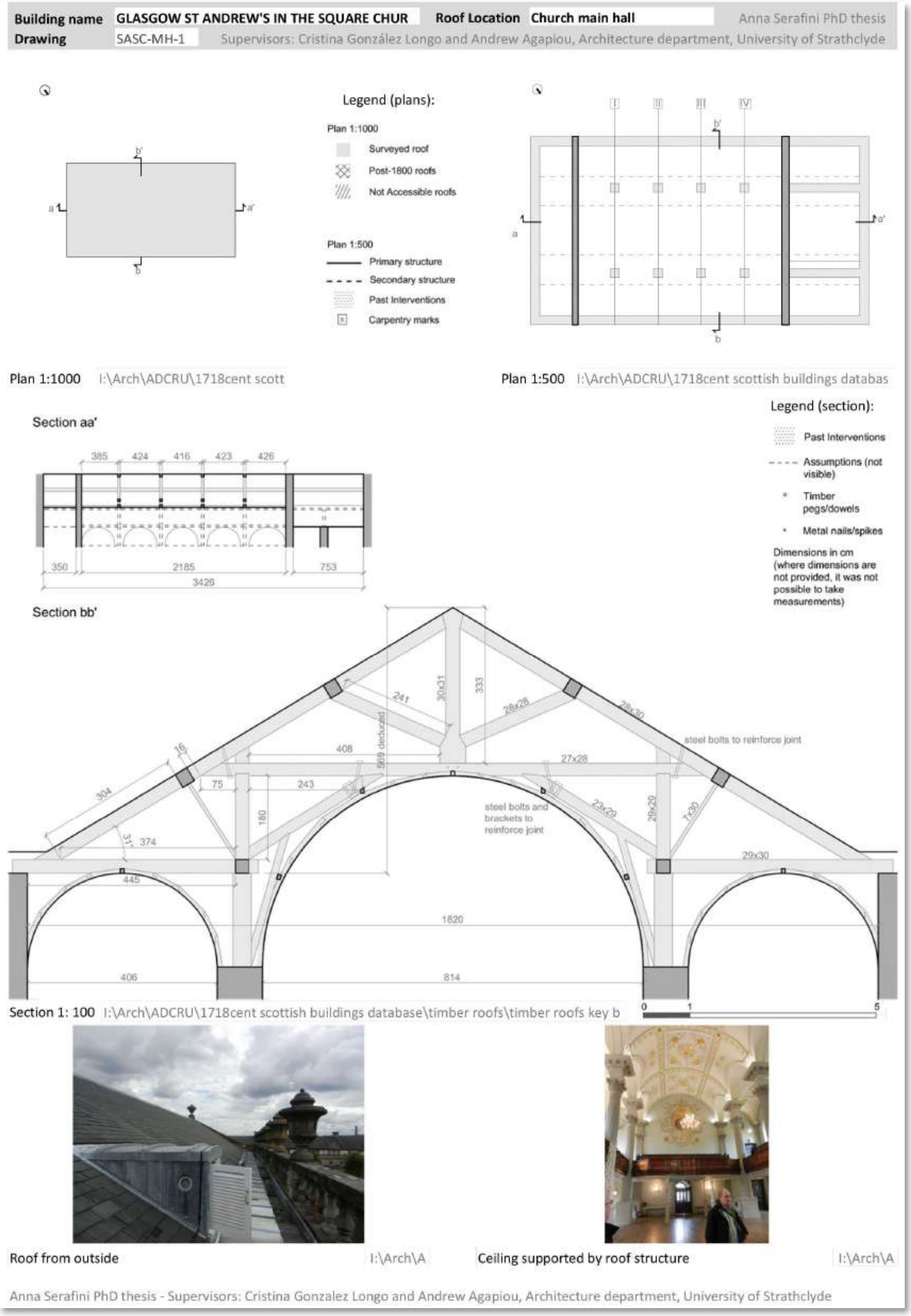


Figure 68: Second section of the structured form: plan and sections of the roof structure (this example shows St Andrew's in the Square church)

INITIAL SURVEY | **Building name** GLASGOW ST ANDREW'S IN THE SQUARE CHU | **Roof location** Church main hall

Survey date(s) 31/08/2015 | See drawing: SASC-MH-1

Roof Geometry: Two-pitch gabled

Roof Max Span [m]: 8.4 - 4 | Roof Height [m]: 7.7

Roof Pitch/es [°]: 31 | Roof Length [m]: 34.3

Type of Primary Structure: 2D framing
Truss ✔ PRINCESS-POST
Frame

Average Distance in between Primary Structure [m]: 4.5

Type of Secondary Structure: common rafters, purlins, sarking
Sarking boards: width [cm] | thickness [cm]

Connection with lateral walls: None

Connection with gables: purlins

Roof Construction Period: From 1739 To 1756 Identified by: Estimated

Roof General Description: Gabled roof with steeple on northwest side. Steeple structure wasn't surveyed. Main roof supported by two transversal walls and 4 princess post trusses in the central part. All three posts have slanted struts on both sides. Trusses span reduced by intermediate columns, one on each side. Original plaster ceiling underneath.

Roofing Material: slate

Roofing Material Fixing: Metal nails

Timber elements' Section Shape: Rectangular, Square

Rafter Scantling [cm] H: 30 B: 28 Or Purlin - H: B

Timber elements' Dressing: rustic (hand-axed), rustic (hand-sawn) | Bark

Joint Types: joggle, mortice and tenon, notch

Fasteners Types: Timber dowel

Joints description: All mortice and tenon, timber dowels only between central post and collar. Central post has joggles. Lateral post and slanted strut between lateral post and collar have notches. Fasteners not visible.

Wood Species: pinus sylvestris | Way of identification: direct micro

Carpentry Marks Types: small chiseled roman numerals, strange marks (from scandinavia?)

Carpentry Marks Description: In sequence from I to IIII (east to west)

Signs of reused timbers

Timber Treated

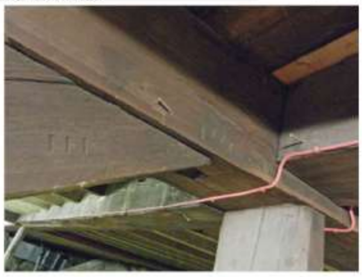
Other Materials: Resin and steel bolts/brackets

Dendrochronology

Roof structure | link I:\Arch\A

Connection with wall | link I:\Arch\A

Timber dressing | link I:\Arch\A



Joints and carpentry marks | link I:\Arch\A

carpentry marks on sarking | link I:\Arch\A

Anna Serafini PhD thesis - Supervisors: Cristina Gonzalez Longo and Andrew Agapiou, Architecture department, University of Strathclyde

Figure 69: Second section of the structured form: geometrical and typological information related to the roof structure (this example shows St Andrew's in the Square church)

The last page of this section of the form includes information about its use, insulation, decorative features, unfavourable conditions, accessibility issues, past interventions, signs and causes of material degradation or mechanical damage (Figure 70). The effect of past interventions is particularly critical to evaluate, as they can be localised or involve the whole structure and differently affect the original behaviour of the structure (Parisi et al., 2013); thus the form includes only a description and eventually a picture/drawing of past interventions, not their evaluation.

An important distinction has been made between damage effects and causes. Damage effects (deformations, displacements, rotations, cracks, etc.), defined with the help of the work carried out by Tampone (1996, 2007, 2016) and by TG3 of WG1 of COST Action FP 1101 on traditional carpentry (Sobra et al., 2015), are recorded for each level (system, unit, element, connection) (Figure 64), and for each of the effects the damage status and role are estimated. The damage status can be 'active' or 'non-active', but it is not always possible to judge. Therefore, a simple 'intervened on' is included, meaning that an intervention has been done to repair the damage but no evaluation on its effectiveness is given. Regarding the role, a structure is often affected by a sequence of damage rather than a single one, and it is important to identify the first one(s) that caused the others: this is defined 'primary' damage, while all the others are defined as 'secondary'.

The causes of damage can also be estimated; the forms previously discussed (Frese and Blas 2011; Hansson 2011; Toratti 2011) have helped in defining them:

- Poor design (insufficient dimensions, inefficient joints, inefficient overall arrangement);
- Poor construction (poor material quality/seasoning/treatment, poor detailing, design alterations);
- Material degradation (fungi attack, insect attack, metal corrosion);
- Poor maintenance;
- Past interventions (increase of dead loads, repair/consolidations);
- External actions (wind, fire, earthquake, snow, impact loads, settlements).

These can also be recorded as potential causes of damage, called 'unfavourable conditions'. This means they have not caused damage yet but might be a problem in the future, which is why they should be recorded nonetheless. Other unfavourable conditions have been included too, such as poor ventilation, the presence of bats/wasps/pigeons, the presence of open-air water tanks.

Roof space in use ☐ Insulation on ceiling ✔ Insulation on sarking ☐

Decorative features: Original plaster vaulted ceiling underneath

Unfavourableconditions: poor ventilation

Accessibility limitations: lower part of lateral posts not visible

Past interventions: Some sarking and common rafters replaced. Steel bolts added to reinforce joint between rafter and collar. Steel brackets and bolts added to reinforce joint between slanted strut and collar. Checks filled with resin. Insect treatment in 1990s.

Past interventions link I:\Arch\A

Past interventions link I:\Arch\A

Material Degradation: Fungi attack ✔ Insect attack ✔ Humidity stains ✔

Diffuse insect exit holes ☐

Fungi attack close to west gable wall. It's active, they are trying to treat it. Some insect attack on rafters and collar, only in corners.

	Damage Type:	Damage Status:	Damage Role:
Roof Damage			
Unit Damage			
Element Damage	Cracks	Active	
Connection Damage	Disconnection	Unknown	

Material degradation link I:\Arch\A

Estimated cause(s) of the primary damage:

- Poor Design ☐
- Poor Construction ☐
- Poor Maintenance ☐
- Material Degradation ☐
- Past interventions ☐
- Extreme actions ☐
- Other ☐

Damage: purlin cracking link I:\Arch\A

Description of visible damage: Some elements are cracking: purlins, rafters... Some joints between posts and struts are opening. Not sure what the cause might be.

Other Notes

Attachments: I:\Arch\ADCRU\1718cent scottish buildings database\timber roofs\timber

Damage: rafter cracking link I:\Arch\A

Anna Serafini PhD thesis - Supervisors: Cristina Gonzalez Longo and Andrew Agapiou, Architecture department, University of Strathclyde

Figure 70: Second section of the structured form: use and condition of the roof structure (this example shows St Andrew's in the Square church)

2.5.2.3 Detailed assessment of the roof structure

The last section of the form reports the results from the detailed assessment carried out in the case studies (Figure 71). A summary of the characteristics of each structural element type (rafters, collars, etc) and of each structural joint type (joints between rafters and collars, joints between rafters and rafters, etc), as well as the timber species and air temperature and relative humidity measurements, are included at the beginning to give an overview of the geometrical and technological characteristics of the roof structure and its environmental conditions.

Elements have been classified as working in compression, tension, bending or shear, or a combination of the above (Figure 64). Their length, section shape, timber species and timber dressing are specified. Joints have been classified according to Sobra et al. (2015) (Figure 71). Their stresses can be estimated and the fastener types (wooden pegs/keys/dowels/cleats or metal nails/straps/bolts) and species can be recorded too (Figure 71). If an element or a joint are different from the others of their own type (e.g. a rafter is longer than the other rafters) this can be specified in the elements/joints sub-form described below.

Each unit (frame, truss, etc) has a sub-form where there is a summary of the main problems identified in that unit (Figure 71). Each element and joint is then analysed in further sub-forms, if needed (Figure 71). The element sub-form includes information related to:

- Dating (original construction, later, recent), signs of reuse, past interventions, accessibility issues, nominal and minimum size of the section, single or composite element;
- Strength affecting defects and strength class according to UNI 11119 (2004);
- Type of material degradation, status (active, non-active, unknown) and way of identification (estimated, determined); the location is specified in the drawings;
- Type of mechanical damage (Figure 64), status, role (primary, secondary, unknown) and causes (poor design, poor construction, degradation, past interventions, external actions, poor maintenance);
- Extent of material degradation and damage based on visual inspection or in situ testing;
- Results of in situ testing for each measurement point.

The joint sub-form includes a description of its geometry and information on the mechanical damage affecting it (Figure 64); the material degradation is already recorded in the elements section. A picture/drawing of the element and of the joint can be included as well. The forms are followed by drawings were all the test results are reported in plan and section (Figure 55, Figure 56). Since there is not at date a codified representation mode for the condition survey of timber structures (Augelli, 2014), a legend has been devised looking at other examples and aiming at maximum clarity.

DETAILED SURVEY **Building name** STIRLING CASTLE_PALACE **Roof location** 4: SW range

Survey date(s) 10/02/2016 07/04/2016 20/05/2016 16/06/2016

Elements: lengths, section shapes, stresses applied, timber species, timber dressing See drawings SCP-SW-1, SCP-SW-2

Element type:	Length [cm]	Section shape:	Working in (estimated):	Timber species # :	Timber dressing:
Rafters	530	rectangular	bending, compression	pinus sylvestris	3 hand axed faces and 1 hand sawn
Collars	440	rectangular	bending, compression, tension	pinus sylvestris	the visible face is hand axed
Sarking		sheet	bending, tension	pinus sylvestris	hand sawn
Sprocket rafters		rectangular	bending, compression		

* estimated based on drawings because not fully accessible

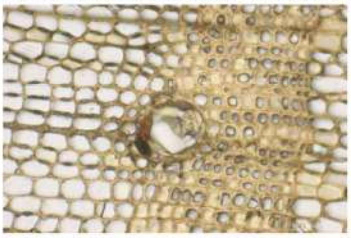
\# identified with a light transmission microscope analysing maximum 2 samples for each element type - based on visual inspection the other elements have been assumed to be of the same species

Joints: types, stresses applied and timber species See drawings SCP-SW-1, SCP-SW-2

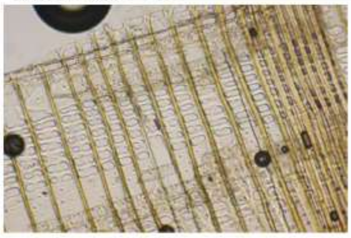
Joint position:	Joint type:	Working in (estimated):	Fastener type:	Timber species # :
rafter & rafter	Corner halved	compression	nails	
rafter & collar	Encounter dovetail	compression, tension	nails	

\# identified with a light transmission microscope analysing maximum 2 samples for each fastener - based on visual inspection the other fasteners have been assumed to be of the same species

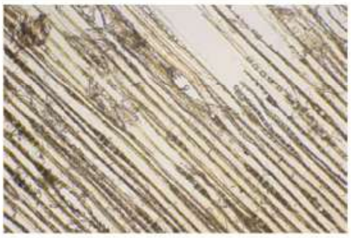
Microscopic identification of the timber species See drawing SCP-SW-2



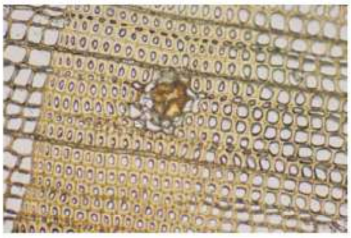
Rafter: transv. Section x100 I:\Arc



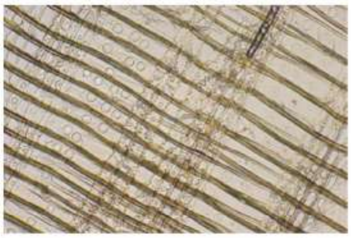
Rafter: radial section x100 I:\Arc



Rafter: tang. Section x50 I:\Arc



Sarking: transv. Section x100 I:\Arc



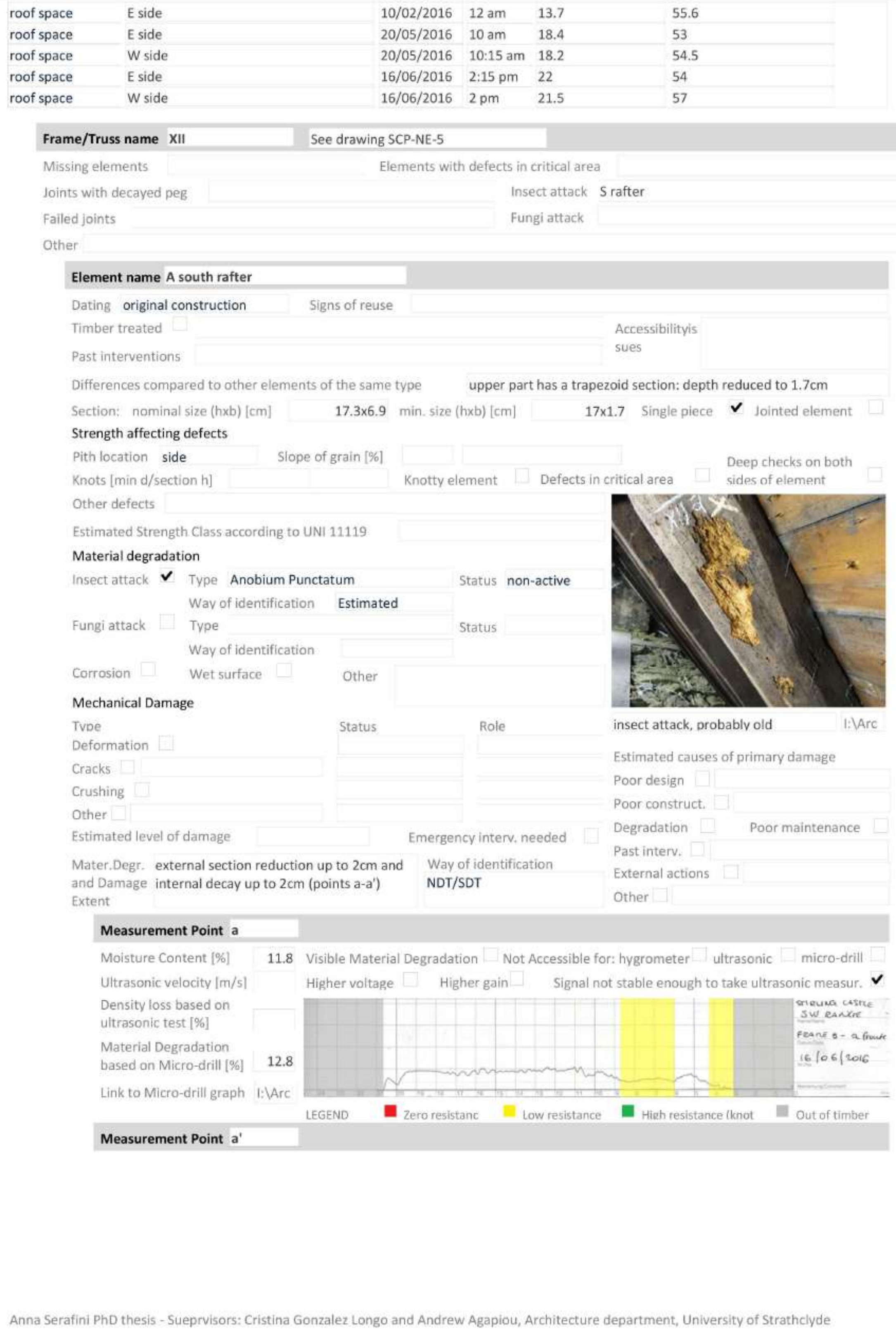
Sarking: radialection x100 I:\Arc

Sarking: tang. section x50 I:\Arc

Air Temperature and Relative Humidity measurements See drawing SCP-SW-2

Location	Location description	Date	Time	Air temperature [°]	Air relative humidity [%]
roof space	W side	10/02/2016	12 am	13	59

Anna Serafini PhD thesis - Sueprvisors: Cristina Gonzalez Longo and Andrew Agapiou, Architecture department, University of Strathclyde



roof space	E side	10/02/2016	12 am	13.7	55.6
roof space	E side	20/05/2016	10 am	18.4	53
roof space	W side	20/05/2016	10:15 am	18.2	54.5
roof space	E side	16/06/2016	2:15 pm	22	54
roof space	W side	16/06/2016	2 pm	21.5	57

Frame/Truss name XII — See drawing SCP-NE-5

Missing elements — Elements with defects in critical area

Joints with decayed peg — Insect attack: S rafter

Failed joints — Fungi attack

Other

Element name A south rafter

Dating: original construction — Signs of reuse

Timber treated ☐ — Accessibilityissues

Past interventions

Differences compared to other elements of the same type: upper part has a trapezoid section: depth reduced to 1.7cm

Section: nominal size (hxb) [cm] 17.3x6.9 — min. size (hxb) [cm] 17x1.7 — Single piece ✔ — Jointed element ☐

Strength affecting defects

Pith location: side — Slope of grain [%]

Knots [min d/section h] — Knotty element ☐ — Defects in critical area ☐ — Deep checks on both sides of element ☐

Other defects

Estimated Strength Class according to UNI 11119

Material degradation

Insect attack ✔ — Type: Anobium Punctatum — Status: non-active

Way of identification: Estimated

Fungi attack ☐ — Type — Status

Way of identification

Corrosion ☐ — Wet surface ☐ — Other

insect attack, probably old — I:\Arc

Mechanical Damage

Type — Status — Role

Deformation ☐

Cracks ☐

Crushing ☐

Other ☐

Estimated causes of primary damage

Poor design ☐

Poor construct. ☐

Degradation ☐ — Poor maintenance ☐

Past interv. ☐

External actions ☐

Other ☐

Estimated level of damage — Emergency interv. needed ☐

Mater.Degr. and Damage Extent: external section reduction up to 2cm and internal decay up to 2cm (points a-a') — Way of identification: NDT/SDT

Measurement Point a

Moisture Content [%] 11.8 — Visible Material Degradation ☐ — Not Accessible for: hygrometer ☐ ultrasonic ☐ micro-drill ☐

Ultrasonic velocity [m/s] — Higher voltage ☐ — Higher gain ☐ — Signal not stable enough to take ultrasonic measur. ✔

Density loss based on ultrasonic test [%]

Material Degradation based on Micro-drill [%] 12.8

Link to Micro-drill graph: I:\Arc

STIRLING CASTLE
SW RANGE
FRAME 5 - a (south)
16/06/2016

LEGEND: Zero resistanc — Low resistance — High resistance (knot — Out of timber

Measurement Point a'

Anna Serafini PhD thesis - Sueprvisors: Cristina Gonzalez Longo and Andrew Agapiou, Architecture department, University of Strathclyde

Figure 71: Third section of the structured form: detailed information related to the elements, joints, timber species and results of the tests carried out in the roof structure (this example shows the South-West range of Stirling Castle Palace)

2.5.3 Users interface

The form described above has been used during the surveys to remember which parameters needed to be recorded and thus obtain consistent results. Since it was impractical to bring the computer in the roof spaces during the surveys, a printed form was used on site and the results were later digitally recorded. The development of a phone application based on the assessment form described above, which would allow to digitally record the data directly on site, was started in collaboration with a research group at ITAM in Prague (Cacciotti et al., 2015), but the project was not completed due to lack of funds.

Nevertheless, the use of the form has allowed to identify different structure typologies and typical pathologies, from which vulnerability factors to predict failure mechanisms and identify urgent interventions could be derived in the future. Since the form is based on classifications established together with the leading researchers in the field (members of COST Action FP1101), it can potentially be used by any other researcher or professional assessing timber roof structures. For this purpose, a user-friendly interface has been devised.

Drop-down menus with fixed lists have been included to help filling the data, as they give suggestions, and analysing it afterwards, as data filled in as free text is always less homogeneous and less easily searchable. Items can be added to the drop-down lists and more than one choice can be selected where appropriate. ‘Other’ and ‘unknown’ have been included as choices in every drop-down menu, to not force in choosing something that does not match our judgment. Descriptions and pictures/sketches can also be added.

While providing space for all the information that one might want to record, all the fields have been left as ‘non-required’, so that they can be left blank: only the information that is available and useful for the specific purpose of each inspection should be recorded. Data can be changed and added at any time later on.

There are many terminology issues, as types of roof structures, elements and connections have different names in different countries, and even the terminology associated to different damage/failures types is not always clear for English-as-a-second-language speakers. Therefore it has been necessary to fill a glossary (reported at the beginning of this volume) and enrich the form with drawings/sketches such as the ones in Figure 65 or Figure 66 that work as legends for the drop-down menus and other terms that might be misinterpreted. Many terminology issues remain though: a work on terminology is a complex and long activity that was outside the scope of this work.

2.6 Conclusions

The review of the tools, methods and standards available in Europe for the assessment of existing timber structures highlights that recent research has made impressive progress developing many non-destructive and semi-destructive testing methods. These form, toghether with visual inspection and visual strength grading, the state-of-the-art methodology for the assessment of existing timber structures. Unfortunately, some developed devices are not on the market yet and most testing methods require considerable skills and experience and can be expensive and labour intensive. Moreover, many countries, Scotland included, do not have the relative regulations and standards. This makes it difficult to implement the-state-of-the art methodology in practice and to reach a confident structural assessment.

In order to improve knowledge on seventeenth- and eighteenth-century Scottish timber roofs structures and contribute in improving their conservation, we have devised and used, based on this review and on the techniques and tools available to Scottish professionals, a methodology to identify, research and assess this heritage. This methodology has included the creation of a relational database with related mapping and a digital structured form to handle the research data, archival research and in situ surveys. More than 1500 seventeenth and eighteenth century Scottish buildings have been identified, the roofs of 53 buildings or groups of buildings were surveyed and 8 case studies where investigated in detail. Classifications of types of roof structures and mechanical damage were also developed.

3 The historic development of seventeenth- and eighteenth-century timber roof structures in Scotland within the European context

This chapter traces the historic development of timber roof structures in Scotland through seventeenth and eighteenth centuries within the European context. The aim is to demonstrate that these roofs form a heritage of great extent and quality whose study can contribute to the understanding of the history of European carpentry. The first section sets the architectural context of seventeenth- and eighteenth-century Scotland, analysing the development of castles, villas and country houses, with special attention to the structural implications for roofs and the main actors. Research carried out up to now on Scottish timber roofs is then discussed by highlighting the main findings and the subject matters that need further investigation. The third section traces the development of Scottish timber roofs building upon archival documents and first hand data collected during the initial surveys of 53 buildings and the in depth investigations in 8 case studies. Overall structural arrangements, construction methods and details, the material employed and the role of wrights, architects and patrons are discussed within the European context to identify distinctive Scottish features and possible foreign influences.

3.1 The architectural context

3.1.1 Tower Houses, laird houses and villas: the increasing use of timber

The earliest houses of the Scottish landed classes are often called tower houses because they are characterized by a predominantly vertical development. From a structural point of view they are basically apartments placed vertically and connected with turnpike stairs; they employ very thick walls - up to 2.7m before seventeenth century (Gonzalez Manich et al., 2017) - and masonry barrel vaults, some even for the roof (Figure 72) (Hanke, 2006). The earliest plans are square or rectangular

(Smailholm Castle, fifteenth century), then L shaped (Neidpath Castle, late fourteenth century) (Figure 72) and Z shaped (Claypots Castle, 1569-88) (Figure 73); some also have a courtyard layout (Aldie Castle, early sixteenth century) (Dunbar, 1978). The spans are generally below 6m. The thick walls rise up to the roof covering, creating independent structural units, even when L and Z plans are introduced (Figure 73). This was clearly easier than creating corner structures. Steep gable walls are therefore a fundamental part of these houses, both from a structural and aesthetical point of view (Figure 73).

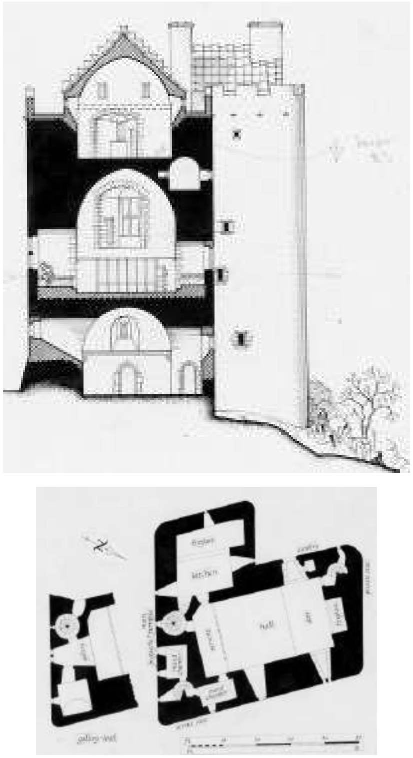


Figure 72: Neidpath Castle (late fourteenth century): section (RCAHMS DP 043860, 1959) and plan (RCAHMS DP 043862, 1964)

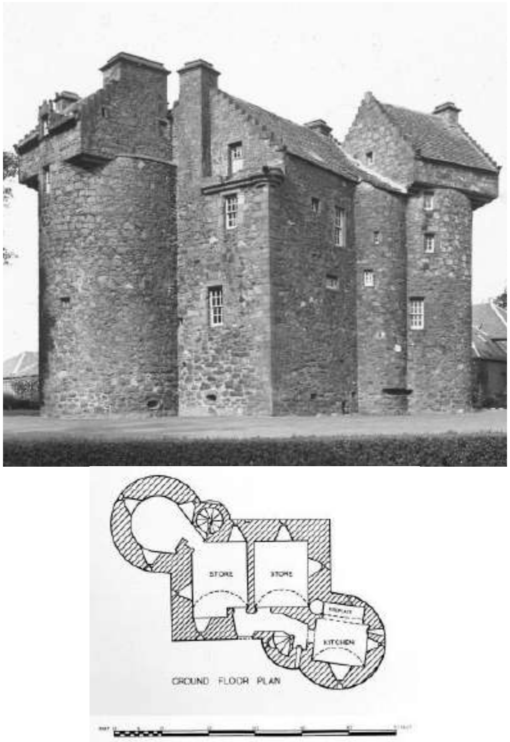


Figure 73: Claypotts Castle (1569-88): view from West (RCAHMS SC1324316, 1971) and plan (RCAHMS SC1202662, Undated)

The construction and extension of many of these tower houses sees a boom in early seventeenth century, when king James VI becomes king James I of England and moves to London, increasing the power of the landed classes. This new building wave is characterized by changes in the construction process. The direct labour system, where the commissioner himself hires tradesmen and supervises the building operations, is slowly replaced by the contract system, where a tradesman becomes responsible for hiring labour, providing materials and supervising the works: Master Masons build, remodel and extend the houses and castles of the landed classes, while Masters of Works mainly take care of the royal projects (Dunbar, 1976).

Sir James Murray of Kilbaberton (d. 1634), Royal Master of Works since 1607, is the first master mason to become part of the gentry (MacKechnie, 1994). He designed the Palace at Edinburgh Castle (1617), the North wing of Linlithgow Palace (1618-24), his own house (Baberton House, 1622-3) (Figure 74), the remodelling of Holyrood Abbey (1630) and New Parliament House in Edinburgh (1631-40) (MacKechnie, 1994). Pinkie House (1613), Winton House (1620-8) and George Heriot Hospital (1628-47) have also been attributed to him (MacKechnie, 1994). He worked closely with William Wallace (d. 1631) Royal Master Mason, introducing new decorative patterns such as buckle quoins (MacKechnie, 1994) (visible in the corners of Baberton House, Figure 74) and developing a more formal and controlled design of plans by relocating the private wing from the rear to the front facade (McKean, 2001). Murray's and Wallace's houses, in contrast with earlier tower houses, are characterized by a horizontal development rather than a vertical one, which is why they are often called 'villas' rather than castles (McKean, 2001). However, at roof elevel they are still characterized by steep gable walls (Figure 74).

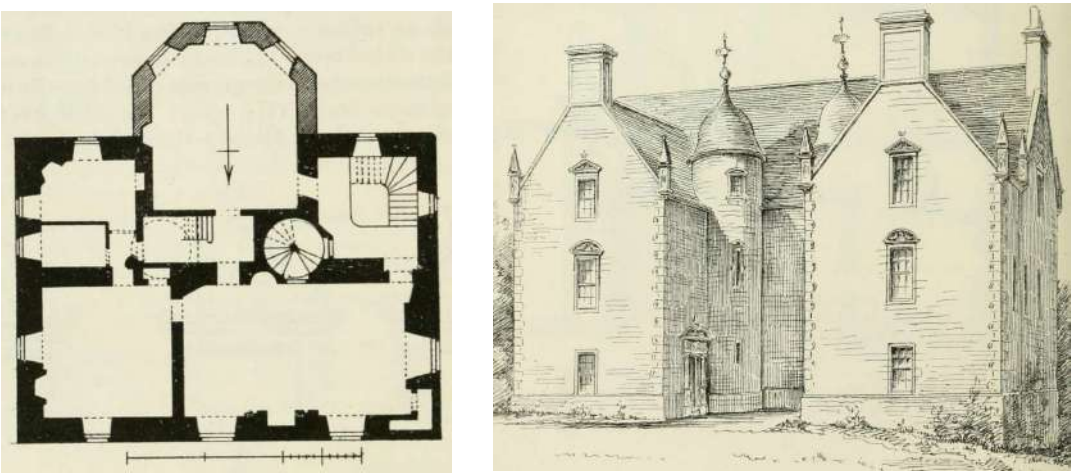


Figure 74: Baberton House (1622-3): plan and view of the South-East facade before the eighteenth-century additions (Macgibbon and Ross, 1887-92)

Since Master Masons were the main actors in the architectural boom promoted by the landed classes, they soon became more important than the Masters of Works (Summerson, 1993). The Mylne family covered the role of Royal Master Mason for generations: John Mylne (1611-67) designed Edinburgh Tron Church (1636) and Cowane's Hospital (1637) and worked at Holyrood Palace (1671-9); later his son Robert (1633-1710) worked closely with the leading Scottish architects of late seventeenth century (Harding, 2012). Wrights probably had an important role as well, although they have not been studied in detail: James Baine (1630-1704), Royal Master Wright, is the only wright known for acting as main contractor in important projects such as Panmure House in Angus (1666), Glamis Castle (1670-89) and Brechin Castle (1688-91) (Newland, 2012b).

While Murray's style is continued by Sir Anthony Alexander (d. 1637) in the Southern part of Scotland (Argyll's Lodging, 1634), the Bell family of masons builds a series of tall proud tower houses in the North-East: Midmar Castle, Crathes Castle, Fraser Castle (all late sixteenth century) and Craigievar Castle (early seventeenth century) (Glendinning and MacKechnie, 2004). However, they seem to be the exception rather than the rule because tower houses are slowly replaced everywhere by larger, lower and more comfortable laird houses and villas (McKean, 2001), such as Fountainhall House (extended in early seventeenth century), Pilmuir House (1624) and Pinkie House (1613).

In these laird houses and villas double pile plans become common and more importance is given to symmetry so T plans (Pilmuir House, 1624) and U plans are preferred, even in the North (Craigston Castle, 1604-7) (Dunbar, 1978). In structural terms the main change is that stone vaults are no longer used at most floor levels as in earlier houses (Figure 72), but only at lower levels: timber becomes more common for horizontal structures (Figure 75). This change in construction techniques and materials, motivated by the growing imports of timber from Scandinavia, allows covering slightly bigger spans (up to 7m) and reducing the thickness of walls - down to 1m (Gonzalez Manich et al., 2017) -, as well as introducing more windows of bigger dimensions (Newland, 2012c) (Figure 75). Another important development is the introduction of decorated ceilings, in timber and later in plaster (Figure 75): roof structures are no longer visible and they have to carry this additional weight.

The predominant approach is to remodel and extend the old houses, to build by accretion, rather than from scratch, in order to conserve the original family seats; but things change during the latest part of seventeenth century when new big country houses are designed and built with less and less reference to the original castellar style (Glendinning and MacKechnie, 2004).

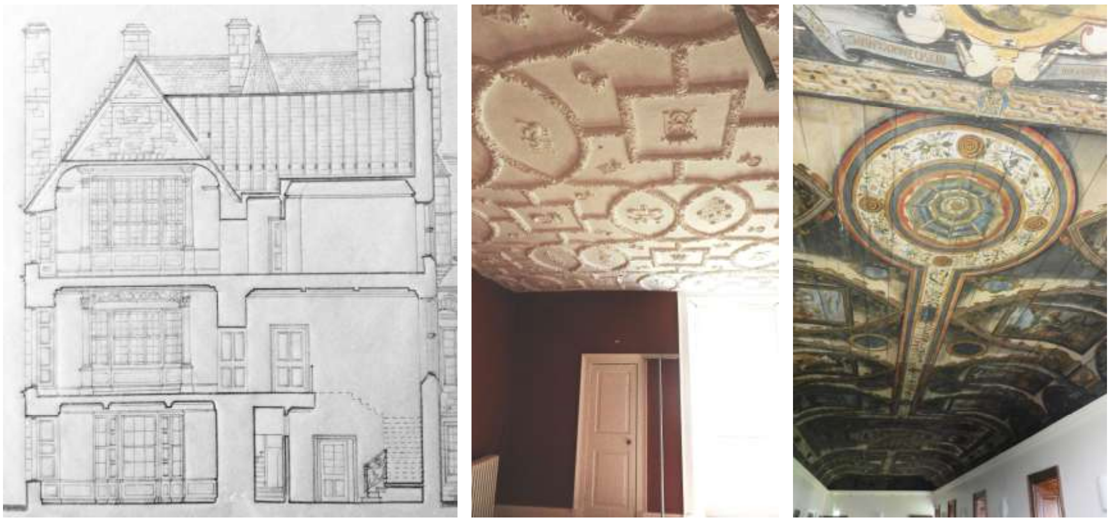


Figure 75: Pinkie House (1613): section (RCAHMS MLD 69/29, 1947) and decorated ceilings

3.1.2 Country houses: shallower pitches and wider spans

The two dominant architects of the second half of seventeenth century are Sir William Bruce (1630-1710), landowner and government official, and Mr James Smith (1645-1731), mason and last Royal Master of Works before the Union. They still remodel and expand existing buildings as Holyrood Palace (1671-9), Balcaskie House (1668-74), Drumlanrig Castle (1679-98), and Dalkeith Palace (1702-11), but their designs integrate exteriors, interiors and the landscape within a single harmonious approach (Glendinning and MacKechnie, 2004). They also start designing and building new houses with no references to the Scottish castle style: Kinross House (1679-93) (Figure 76), Melville House (1697-1703), Hopetoun House (1699-1701), Yester House (1699-1715), Auchindinny House (1702-7) and Newhailes House (1702-20). Smith, in particular, takes direct inspiration from the baroque architecture he had come in contact with during his studies in Rome, incorporating these references within the local vernacular (González-Longo, 2012).

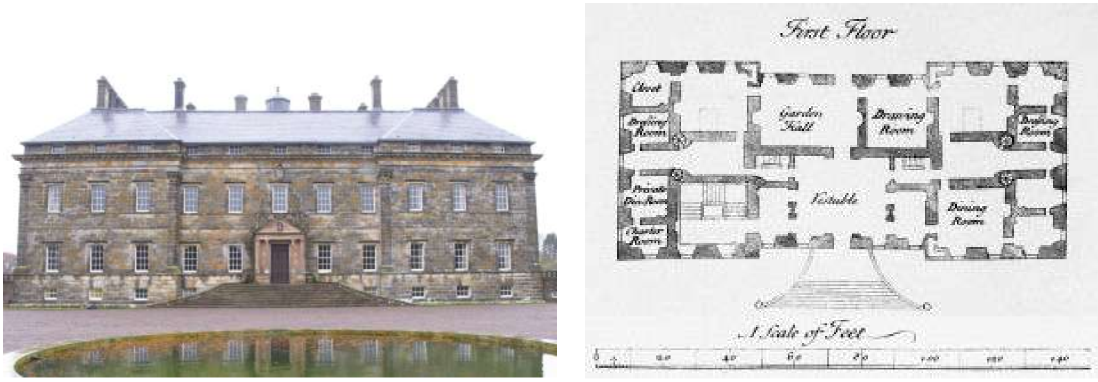


Figure 76: Kinross House (1679-93): view from West and plan (RCAHMS SC 1223494, Undated)

From a structural point of view, Bruce and Smith introduce an important innovation: their country housers are not dominated by tall masonry gables anymore; on the contrary the roofs have hipped and platform arrangements and shallow pitches, in order to harmonize with the facades (Figure 76). This clearly influences the design of roof structures. The dimensions of Bruce and Smith's country houses surpass by far those of the villas of early seventeenth century, but internal spans are not much wider because intermediate spine walls are used. These intermediate walls are to disappear only during the eighteenth century, when big undisturbed spans are achieved.

The political and economic union with England in 1707 brings strong English influences in Scottish architecture. England and Scotland see the rise of Palladianism and 'A book of architecture, containing designs of buildings and ornaments' by James Gibbs (1728) – a Scottish architect who went to Rome and practiced mainly in England - becomes one of the main sources of inspiration for contemporary designers (Glendinning and MacKechnie, 2004). Eclecticisim also spreads allowing for different interpretations of the antique combined with the national medievalism, as illustrated by

William Adam's Duff House (1735-40) (Figure 77), 'a medieval castle in a baroque dress' (Dunbar, 1978) or John Adam's neo-gothic Douglas Castle (1757-61, demolished in 1939) (Figure 78) (Glendinning and MacKechnie, 2004).

Figure 77: Duff House (1735-40): view from South

Figure 78: Douglas Castle (1757-61, demolished in 1939): view from South (RCAHMS SC 943434, Undated)

William Adam (1689-1748), industrialist, contractor, quarry-master and designer, rises rapidly to distinction winning patrons such as Sir John Clerk of Penicuik (1675-1755), known as 'arbiter of taste' (Dunbar, 1978), the II Earl of Mar (1675-1732), author of many architectural designs such as the one carried out by Adam in House of Dun (1742-3), and the III Duke of Argyll (1682-1761), promotor of the design and construction of a new town and castle at Inveraray (1744-61). William's buildings reach an internal monumental scale hitherto unknown in Scotland: Yester House, altered and extended by William between 1729 and 1748, together with Robert Gordon's College (1731-2) and Duff House (1737) (Figure 77), are amongst the first Scottish buildings to cover an undisturbed span of 9m. Earlier Scottish buildings reach even bigger spans: the great hall at Darnaway Castle (1387) is 10.7m wide, Edinburgh Parliament Hall (1631-40) is 13m wide, Edinburgh Tron Church (1637) is 16.1m wide. However, the difference with these earlier buildings is that the roof structures of Yester, Robert Gordon and Duff are not exposed: they are hidden behind heavy plaster ceilings that they support (Figure 79). Moreover, William's roofs are much shallower and do not employ gable walls, but hipped arrangements (Figure 79), which further complicates the design of roof structures.

Most of William's projects were completed by his sons after his death. In particular John, the eldest son, continued the family business in Scotland while Robert left for Italy in 1754. John's designs for Dumfries House (1754-9) and the Edinburgh Exchange (now City Chambers, 1753-61), as well as the one for Paxton House (1759-63) devised with his brother James, show a style in line with his father's, although less eclectic (Dunbar, 1978). On the contrary, Robert creates a personal style based on scholarly knowledge of antiquity and picturesque romanticism which he calls 'the movement' (Glendinning and MacKechnie, 2004). The spread of Improvement in 1760s draws him back to

Scotland where he designs many country houses and castles, such as Gosford House (1790-1800) and Culzean Castle (1776-92) (Figure 80**Error! Reference source not found.**), where he easily reaches and surpasses for the first time internal spans of 10m, despite the heavy plaster ceilings.

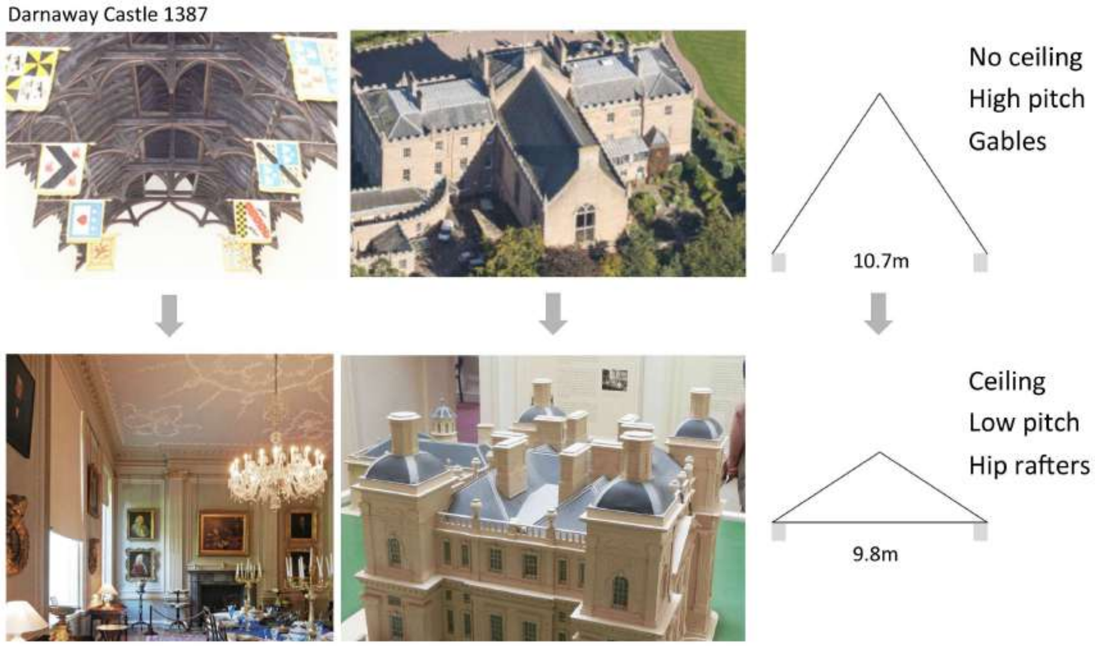


Figure 79: The structural changes in late seventeenth-century Scottish buildings which affected roof structures: gable walls with high pitches - as in Darnaway Castle (top) (RCAHMS DP 161383, 2013, RCAHMS DP 222837, 2015) are replaced by hipped arrangements, low pitches and heavy plaster ceilings - as in Duff House (bottom)

Figure 80: Culzean Castle (1776-92): view from North-East (left) and interior of the Drum tower (right)

Robert is the first Scottish architect to have a broad international influence and leaves little space for contenders such as Robert Mylne (1733-1811), author of Cally (1759-63) (Rykwert, 1985). After his death, in the last years of the eighteenth century, inspiration starts being drawn from Greek sources rather than Roman, as in Cairness House (1791-7) by James Playfair (1755-94) (Glendinning and MacKechnie, 2004).

3.1.3 Churches and military buildings

Seventeenth century is one of the least active periods for religious building, due to the Reformation. Most churches are built in a simple oblong shape, with no subdivision in space, as in late Middle Ages (Tweedside church of Lyne, 1640-5); occasionally a small aisle is added for the laird's burial, creating a T plan (Anstruther Easter, 1634) (Dunbar, 1978). Only a few are centrally planned as Lauder Parish church (1673) designed by Sir William Bruce with a Greek-cross plan (Glendinning and MacKechnie, 2004). St Mary's old parish church in Dairsie (1622) and the Canongate parish church (1688) designed by Smith are instead more ambitious: St Mary has one of the first hipped roofs in Scotland, while the Canongate church achieves an impressive span of about 10m in the central nave.

During the second half of the eighteenth century many churches are erected with impressively wide internal spans: Oakshaw Trinity Church in Paisley (1754-6), with 19.7m span, St Andrew's and St George's Church in Edinburgh (1782-4), the first UK church with an elliptical plan of 18.9m span (Figure 81), and Tron church in Glasgow (1793-4, now a theatre), rebuilt by the Adams after a fire with a 17.8m span, incorporating an internal dome.

Figure 81: St Andrew's and St George's church in Edinburgh (1782-4): view from South-East (left), plan (centre), view of interior (right)

As a consequence of the various wars, uprisings and English occupations, both seventeenth- and eighteenth-century also see the construction of many military buildings, designed by the leading architects of the period, which work in parallel for the rich gentry and for the Crown: Bruce and Smith are Surveyors of the Royal Works from 1671 and 1683 respectively, Robert Adam is Architect of the King's Works from 1761 (Glendinning and MacKechnie, 2004). Fortifications are built both during the English occupation in 1650s (Citadels in Ayr, Perth, Inverness, Inverlochy, Leith) and after the Jacobite uprising in the first half of the eighteenth century (barracks in Inversnaid, Bernera, Kiliwhimen and Ruthven, and Fort August, Fort William and Fort George) (Tabraham, 1995). Unfortunately, because of the destruction brought by the wars and uprisings most of these buildings have been demolished or are today ruinous. Fort George (1747-69), designed by the English engineer Colonel William Skinner and built by the Adams, is the best preserved and probably the last Scottish military construction with architectural significance.

3.1.4 Urban development: grand public buildings and foreign builders

Many of the mentioned building operations carried out in seventeenth century, such as George Heriot Hospital, New Parliament House, and Holyrood Palace, were also aimed at expanding and improving Edinburgh to establish the capital as a distinct focus of power within Britain. During this expansion some architects become property developers: Robert Mylne, for example, designs and builds the high residential blocks of Milne's Square (1684-8) and Milne's Court (1695) in Edinburgh. Glasgow starts emerging as a significant urban centre as well, with the enlargement of its tolbooth (1625-7) and the construction of one of the largest buildings of the period: Glasgow College (1632) (Glendinning and MacKechnie, 2004).

During eighteenth century over 100 new towns are funded on the coasts and towns and cities are expanded and improved to house the population displaced by the clearances. Grand public buildings replace tolbooths: some examples are Glasgow's Town Hospital (1732) and Town Hall (1735) designed by Allan Dreghorn (1706-65), Dundee Town House (1731-3) designed by William Adam, Edinburgh City Chambers (1753-61) designed by John Adam (Glendinning and MacKechnie, 2004).

During the building of Edinburgh New Town, designed by James Craig in 1766, a new wave of speculative developments is guided by a vast group of builders who form a new incorporation, the "Society of Master Builders, Wrights and Masons" led by one mason and one wright, and partly replace architects in designing and building small groups of houses and tenements (Lewis, 2006). Wrights are active builders just as much as masons, as testified by the wright John Bourgh who contracts many craftsmen and Deacons of the St Mary's Chapel incorporation to work for him in building houses in the New Town (Lewis, 2006). What is particularly interesting is that some of these builders had come from London, perhaps with the Adams, bringing along their wealth of technological knowledge (Lewis, 2006).

3.1.5 Discussion within the European context

Figure 82 summarises the development of architecture in Scotland discussed above. As underlined by Summerson (1993), it is quite different from the one in England: in Scotland there is a strong persistence of native types, in fact tower houses and castles remain almost unchanged up to seventeenth century. Summerson (1993) argues that this 'delayed development' is due to Scotland always being at war and isolated from the rest of Europe, but McKean (2001) disagrees and identifies the cause in the Scottish veneration for ancestors and family, which brought to the predilection to reuse and adapt ancient motifs rather than adopt new ones.

Whatever the reason, it is true that up to early seventeenth century traditional Scottish houses are characterized by a vertical development, thick walls, reduced spans and stone vaults, recalling medieval European architecture rather than the contemporary one. It is only during the first part of seventeenth century that these houses gradually develop into villas and country houses, three centuries later than in England and more than four centuries later than in southern Europe. Scottish castles are transformed by the introduction of timber used for horizontal structures: walls get thinner, spans increase slightly and windows become larger and in bigger quantity. At the same time, decorated ceilings become fashionable, thus timber structures are no longer exposed and have to carry the additional load of these decorations. During the latest part of seventeenth century Scottish architecture changes even more significantly: gable walls are abandoned in favour of hipped and platform arrangements and pitches become shallower, to adapt the roof geometry to the new architectural taste, now closer to the English and European one.

These developments are accompanied by the gradual change in the labour system, which sees the emergence of craftsmen working as contractors and designers, and later professional architects, property developers and builders, even from abroad. Some of them travel and take inspiration from the architecture of other countries such as Italy, France and England. Some foreign influences in Scottish architecture have in fact already been traced (González-Longo, 2012, Howard, 2001, Ottenheym, 2007), but related to stylistic and architectural features rather than construction techniques and materials. This is because contributions to Scottish construction history are still very few (Bell, 2004, Gonzalez-Longo and Theodossopoulos, 2012, Jenkins, 2012, Scottish Vernacular Buildings Working Group, 1976, Walker, 2006). In particular, since Scottish architectutre has always been considered a 'stone architecture', timber structures and wrights have been little investigated so far. We know, however, that any stylistic change demands for a change in construction methods; this is particularly true for roof structures since the span that a roof structure can achieve necessarily restrains the width of the space that can be built below it. The next sections of this chapter discuss how timber roof structures have developed in correspondance to the architectural innovations described above and what role wrights and architects had in this development.

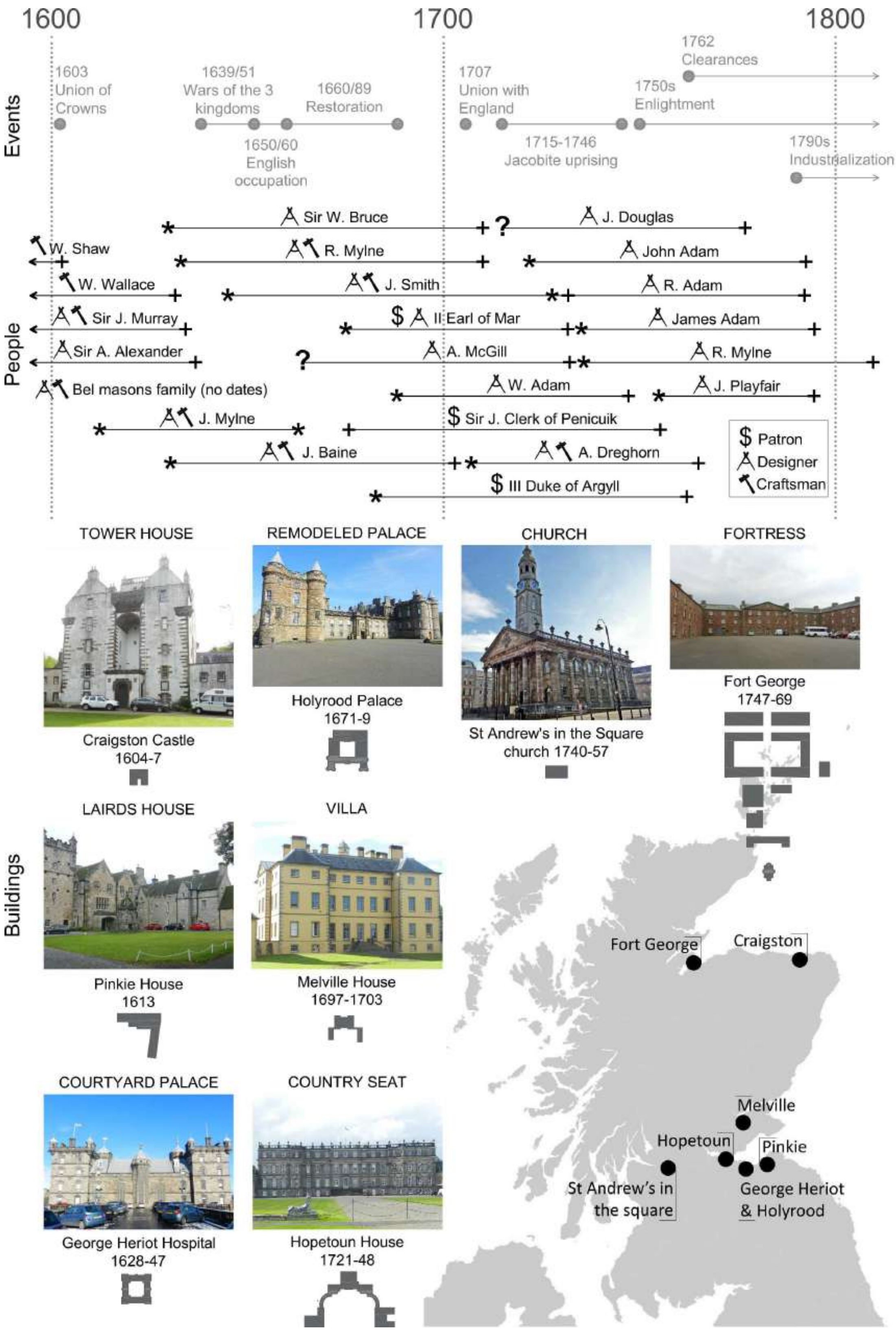


Figure 82: Timeline showing the main historical events of seventeenth- and eighteenth-century Scotland, the main patrons, craftsmen and designers, and a few representative buildings of the period

3.2 Existing knowledge on timber roof structures in Scotland

3.2.1 Structural arrangements

3.2.1.1 Types of roof structures

Timber roof structures are generally subdivided into 'common rafter roofs' and 'purlin roofs' (Corvol-Dessert et al., 2009). The German terminology is the most accurate in describing them (Lohrum and King, 2006). Common rafter roofs are called *Sparrendach:* a pair of *Sparren*, or rafters, are tightly joined at the apex, while their feet are fixed somehow against shifting (Figure 83). Their rigidity may be helped by secondary elements placed inside the frame (collars, braces, struts, etc…). Their pitch is usually steep (>40°) and the frames are very close, therefore a lot of timber is employed.

Purlin roofs, instead, are called *Pfettendach*: a pair of inclined pieces called *Rofen*, or common rafters, are carried by *Pfette*, purlins (Figure 84). The rafters, devoid of any load-bearing function, are either joined at the apex, or fixed at the base. The purlins are supported by posts, gables and/or frames/trusses, spaced at wide intervals, therefore these systems use less timber. Many roofs are actually 'false purlin roofs': in these roofs the purlins are called *Rähm* because they do not perform a load-bearing function but only a stiffening one (Figure 85, Figure 86). They were very useful in the erection process (Binding 1991 in Hanke 2006).

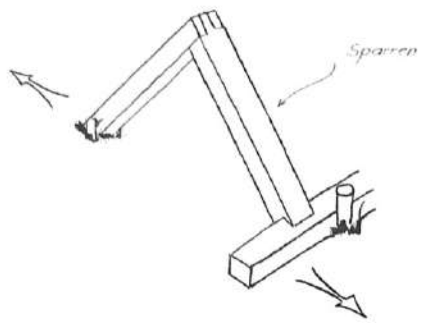


Figure 83: Schematic of common rafter roofs, called Sparrendach in German (Lohrum and King, 2006)

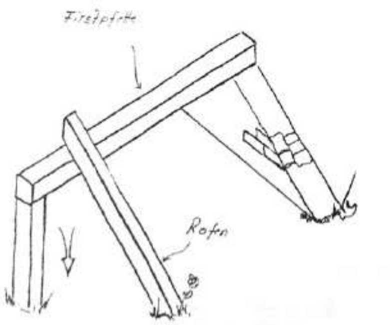


Figure 84: Schematic of purlin roofs, called Pfettendach in German (Lohrum and King, 2006)

Common rafter roofs can be classified in different ways, according to the presence of certain features: posts, scissor braces, longitudinal bracing, trestles, etc. Many countries have their own specific classifications. There are however three types which can be considered a specific group of their own: trussed roofs, cruck roofs and hammer-beam roofs.

The definition of truss is controversial as the term is often used for different types of structures. It is defined as 'a structural framework of wood or metal, esp one arranged in triangles' (Collins Dictionary, 2016), or 'a structure composed of a combination of members, usually in some triangular arrangement so as to constitute a rigid framework' (Harris, 2006). According to these definitions, however, a common rafter roof with a tie-beam is a truss. Yeomans (1992) tries to narrow down the definition by describing the trussed roof as a structure with hanging posts that act as ties, 'trussing up' the tie-beam and thus counteracting its deflection and creating an efficient triangulation (Figure 87, Figure 88). These are also called 'Italian or Italianate trusses' (Gomme, 2002, Innocent, 1971).

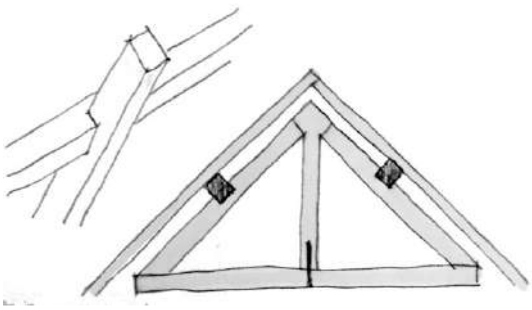


Figure 85: Schematic of purlin roof supported by trusses (trenched purlins)

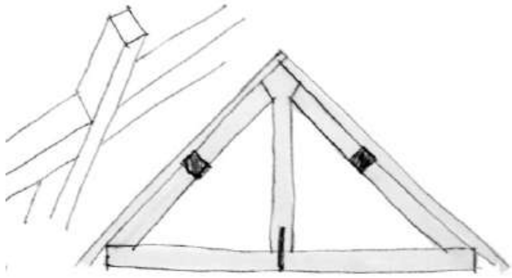


Figure 86: Schematic of trussed roof with longitudinal bracing (butt purlins)

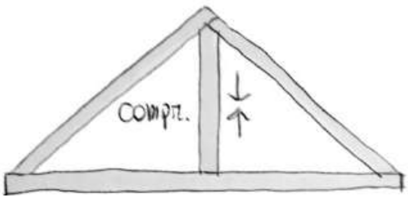


Figure 87: Schematic of king post in compression

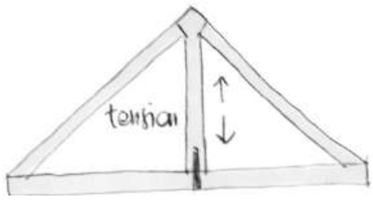


Figure 88: Schematic of hanging king post in tension

Crucks are composed of pairs of inclined blades placed on the ground and meeting at the apex of the roof (Corvol-Dessert et al., 2009) (Figure 89). Hammer-beam roofs are composed of principal frames resting on sole pieces (the hammer-beams) extended beyond the vertical plane of the wall and supporting a hammer-post at their inner end, which rises to the collar forming a triangular support for the frame; the hammer-beam also forms a lower triangle with a wall-post and an arch brace (Courtenay, 1985) (Figure 90).

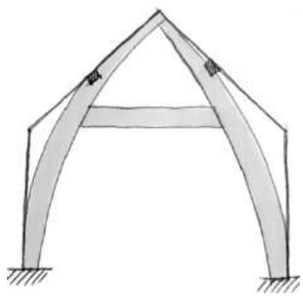


Figure 89: Schematic of cruck roof

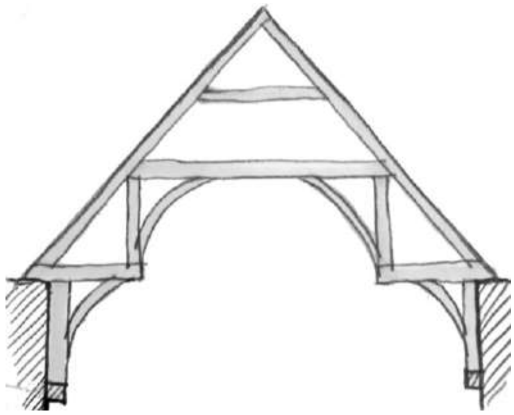


Figure 90: Schematic of hammer-beam roof

3.2.1.2 Continental Europe

Historically, North Europe preferred using common rafter roofs. The earliest examples consist in a series of closely spaced identical frames composed of a pair of rafters and a tie-beam, supported by simple or double wall plates; eventually collars, struts, braces and posts are included with different combinations. No longitudinal bracing other than the roof covering were employed (Figure 91).

A common pattern of development of this simple roof is followed by Germany, Netherlands, Sweden, Denmark, North of France, Belgium, Czech Republic, Romania, Slovakia, Poland (Bláha, 2006, Corvol-Dessert et al., 2009, Eissing, 2009, Gogolin, 2008, Janse, 1989, Madsen, 2013, Suchý et al., 2008, Szabó and Kulin, 2005, Thelin and Linscott, 2008). The twelfth and thirteenth centuries see a significant development of carpentry techniques due to the introduction of Gothic architecture. In order to reduce the amount of timber used and be able to bridge increasingly wider spans with vaulted ceilings, carpenters divide frames into primary frames – load-bearing – and secondary frames, supported by plate purlins under the collars (which also provide the first elemental longitudinal stiffening) (Figure 92, Figure 93). The tie-beams of the secondary frames are often replaced by hammer-beams or sole pieces (Figure 92, Figure 93), which allows dividing the roof into bays and introducing a vault in each bay or a barrel vault interrupted only by the primary tie-beams.

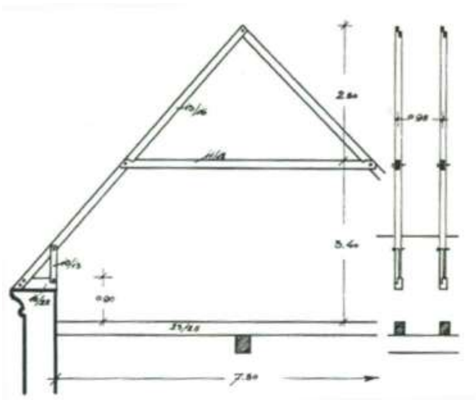


Figure 91: Common rafter roof in St Kastor church in Karden, Germany (1216) (Binding, 1991)

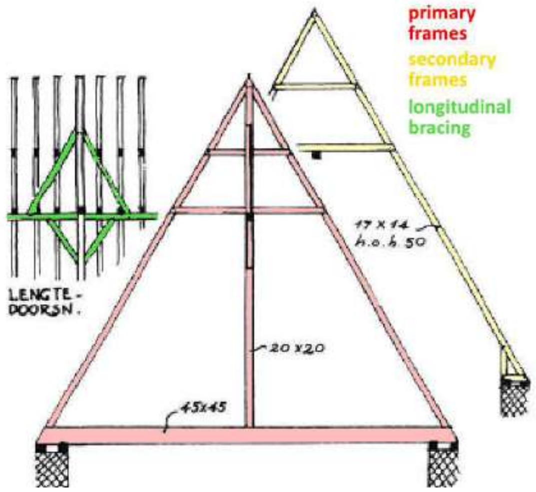


Figure 92: Common rafter roof with primary and secondary frames and longitudinal bracing in the Vrouwe Church in Kortrijk, Netherlands (1250) (Janse, 1989); colours added by author

In order to reduce the increased horizontal thrust of the roof produced by the removal of the tie-beams, the pitch of the roofs is increased to 55°-65°; this leads to greater wind pressure which is counteracted by introducing longitudinal bracing (Figure 92, Figure 93). Almost simultaneously the subdivision between principal rafters (load bearing) and common rafters (non load-bearing) is adopted (Figure 93), to concentrate the loads only in certain areas of the supporting walls.

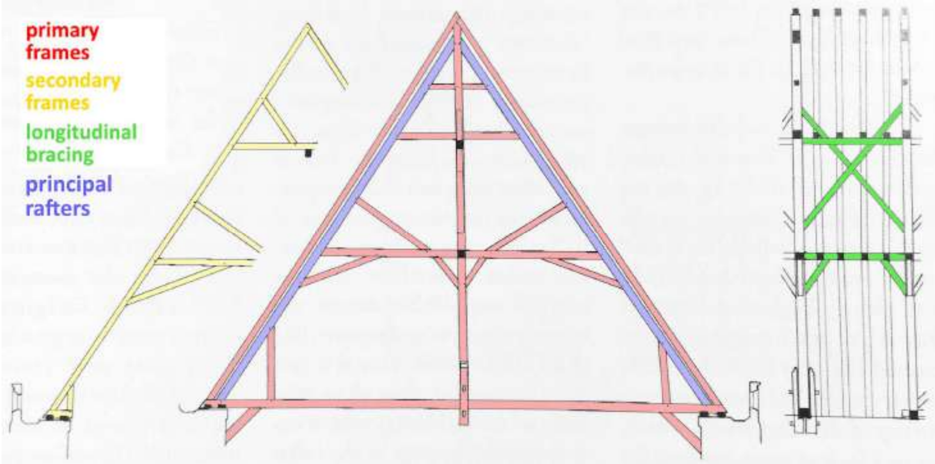


Figure 93: Common rafter roof with principal rafters, primary and secondary frames and longitudinal bracing in Saint-Pierre Cathedral, France (thirteenth century) (Corvol-Dessert et al., 2009); colours added by author

During fifteenth and sixteenth centuries the shortage in timber supplies forces to use shorter timber in lesser quantity: multi-tiered structures using portal frames or 'trestles' (Figure 94), already used in Belgium since the thirteenth century (Corvol-Dessert et al., 2009) and in Germany since the fourteenth century (Caston, 2006), become common. Elements now have different scantlings depending on their structural role, rather than being uniform in size as in the previous roofs. The ridge beam, previously used mainly in Scandinavia (Madsen, 2013), becomes common in other countries too, to ensure a solid longitudinal framing. In order to reduce the roof height and use less timber, mansard roofs are introduced in France (Figure 95), also through treatises (Forneau, 1767, Mesange, 1753). De l'Orme (1578) suggests an innovative arch system but this is fully exploited only from nineteenth century (Gómez Sánchez, 2006).

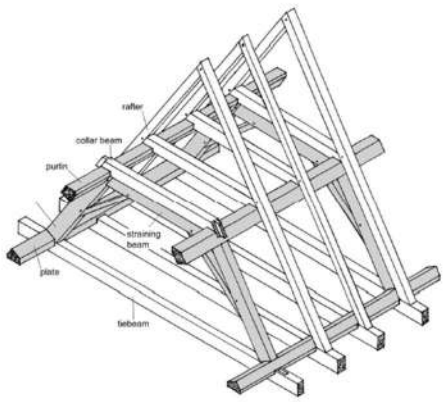


Figure 94: Schematic of German portal frames/leaning trestles (Holzer and Kock, 2008)

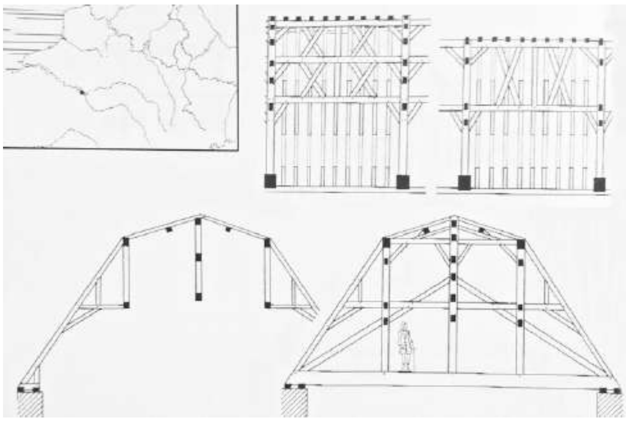


Figure 95: Mansard roof at the Sorbonne Chapel in Paris (1635-42) (Corvol-Dessert et al., 2009)

Purlin roofs were instead commonly used in Southern Europe: Italy, Switzerland, Austria, South France (Figure 96), South Germany (Figure 97), Spain and Greece (Hoffsummer, 2011, Munafò, 2002, Ostendorf, 1908, Tsakanika, 2007). They become common in North Europe only from the end of the Middle Ages, as means to reduce the amount of timber used: in North France and Belgium from fifteenth century (Corvol-Dessert et al., 2009), in Netherlands from 1500 (Janse, 1989), in Czech Republic at the end of eighteenth century (Bláha, 2006).

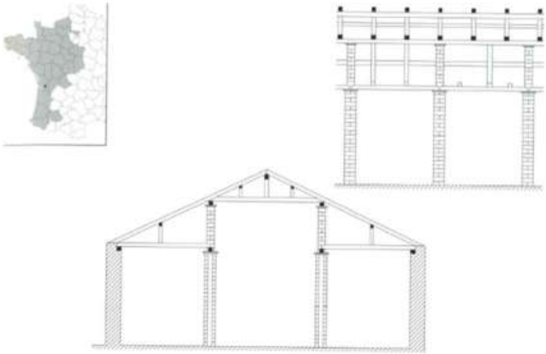


Figure 96: Purlin roof of Hopital Neuf in Pons (1220-54) (Hoffsummer, 2011)

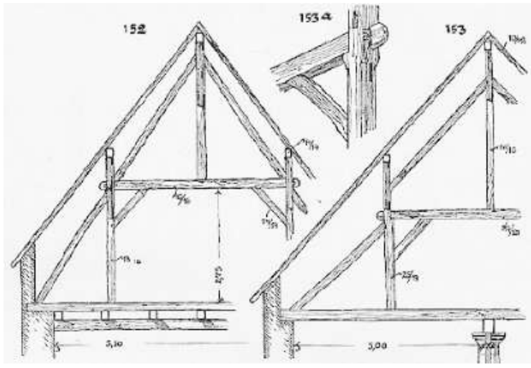


Figure 97: Purlin roofs in Germany (Ostendorf, 1908)

In Italy purlin roofs (Palladio, 1570, Vitruvius Pollio, 1556) and trusses (Figure 98) (Valeriani, 2005) are used since the Roman times and are still used today. Tension-absorbing posts, a characteristic feature of 'itlianate trusses', appear from twelfth century in France (Figure 99) (Corvol-Dessert et al., 2009) and from fifteenth century in Germany (Eissing, 2009). However, 'italianate' trusses are also characterized by timbers with bigger sections which allow to reach shallower pitches whilst covering bigger spans and using less timber, since the trusses are more widely spaced (Figure 98).

Figure 98: Trusses in Sant'Agata di Mugello church in Scarperia, Florence (sixteenth century) (Tampone, 1996)

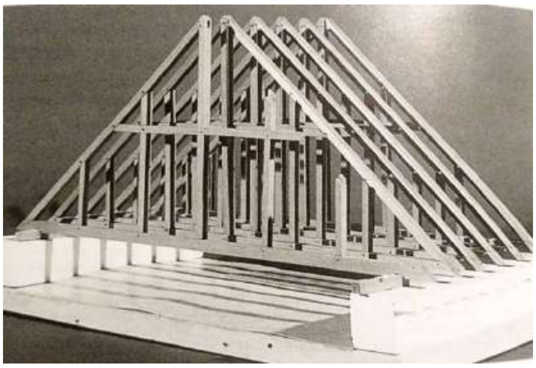


Figure 99: Roof with tension-absorbing posts in Saint-Pierre-de-Montmartre church in Paris (1164-74) (Corvol-Dessert et al., 2009)

This is why italianate trussed roofs gradually replace common rafter roofs in many countries during seventeenth, eighteenth and nineteenth centuries, as testified by carpentry treatises (Gómez Sánchez, 2006). In all countries the common rafter roof and the trussed roof coexist for some time until the trussed system is well understood and definitely established as predominant.

3.2.1.3 England

Crucks are widely used in English vernacular architecture from twelfth up to nineteenth century (Alcock, 1981) (Figure 135). The oldest examples, dating from the fifth century, are actually in Netherlands and Germany, but they seem to disappear from North Europe soon after (Corvol-Dessert et al., 2009).

English houses and churches are however covered mainly with common rafter roofs, just like the rest of North Europe (Hewett, 1980). The earliest examples are quite simple, with uniform scantlings and no longitudinal stiffening elements (Figure 100) (Fletcher and Haslop, 1969, Hewett, 1980, Smith, 1958). In the second half of the thirteenth century king and crown posts are introduced (Fletcher and Spokes, 1964, Munby et al., 1983) and false purlins such as butt purlins (already used at the ridge of crucks) start being used as longitudinal bracing in churches in the South (Hewett, 1980, Smith, 1958). This is in line with the rest of North Europe. However, by the end of thirteenth century, side purlins (which are true purlins) are used, and simultaneously rafters are subdivided into principal (load-bearing) and common (non load-bearing) (Figure 101), which allows removing some of the tie-beams (Fletcher and Spokes, 1964, Hewett, 1980, Munby et al., 1983, Smith, 1958). This is one of the earliest examples of use of side purlins in North Europe (Hanke, 2006).

In contrast to the rest of North Europe, England, just like Scotland, remained mainly feudalistic and did not develop a powerful civic class up to seventeenth century. It was thus the nobility rather than burgesses commissioning ambitious architecture, corresponding to castles and palaces rather than churches and public buildings (Summerson, 1993). This is why most of the innovations in carpentry, such as the introduction of side purlins, are introduced in domestic architecture first (Hanke, 2006). One of the main features of these palaces and castles was the great hall, which was aisled. In order to make it aisle-less English and Scottish carpenters invented the hammer-beam roof, used during fourteenth, fifteenth and sixteenth centuries (Figure 102) (Hewett, 1980, Smith, 1958).

The English preference for exposed roof structures (Brandon and Brandon, 1849), which brings to the development of hammer-beam roofs rather than trestled structures, together with the use up to nineteenth century of crucks and the early introduction of side purlins differentiates England from the rest of continental Europe (Hanke, 2006). However, seventeenth and eighteenth centuries are marked by important changes both from a political and an architectural point of view, which reinforce the connections between England and Scotland and also between Britain and continental Europe. This clearly influences developments in roof carpentry.

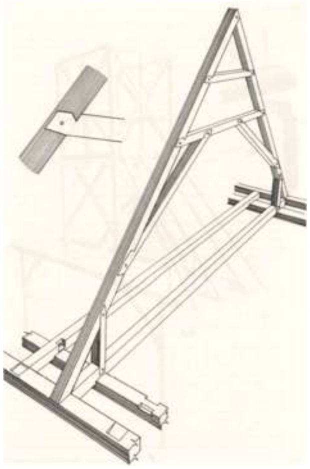


Figure 100: Reconstruction of common rafter roof of Waltham Abbey in Essex (twelfth century) (Hewett, 1980)

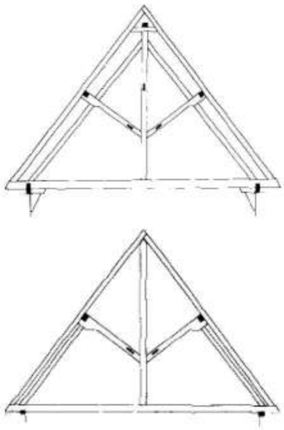


Figure 101: Roofs with side purlins and principal rafters in Chichester: Cathedral (top) and Bishop's Palace (bottom) (late thirteenth century) (Munby et al., 1983)

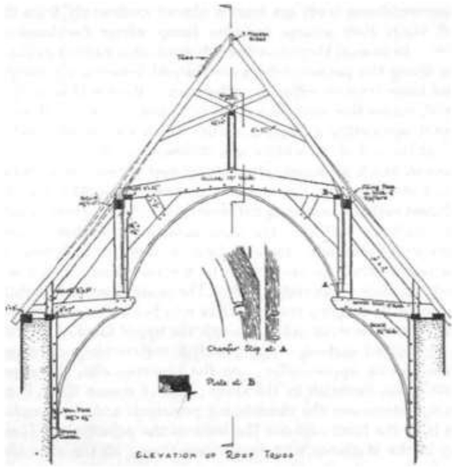


Figure 102: Hammer-beam roof over Stranger or Pilgrim's Hall in Winchester (early fourteenth century) (Smith, 1958)

Italianate trussed roofs are introduced in England in early seventeenth century by the architects I. Jones (Figure 103) and later C. Wren (Campbell, 2002, Yeomans, 1986b, Yeomans, 1992). This is a big innovation in English roof carpentry because the use of tension-absorbing elements, such as the hanging posts used in italianate trusses, was completely alien to England up to then: crucks, common rafter roofs and hammer-beam roofs employ in fact only compression members. Moreover, iron straps and scarf joints, both in use in italianate trusses, had never been used in England before. Yeomans (1992), Campbell (2002) and Valeriani (2006) have made hypotheses on how this migration of technical knowledge happened.

It appears that seventeenth-century England relied on the import of Italian treatises mainly (Gómez Sánchez, 2006, Yeomans, 1986a); in fact, the first English treatise showing trussed roofs (Price, 1733) is from early eighteenth century (Figure 105). Inigo Jones travelled to Italy, and he possessed various Italian treatises which included various examples of roof trusses, thus it seems highly probable that he took inspiration from these sources (Campbell, 2002, Valeriani, 2006, Yeomans, 1992) (Figure 104). What is interesting to note is that some of Jones and Wren's roof structures do not show a full understanding of the truss system (Yeomans, 1992). It has been argued that the reason for this is that Jones and Wren were influenced not only by Italian sources but by others as well, and that they experimented various solutions adapting the details to the local tradition (Valeriani, 2006).

Other authors produced carpentry manuals in this period but they were all quite practical and kept showing traditional English carpentry and criticising the new fashions in France (mansard roofs) (Gómez Sánchez, 2006). Treatises by Smith (1736), Langley (1740) and Salmon (1767) include many examples of trusses, but they are mostly incorrectly drawn or poorly designed (Yeomans, 1986a). Only late eighteenth-century English treatises (Nicholson, 1797, Pain, 1796) show a thorough understanding of the trussed system: Nicholson (Figure 106), in particular, published the first account in English of the behaviour of the king post truss which clearly explained the nature of the forces in each of the members. This is reflected by practice: the architect J. Essex designs complex trussed roofs during the second part of eighteenth century, whose original solutions prove that the system was well understood and established by then.

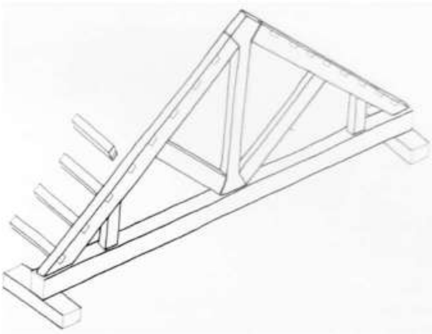


Figure 103: Trussed roof at Stoke Bruerne, designed by I. Jones (1630) (Yeomans, 1992)

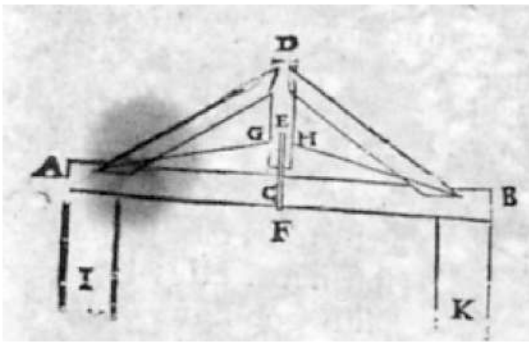


Figure 104: Roof truss drawn by Baldi (1621) at p.102; Yeomans (1992) considers Baldi the main source of inspiration for Jones and Wren, but Valeriani (2006) contradicts this by highlighting the different treatments of the joint post/tie-beam

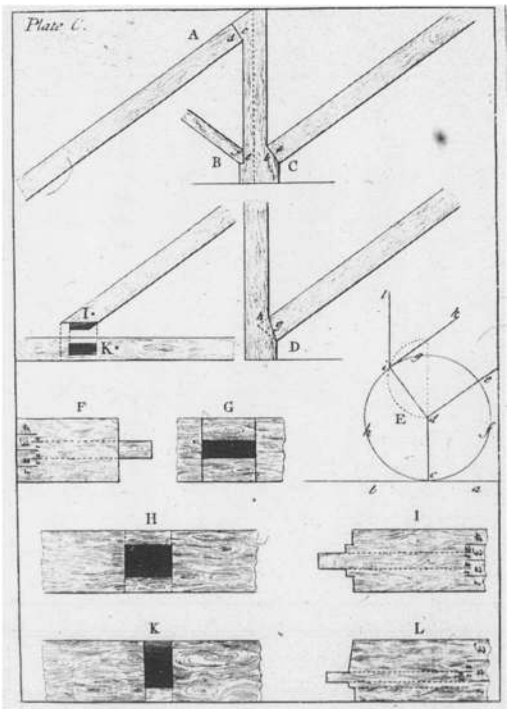


Figure 105: Details of trussed roofs drawn by Price (1733)

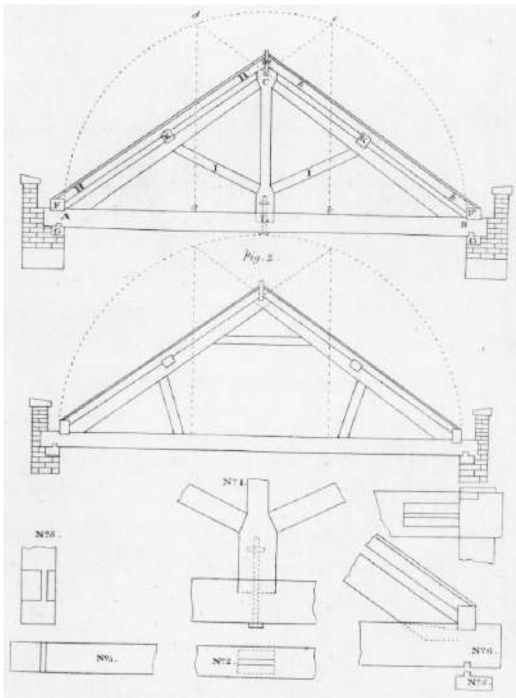


Figure 106: Trussed roofs and details drawn by Nicholson (1797)

3.2.1.4 Scotland

Research on the use of timber in Scottish architecture has been published (Apted, 1966, Bell, 2004, Crone and Sproat, 2011, Peddie, 1883) but there has been little focus on its structural use, particularly in roofs, although scholars such as Hay (1976), Ruddock (1995), Stell (2004) and Hanke (2006) have created a good base for further research. Most of the publications mention few famous roofs, mainly pre-sixteenth century, like that of Darnaway Castle (Stell and Baillie, 1993) (Figure 107), or Glasgow Cathedral (Oldriev, 1916) (Figure 108), whilst very few publications talk about roofs hidden behind timber or plaster ceilings, even though scholars (Hanke, 2006, Ruddock, 1995, Stell, 2004) agree in saying that they represent the great majority of Scottish roofs.

The roofs on which research has focused until 1990s are the 'false hammer-beam' or 'open purlin' roofs of thirteenth, fourteenth and fifteenth century that we find in the great halls of Darnaway Castle (Stell and Baillie, 1993) (Figure 107), Stirling Castle (Crone and Fawcett, 1998), Edinburgh Castle (Crone and Gallagher, 2008) (Figure 109), Holy Rude church in Stirling (Hay, 1976) (Figure 110) and in the seventeenth century Tron church and Parliament Hall in Edinburgh (Gomme, 2002). Another example of open purlin roof has been identified by Hanke (2006) in documents held at RCHAMS archives: the one in St John Church in Perth (1448) (RCAHMS SC 830680, 1927), still existing and similar to the one in Holy Rude church (Appendix A).

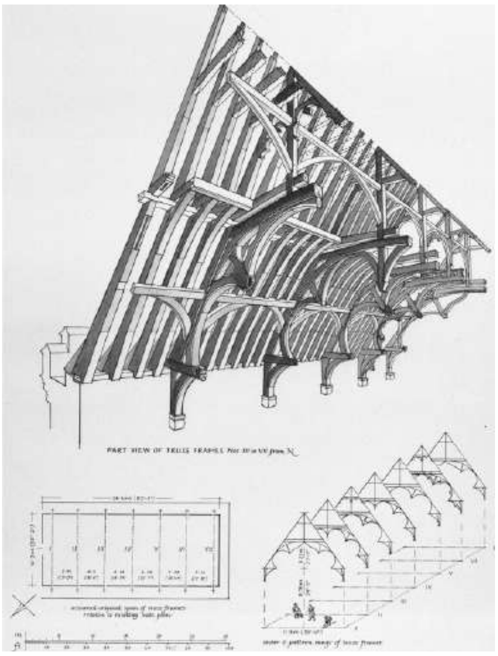


Figure 107: The roof of Darnaway's Castle Great Hall (1387) (RCAHMS SC 433080, 1998)

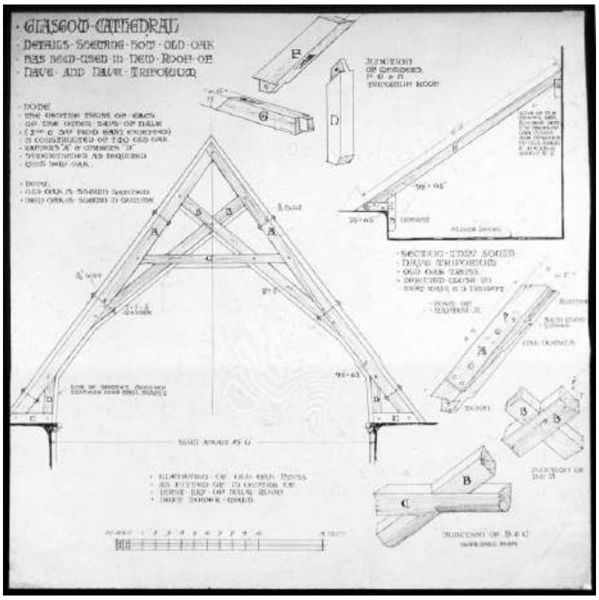


Figure 108: The roof of Glasgow Cathedral's central nave (thirteenth century) (RCHAMS DPM 1900/67/2, 1909)

Figure 109: The roof of the Great Hall at Edinburgh Castle (1510) (RCAHMS SC 1201162, 1888)

Figure 110: The roof of the central nave of Holy Rude church in Stirling (1455) (RCAHMS SC 738897, 1959)

These roofs are aligned with the English tradition of hammer-beam roofs, devised to span a wide space without the need of intermediate supports. Darnaway Castle's roof, in particular, can be seen as a 'proto-hammerbeam' roof since it predates the first English hammerbeam roof at London's Westminster Hall by roughly 20 years (Hanke, 2006). They are, however, different from the English ones because the hammer-post is often missing or its stiffening action is reduced by the fact that the hammer-beam is tenoned into its foot rather than vice versa (Gomme, 2002, Stell and Baillie, 1993). This is why they are called by Hanke (2006) 'open purlin' roofs or 'false hammer-beam' roofs. Gomme (2002) suggests that the structural arrangements of these roofs are devised in this way also to obtain decorative patterns able to convey a certain message.

These complex and elaborate open roofs, employing wall-plates, posts, struts, principal rafters, purlins and curved longitudinal braces, seem however to represent an exception rather than the rule, since most buildings of the period in Scotland are characterized by reduced spans. Scholars have investigated cruck structures covering cottages, farms and other vernacular buildings (Dunbar, 1956-7, Fenton and Walker, 1981, Hay, 1976, Stell, 1981) (Figure 111), and Hanke (2006) has highlighted the interesting use of massive stone vaults as roof structures in many buildings dating from thirteenth to seventeenth century (Figure 112). Nonetheless, Stell (1992, 2004), Ruddock (1995), Hay (1976) and Hanke (2006) all agree that up to nineteenth century the majority of Scottish roofs is characterized by a common rafter form: a sequence of closely spaced rafter couples, with no distinction between principal (load-bearing) and common (non load-bearing) rafters, whose rigidity is provided transversally by one or two collar beams and longitudinally by the gable walls and the sarking boards. Rafters simply sit on the wall-head, but additional rigidity is often provided by rafter feet with the ashlar post extended downwards on the masonry and occasionally rubble infill in between them. Timbers have square uniform scantlings and are jointed with mortice and tenon joints secured by wooden pegs. No wall-plates, tie-beams, purlins or struts are used.

Figure 111: Cruck-framed Cottage in Torthorwald (RCAHMS SC 383456, 1970)

Figure 112: Massive stone vaults in Dunglass Parish Church (1423) (RCAHMS SC 1164646, Undated, RCAHMS SC 1171792, Undated)

Although scholars agree on this description of Scottish common rafter roofs, very few examples are mentioned and even less are actually published in detail: the roof of Alloa Tower (Figure 113) and that in a town house in Kirkcaldy (Figure 114), both described by Ruddock (1995), and two other roofs described by Crone et al. (2004) (Figure 115) and Peddie (1883) (Figure 116).

Besides these four examples, no other common rafter roof had been reported in literature prior to Hanke's research (2006). He is the only one who has extensively researched these simpler roofs, which he calls 'rafter single roofs'. His investigation is focused on roofs in Midlothian and Fife of a date up to mid-seventeenth century (Figure 117) and relies primarily on documents held at RCAHMS archives, although he has also surveyed some roofs.

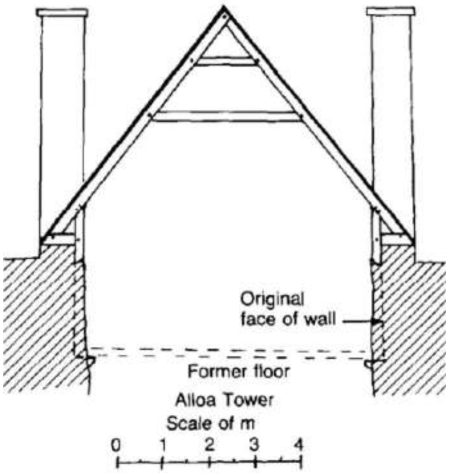


Figure 113: The roof of Alloa Tower (1497, maybe older) (Ruddock, 1995)

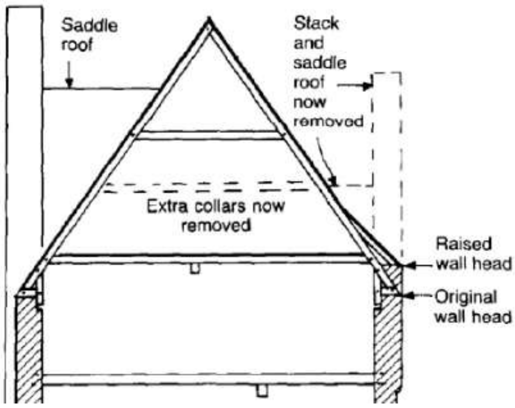
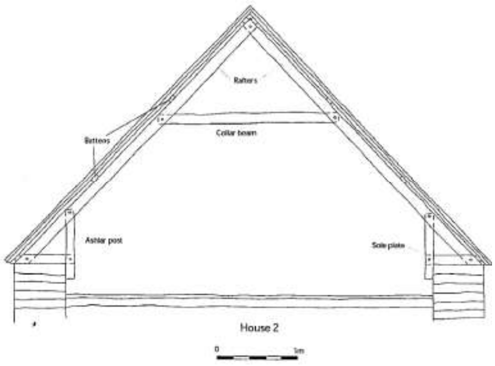


Figure 114: The roof of 339-343 High Street, Kirkcaldy (1600) (Ruddock, 1995); the graphic scale in Figure 113 is valid for this Figure too



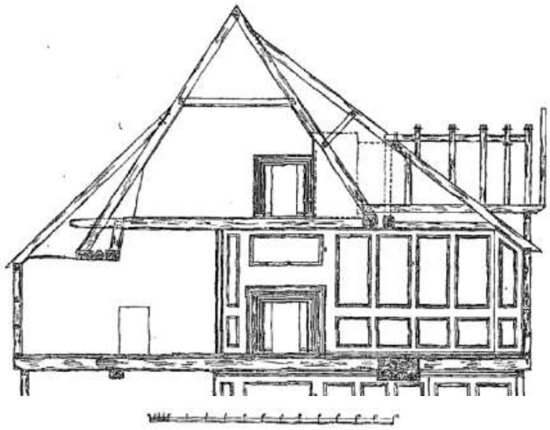


Figure 115: The roof of 68-74 High street in Brechin (1575) (Crone et al., 2004)

Figure 116: The roof of a tenement in Edinburgh Lawnmarket (1580), demolished before 1884 (Peddie, 1883)

Type	1251 – 1350	1351 – 1450	1451 – 1550	1551 – 1650
Massive vaults		OOOOOOO	OOOOOO	O
Mock vaults				
Rafter single roofs		O	OO	OOOOOOOOOOOO OOOOOOOOOOO
Purlin roofs			OOOOO	OO
Flat roofs			O	
Pyramidal roofs				O

Figure 117: The evolution of roof construction in South-East Scotland until 1650, extracted from Hanke (2006)

The drawings and pictures collected by Hanke (see examples in Figure 118, Figure 119, Figure 120, Figure 121; the full list is in Appendix A together with other documents we have found) show that the vast majority of Scottish buildings up to 1650 are covered by simple common rafter roofs in line with the description given by Stell (1992, 2004), Ruddock (1995) and Hay (1976).

Hanke (2006) argues that although these type of roofs are aligned with the Romanesque North-West European school of carpentry, some features are distinctively Scottish: the sarking, the rafter foot with the ashlar post extended downwards on the masonry (Figure 123) and the absence of wall-plates, tie-beams and purlins. It is true that although timber boards similar to the Scottish sarking are used elsewhere (Bertolini Cestari et al., 2015, Corvol-Dessert et al., 2009, Janse, 1989, Pompejano et al., 2015, Thelin and Linscott, 2008) and similar rafter feet can be found in France and Netherlands (Courtenay, 1985) (Figure 124) they have not been so persistently used throughout the centuries as in Scotland. Moreover, Hanke (2006) correctly emphasizes that the use of this simple common rafter form without wall-plates, tie-beams and purlins up to mid-seventeenth century is remarkable considering that queen/king posts, longitudinal bracing, principal rafters and the subdivision into primary and secondary frames start being introduced in England (Fletcher and Spokes, 1964, Hewett,

1980) and Continental Europe (Bláha, 2006, Corvol-Dessert et al., 2009, Eissing, 2009, Gogolin, 2008, Janse, 1989, Szabó and Kulin, 2005, Thelin and Linscott, 2008) since twelfth century, as discussed in the previous section.

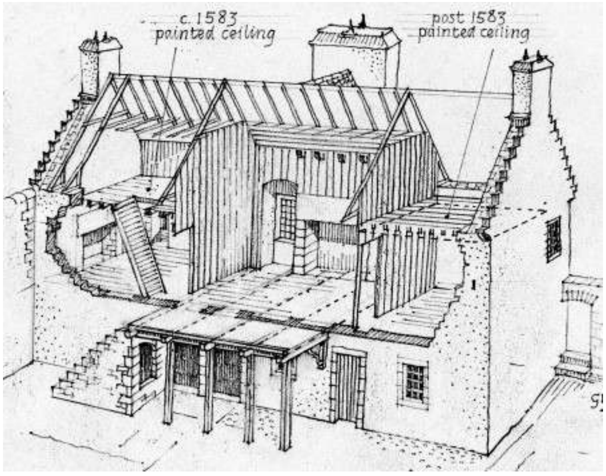


Figure 118: The roof of Dysart Bay Horse Inn (1583) (RCAHMS SC 989070, 1969) in Hanke (2006)

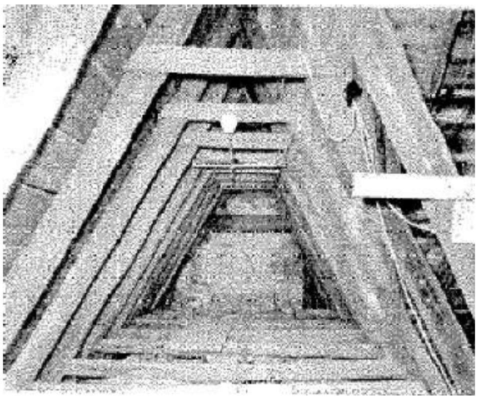


Figure 119: The roof of Northfield House (1611) (Hanke, 2006)

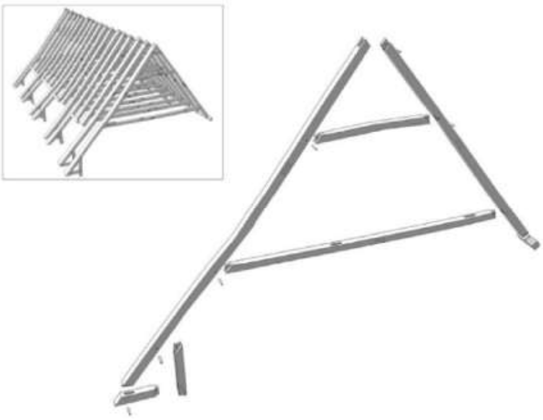


Figure 120: The roof of the North range of Newark Castle (1598) (Hanke, 2012)

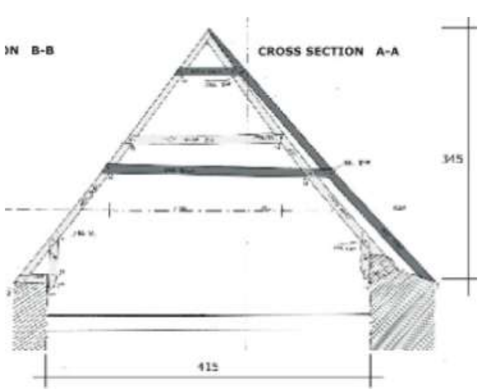


Figure 121: The roof of Halkerston Lodge (1638-42) (Hanke, 2004)

Hanke (2006) explains the absence of wall-plates and purlins with the constant presence of gable walls and of the sarking which provides longitudinal rigidity by connecting all the rafters together and with the gable walls. This explanation is reasonable since gable walls disappear in Scottish buildings only at the end of seventeenth century, as previosuly discussed. According to Ruddock (1995), the lack of wall-plates may also find an explanation in the compression-transferring nature of the extended ashlar post (Figure 123), which differentiates the Scottish rafter foot from the typical English one (Figure 122).

Moreover, Hanke (2006) argues that Scottish wrights did not use principal rafters and tie-beams because the thick and heavy stone walls of medieval and renaissance Scottish buildings easily counteracted the horizontal thrust resulting from these roofs. This explanation is also reasonable: the thickness of walls starts being reduced already at the beginning of seventeenth century, as previously discussed, but it rarely reaches widths lower than 1m (Gonzalez Manich et al., 2017) and never reaches the diaphanous dimensions of Gothic architecture (Hanke, 2006). According to Ruddock (1995), the spreading of the rafters is also counteracted by the rafter feet arrangement, but our surveys have proven this to be largely incorrect, since the mortice and tenon joints of the rafter feet are capable of resisting very little tension forces.

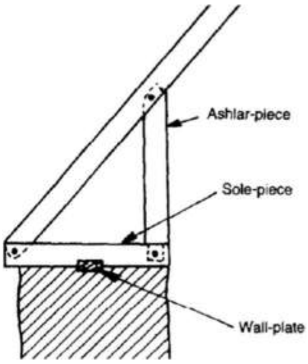


Figure 122: Schematic of the English rafter foot (Ruddock, 1995)

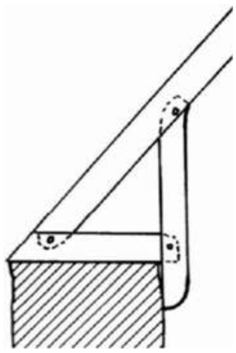


Figure 123: Schematic of the Scottish rafter foot (Ruddock, 1995)

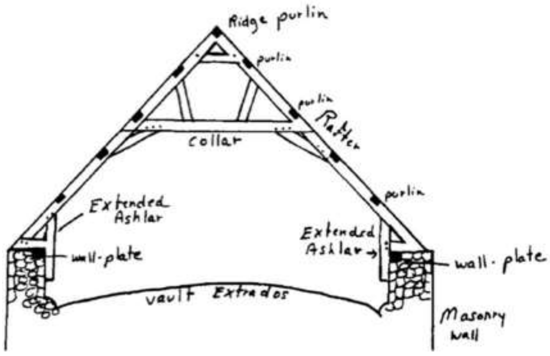


Figure 124: The roof of Ruldoc Abbey Church in Holland (twelfth century) with a rafter foot similar to the Scottish one (Courtenay, 1985)

Besides the open purlin roofs previously discussed, few other exceptions to the simple common rafter roofs are mentioned in literature: the purlin roof in Newark Castle (1597-99) (Hanke, 2012), the scissor-braced common rafter roofs in Glasgow Cathedral (thirteenth century) (Oldriev, 1916) (Figure 108), Moray House (seventeenth century) (Hanke, 2004) (Figure 125) and Ardchattan Priory (thirteenth century) (Hanke, 2006, Hay, 1976) (Figure 126), and the arch-braced common rafter roofs in Bardowie Castle (1566) and Linlithgow Town House of the Knights of St John (early sixteenth century, demolished) (Hanke, 2006, Hay, 1976) (Figure 127). Hanke (2006) identified the roof of Linlithgow Town House as an open purlin roof, but the available drawing (Figure 127) shows butt-purlins which contribute to the longitudinal stability rather than having a load-bearing function. This roof is particularly interesting as it is the only known example of Scottish rafter roof with primary and secondary frames and longitudinal bracing.

These exceptions suggest that Scottish wrights had the skills and expertise to design and construct more complex structures, when needed, and that they knew how to make an efficient use of timber. This raises the question to why they mostly opted for common rafter roofs recalling the technology used during the early Middle Ages in the rest of Europe. Hanke (2006) argues that the limited spans of domestic architecture built up to mid-seventeenth century in Scotland and the fact that roof structures start being hidden behind elaborate timber and plaster ceilings, relieving them from any aesthetical function, explains the persistent use of common rafter roofs. The examples we have previously discussed and other documents we have found in RCAHMS archives (Appendix A) confirm however that common rafter roofs were in use much earlier than 1600, even exposed.

Figure 125: The scissor-braced roof of Moray House (1623) (Hanke, 2006)

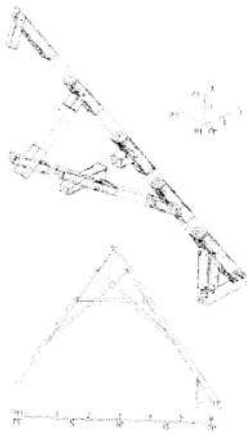


Figure 126: The roof of Ardchattan Priory (fifteenth century) (Hanke, 2006)

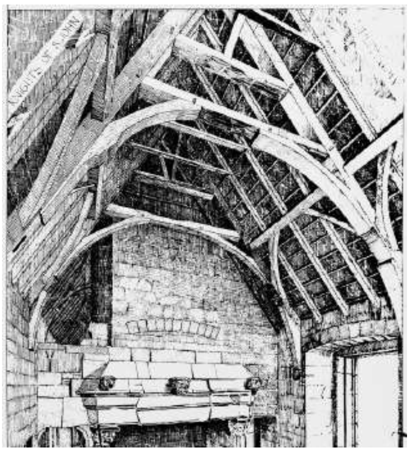


Figure 127: The arch-braced roof of Linlithgow Town House of the Knights of St John (early sixteenth century, demolished) (RCAHMS SC 1047690, 1886)

Hanke (2006) suggests that shortage of timber in post-medieval Scotland might be another reason for this simplification in roof construction. There are however some issues contradicting this which Hanke himself discusses. It is true that the parliament in 1503 passed Acts to protect Scottish woods from over use because Scottish forests had been 'utterly destroyed' (Newland, 2010); however, Scotland had been importing Baltic timber even before that date, thus the parliament Acts only resulted in an increase in timber imports (Crone and Mills, 2012); therefore shortage of timber was a problem only in rural areas where it was difficult to transport to. Moreover, shortage of timber in central Europe actually resulted in further innovation and optimization (Hoffsummer, 2007). On the other hand the reliance on foreign timber trade might have favoured timber architecture characterized by few standardised items such as deals and straight, relatively short timber elements, which were cheap and easy to retrieve (Hanke, 2006). This did not affect the ability of Scottish wrights to produce outstanding timber structures such as the ones in Edinburgh Parliament Hall (Figure 128) and Tron Church (Figure 129), but it prompted them to use in the vast majority of cases simple redundant common rafter roof structures.

Very little is known about Scottish roofs after mid-seventeenth century, since very few examples are mentioned in literature (Figure 130). Hay (1976) affirms that common rafter roofs continue to be used, the only difference being the joints between collars and rafters which become lapped/halved and dovetailed rather than mortice and tenon, secured by metal nails rather than timber pegs. He mentions Skellater House (eighteenth century) as example, and Hanke (2008) describes the same kind of joints in Auchindinny House (1707), and Burntisland Parish Church (1748-1822), but neither of them provides a full survey of these structures nor do they discuss the reasons for these technological developments.

Figure 128: The roof of Parliament Hall in Edinburgh (1631-40)

Figure 129: The roof of Tron Church in Edinburgh (1636-48)

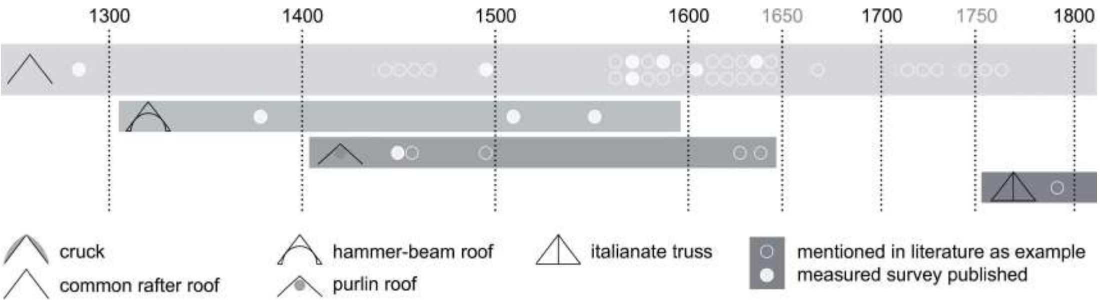


Figure 130: Timeline of Scottish timber roofs mentioned in literature divided by structural typology (for details see Appendix A); crucks are not included since they are used only in vernacular buildings

Hanke (2006) and Stell (2004) state that saddles and valleys joining up adjacent roofs, as well as hipped arrangements, start being used from late seventeenth century when gable walls disappear, as in Holyrood Palace (1671-9). Few earlier buildings are characterized by intersecting roofs and confirm once again that Scottish wrights possessed the technical knowledge necessary to erect more complex structures, but chose to employ this knowledge only occasionally: St. Nicholas church in Dalkeith (after 1390), Tullibardine Chapel (1446) (Figure 131), St. Salvator's church in St Andrews (c. 1450), Northfield House (c. 1590) and Newark Castle (1597-99) (Figure 132) (Hanke, 2008).

Gomme (2002) affirms that after mid-seventeenth century open purlin roofs are superseded for the wide spans of country houses by flat roofs with horizontal beams of large dimensions and Italian king-post trusses. Unfortunately, Gomme (2002) does not mention any example to argue his statement. Hanke (2006) disagrees with Gomme and states that Bruce and Smith continue employing common rafter roofs in their late seventeenth- and early eighteenth-century country houses. According to him, trussed roofs are introduced in Scotland by William Adam when he designs the New College Library in Glasgow in 1720 (demolished) (Figure 133). However, just like Gomme, he does not provide any evidence for this statement; the only built trussed roof he mentions is over the late eighteenth-century St Andrew and St George's church in Edinburgh (1782-4) (Figure 134).

Figure 131: The roof of Tullibardine Chapel with intersection visible on the left (Author)

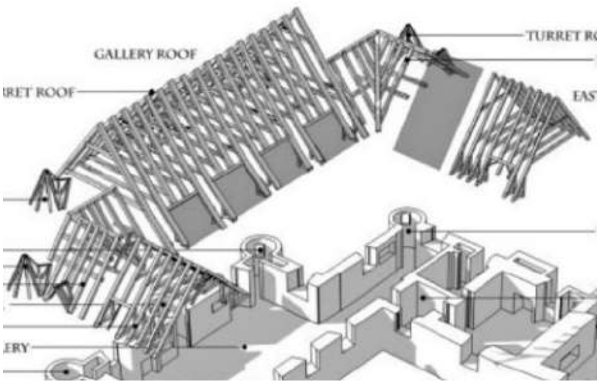


Figure 132: Schematic of the roofs of Newark Castle with intersections visible on top right and bottom left (Hanke, 2012)

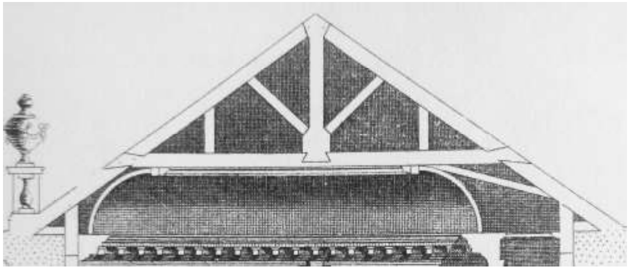


Figure 133: William Adam's design for the roof of Glasgow New College Library, 1720 (Adam, 1812)

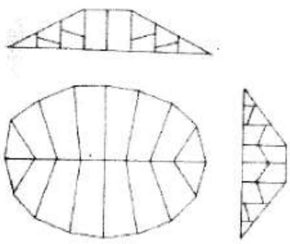


Figure 134: Schematic of the roof of St Andrew and St George's church (1782-4) (Hanke, 2008)

In conclusion, research up to now confirms that up to mid-seventeenth century Scottish roof carpentry is in line with the English one but develops distinctive features in hammerbeam roofs and common rafter roofs especially (Figure 135). However, despite the valuable contributions of Stell (1992, 2004), Ruddock (1995), Hay (1976), Crone et al. (2004) and Peddie (1883) and the extensive investigation carried out by Hanke (2004, 2006, 2008, 2009, 2012), there is still a significant lack of knowledge on the extent and nature of seventeenth- and eighteenth-century timber roofs in Scotland, caused mainly by the scarcity of measured surveys, as highlighted in Figure 130. First hand data is needed to corroborate the hypothesis made and in particular to understand how roof design has evolved after mid-seventeenth century.

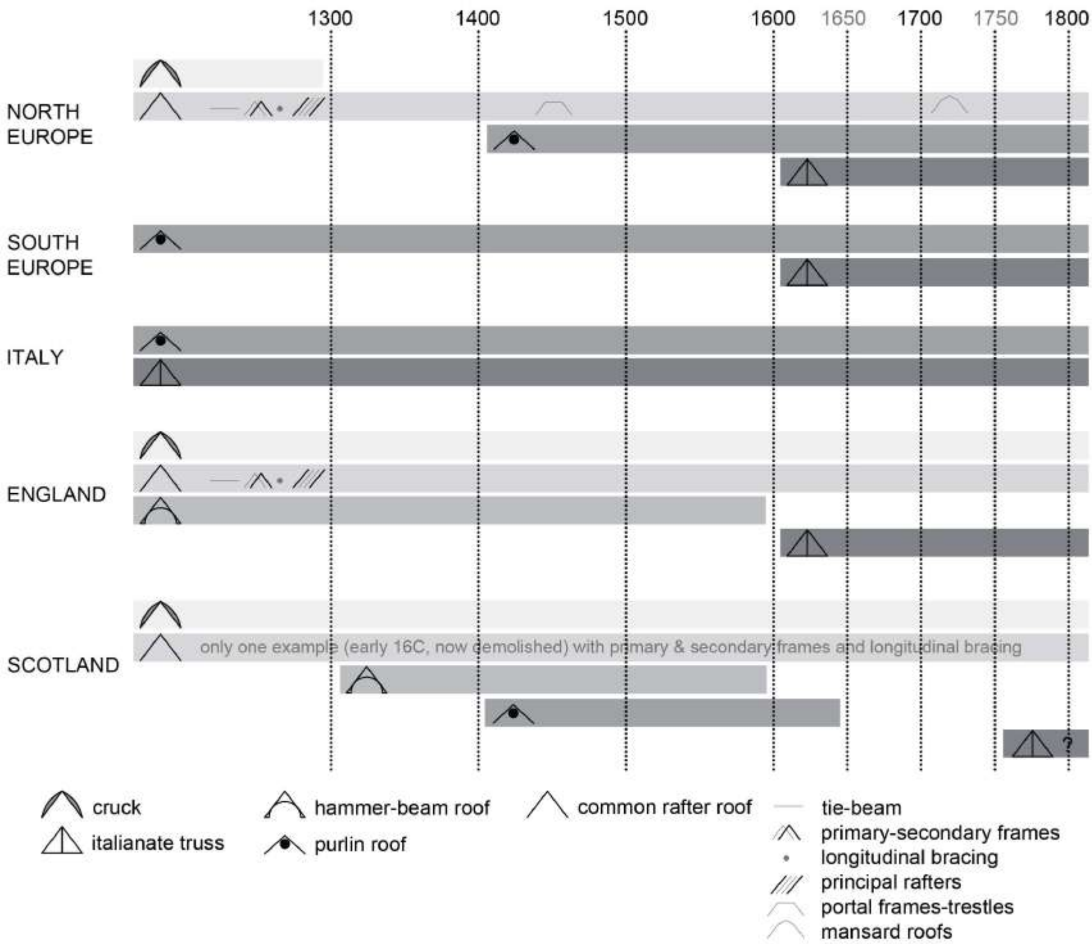


Figure 135: Timeline of different roof structures types used in continental Europe and England, compared to what is reported in litertature about Scottish roofs

3.2.2 Timber species and provenance

A big part of the timber used in seventeenth- and eighteenth-century Scottish roof structures is not native Scottish. In that period, local Scottish wood had a reputation for being of lower quality and it was difficult to transport it throughout the country; thus Scotland started very soon to import timber from the Baltic regions and Scandinavia. Newland (2007, 2010, 2011, 2012a, 2012b, 2012c) and Thomson (1991) have researched the timber sourcing and trade during seventeenth and eighteenth centuries respectively, mainly through archival documents, whilst Crone (2001, 2008b, 2008a, 2011) has carried out dendrochronological analysis of Scottish timbers, also in collaboration with other scholars (Crone and Fawcett, 1998, Crone and Gallagher, 2008, Crone et al., 2004, Crone and Mills, 2007, Crone and Mills, 2008, Crone and Mills, 2011, Crone and Mills, 2012, Crone and Sproat, 2011, Mills and Crone, 2012). Although the sample of analysed roof timbers is limited, the above mentioned research provides us with extremely helpful information on the timber species employed in seventeenth- and eighteenth-century Scottish architecture and their provenance.

Walker (2006) states that several different species were used in Scottish buildings: chestnut, oak, ash, aspen, beech, willow and other hardwoods. Hay (1976) mentions oak and imported fir. However, neither of the two provides any evidence for their statements. Dendrochronological studies have identified exclusively oak (*Quercus sp.*) and Scots pine (*Pinus Sylvestris*) in roof structures (Crone and Mills, 2012) (Figure 136); the preference for these two species has been confirmed by our surveys, as we will discuss in the following chapters. Spruce and fir are often mentioned in records and accounts of the time, but it seems that they were simply used as different terms for pine (Crone and Mills, 2012).

In most buildings there are timber elements coming from different sources and also felled in different dates, due to stockpiling practices, transportation time and reuse of timber, therefore it is not always easy to assess the exact provenance and construction date of the timber (Crone and Mills, 2012). It is relatively easy now to date imported timber, but it is still difficult to date native one because it is rare and there are fewer master chronologies available (Crone and Mills, 2011): this is the issue on which Scottish dendrochronology has focused its research lately (Mills and Crone, 2012). Another important focus should be the post medieval period, since only nine seventeenth- and eighteenth-century roofs have been dendro-dated and provenanced so far (Figure 136). The dendrochronological analysis of more roof structures would certainly allow dating roof structures based on typological aspects with more confidence. Based on the evidence collected up to today we can nonetheless draw an outline picture of the sourcing and use of timber species in Scotland.

During the Middle Ages, oak was considered to be the most valuable of timber, due to its strength and resistance, and used whenever possible for the construction of high status buildings in Scotland (Newland, 2010). During thirteenth, fourteenth and fifteenth centuries local oak is used, as testified by the roofs of Glasgow Cathedral (thirteenth century) and Darnaway Castle (1387) (Crone and Mills, 2012) (Figure 136). By sixteenth century, however, it is hard to find native oak trees suitable for building construction, due to transportation problems and low quality (Newland, 2010). After the Parliament passes Acts in 1503 to protect Scottish woods from over use, domestic timber continues to be felled for commercial use, as testified by the roof timbers in Newark Castle (1598) (Crone, 2008b), Drum Castle (1598-1621) (Crone, 2011) and Crathes Castle (1589-1591) (Crone and Mills, 2007) (Figure 136), but many woodlands start disappearing quickly and Scotland has to look abroad for new timber sources (Newland, 2010).

The import of oak, pine (called *redwood*) and spruce (called *whitewood*) from the eastern Baltic and Scandinavia increases. Norway dominates the market from 1550 (Crone and Mills, 2012, Newland, 2010). In some occasions Norwegian timber is specifically requested for building works in Scotland (Newland, 2010): George Heriot Hospital’s governors, for example, order a ship to be sent specifically to Norway to buy timber for the construction works in 1627 (Lockhart, 2003).

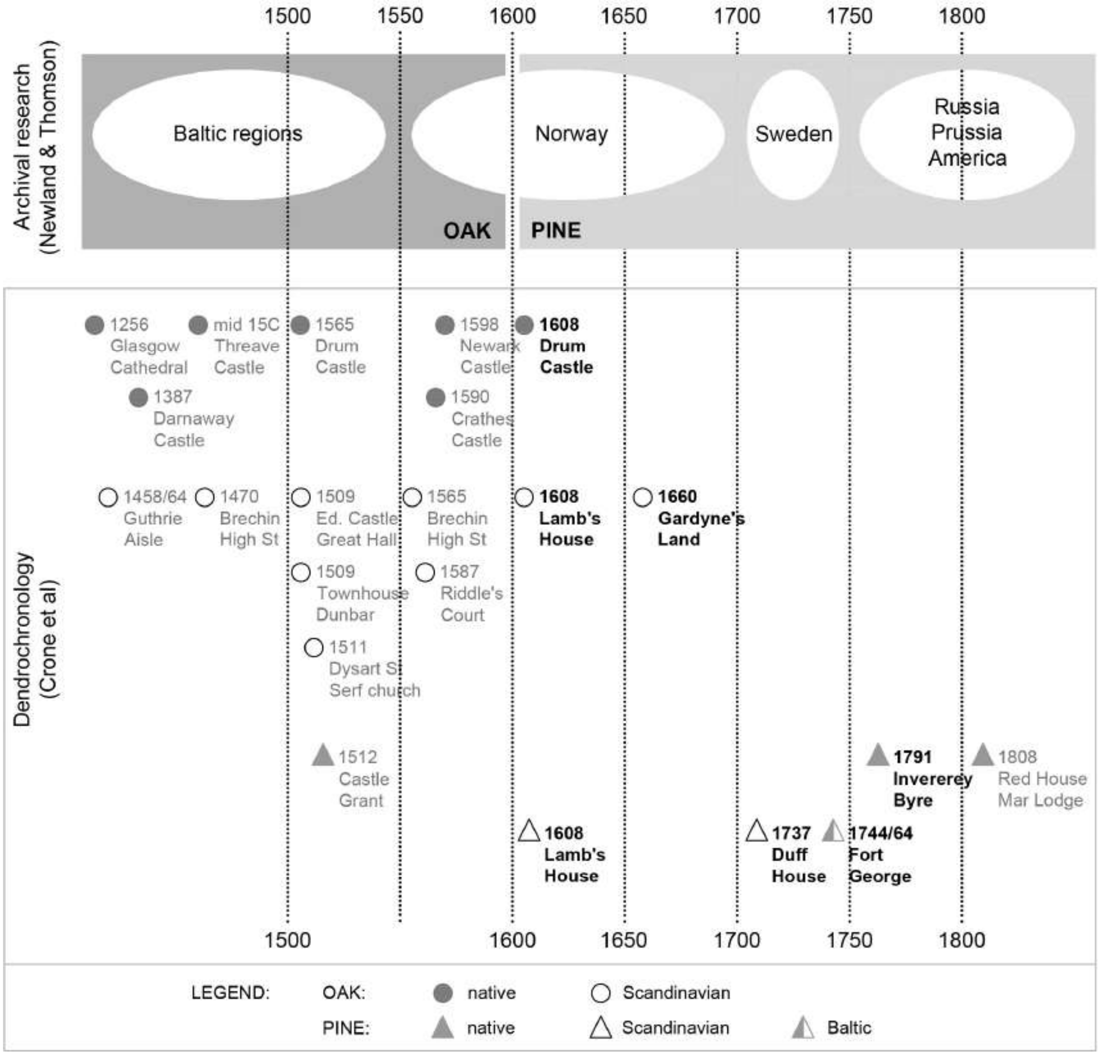


Figure 136: The species and provenance of timbers used in Scottish roofs according to archival research carried out by Newland (2007, 2010, 2011, 2012a, 2012b, 2012c) and Thomson (1991) and dendrochronological analysis carried out by Crone (2001, 2008b, 2008a, 2011) and others (Crone and Fawcett, 1998, Crone and Gallagher, 2008, Crone et al., 2004, Crone and Mills, 2007, Crone and Mills, 2008, Crone and Mills, 2011, Crone and Mills, 2012, Crone and Sproat, 2011, Mills and Crone, 2012)

From 1600 oak is gradually replaced by pine for structural use (Figure 136): the export of oak from Norway is prohibited after 1602 because the remaining supplies are vital for the construction of the Danish-Norwegian fleet (Mills and Crone, 2012, Newland, 2010). Thus seventeenth century is dominated by the import of pine from Norway (Crone and Mills, 2012, Newland, 2010).

In eighteenth century Norway declines as supplier of timber due to the over-exploitation of its natural resources. Imports from Sweden increase dramatically from 1730s and surpass Norway in 1750s (Thomson, 1991). However, because of the difficulty in identifying the specific timber source, roof timbers in eighteenth-century Scottish buildings are often dendro-provenanced as Scandinavian rather than Norwegian or Swedish, as in Duff House (1737) (Crone, 2008a) (Figure 136).

From mid-eighteenth century Scotland starts importing timber from eastern Baltic; the trade is dominated by the import of pine mainly from Prussia and Russia, whose timber is considered to be of better quality than its Swedish and Norwegian rivals (Thomson, 1991). Norway and Sweden keep exporting timber because theirs is cheaper and shorter, therefore more easily manufactured into deals (Thomson, 1991). Baltic pine has been identified in the roofs at Fort George (1761-1767) (Crone and Mills, 2008) (Figure 136). In this period home-grown pine is used as well (Crone and Mills, 2012) (Figure 136). From 1790s timber is also imported from the Americas, as in England (Yeomans, 1992): the West Indies send exotic hardwoods such as mahogany and American Colonies and Canada provide hardwoods such as oak and walnut (Thomson, 1991). These have however not been identified in roof structures: they were probably used for interiors.

3.2.3 The dressing of timbers and the construction process

Norway's dominant position during the sixteenth and seventeenth-century timber trade appears to be due to the use of water-driven sawmills, a new technology which allowed for the mass production of deals and planks (Newland, 2010). Pit saw mills existed in Scotland since early seventeenth century but they were much slower. The water-driven technology reached Scotland by late seventeenth century but it was not so widespread, probably because timber suitable to be processed in this way was very limited or inaccessible (Newland, 2010).

Crone and Mills (2011) and Hanke (2006) state that the earliest surviving Scottish roofs, such as Guthrie Aisle (1464) and 68-74 High street in Brechin (1470), previously mentioned, employ small squared heart baulks, shaped through scoring, hewing and flattening all four faces, often leaving bark on the corners (Figure 137). We have observed the same in the early seventeenth century roofs we have surveyed. Typical cuts of timber bought by the Scottish skippers from Norway included in fact sawn boards for the sarking (deals), and beams for the rafters/collars too small to be further sectioned to obtain more than one beam (Thomson, 1991). It has been suggested that timber elements might have been prefabricated at the source (Hanke, 2006, Newland, 2012c). It is reasonable to think that timbers were roughly dressed at the source in order for them to occupy less space in the ship, but the shrinking effect would not allow to dress timber joints and put them in place after a long period of time (necessary to transport the timber to Scotland).

The earliest evidence of use of saws in Scotland is provided by planks from 1472-6; however, hand sawing does not appear to have become common in Scotland until eighteenth century (Crone and Mills, 2011, Hanke, 2006). It appears earliest in prestigious buildings whose wealthy owners could afford to hire a sawyer (Figure 138) (Crone and Mills, 2011). On the contrary, from eighteenth century technological developments in sawmilling in Scottish ports encourage the import of big squared timber baulks to be further processed by Scottish wrights to meet individual needs

(Thomson, 1991). The balks would be sawn in half, quarters or even more elements: in fact in eighteenth century Scottish buildings timbers have one or more sawn faces. Hewn round-wood is still used up to early nineteenth century but only in lower-status buildings (Crone and Mills, 2011).

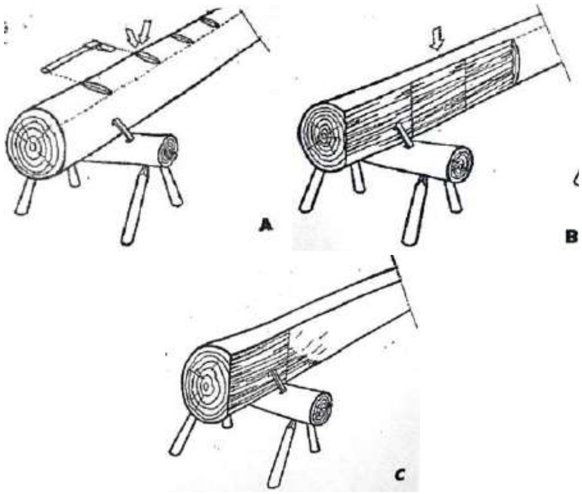


Figure 137: The dressing of timber beams: A. scoring; B. hewing; C. flattening (Drdácký et al., 2006)

Figure 138: Hand-sawn oak collars in the roof of the Mansion House at Drum Castle (1598-1621) (Crone and Mills, 2011)

Hay (1976) hypothesizes that the tools used by medieval and post-medieval Scottish wrights to dress the timber are the same as the ones used by other European carpenters: an axe for felling/squaring/splitting, an adze for smoothing, several types of saw, an auger for boring and a claw hammer. This statement is however quite generic as it is known that different types of axes, adzes and saws were used in the different European countries (Corvol-Dessert et al., 2009). Crone and Mills (2011), based on traces found on historic timbers in 34 buildings, state that until eighteenth century Scottish timbers are dressed with the axe/adze and the minimal use of a pit or frame saw; they are thus hand-axed and hand-sawn. In fact whilst mechanical sawmills exist in Norway since 1530 and in Netherlands since late sixteenth century, the earliest reference to circular saws appears in England in 1767 and in Scotland in 1820 (Crone and Mills, 2011).

Very little is known about the erection process after all the timber elements had been dressed. Hanke (2006) and Crone and Mills (2011) mention the use of roman numerals as assembly marks, but Hay (1976) is the only one discussing their role: he states that the principal members of each frame were marked with the same number, so that they could be correctly assembled; this allowed wrights to prepare the elements away from the site. Frames on site are often not in sequence for this reason: the numbers were used only to match the elements of one frame, then the frames could be placed on the walls in any order.

3.2.4 Wrights and carpentry treatises

Wrights have not been considered worth researching and to date, despite a recent contribution by Newland (2012b), little is known about their relation with architects and their role in the design process. It seems that in seventeenth- and eighteenth-century Scotland there was a sort of hierarchy amongst woodworkers but there is still confusion on the specific terminology since no research has been carried out on this aspect. Whilst literature on English carpentry only mentions the words ‘carpenter’ and ‘joiner’, Scottish scholars employ the words ‘wright’ and ‘carpenter’ interchangeably. The word ‘wright’ has disappeared from English construction vocabulary, superseded by ‘carpenter’ (for heavier structural work) and ‘joiner’ (for furniture and fittings); in fact Davies and Jokiniemi (2012) say that 'wright' is an outdated or vernacular word for a carpenter. The Concise Scots Dictionary (Robinson, 1999) defines 'wright' as 'a woodwright, a carpenter', the Etymological Dictionary of the Scottish Language (Jamieson, 1808) traces the word back to 'wryhta/wurtha: a workman, one by whom anything is framed' from 'wyrc-an: to work'.

In fact seventeenth-century wrights in Scotland used to deal with all the timber work, from roofs, to flooring, windows, furniture, scaffolding, plasterwork, tools for other craftsmen, etc (Newland, 2010). This clearly required expertise and advanced technological knowledge, which is why their social status improved - unlike in England, wrights had a low social profile in Scotland throughout the Middle Ages (Hanke, 2012). During the transition from direct labour to the contract system they started working as contractors (Dunbar, 1976, Newland, 2012b), as in England (Yeomans, 1992), and some even aspired to the role of architect, as James Baine (Newland, 2010). From seventeenth century their role was increasingly important in the construction site, which is why they soon outnumbered masons in St Mary’s Incorporation of masons and wrights in Edinburgh (Newland, 2010). During the eighteenth century some wrights actually became professional architects, as Allan Dreghorn (Lewis, 2015) and city developers, as James Salisbury or John Bourgh (Lewis, 2006).

To become members of St Mary’s Chapel Incorporation, wrights had to do an apprenticeship of six or more years and to produce an ‘essay’ at the end, which normally consisted in creating a piece of furniture (Newland, 2010). They were trained to know the architectural orders, since they were often requested to produce the final essays according to Vignola’s (Barozzi da Vignola, 1562), Scamozzi’s (1615), or Palladio’s (1570) orders. The first mention of Palladio in the wrights' essays occurs in 1692 followed by references to Vignola and Scamozzi (Jones, 1991). This could mean that the Incorporation had a library which included these treatises.

Scamozzi and Palladio show some roofs (Figure 139, Figure 140) and other timber structures (mainly bridges). Other sixteeenth- and seventeenth-century treatises include roof carpentry: Serlio (1545) (Figure 141), Barbaro (1552), Du Cerceau (1576-9) (Figure 142), De l'Orme (1578), Digges (1592), Baldi (1621), Zanini (1629), De Bray (1631). Very few of them, however, discuss it in detail. This is because these first manuals are either more concerned with the overall architectural proportions and appearance of buildings, or they are aimed mainly at helping tradesmen in measuring and estimating costs, to remedy their education lacking in mathematics (Yeomans, 1986a).

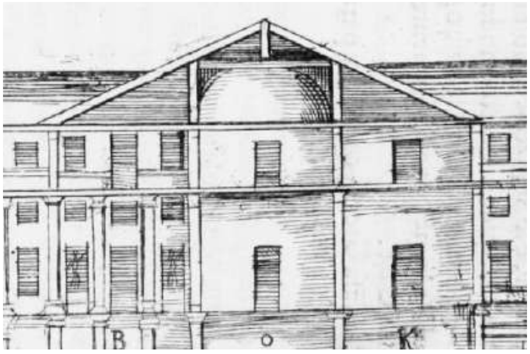


Figure 139: Roof drawn by Scamozzi (1615) at p. 228

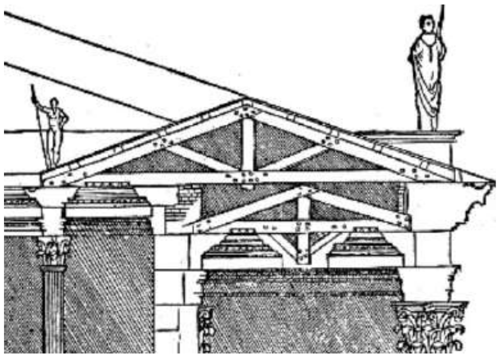


Figure 140: Trussed roof drawn by Palladio (1570) in chapter 12

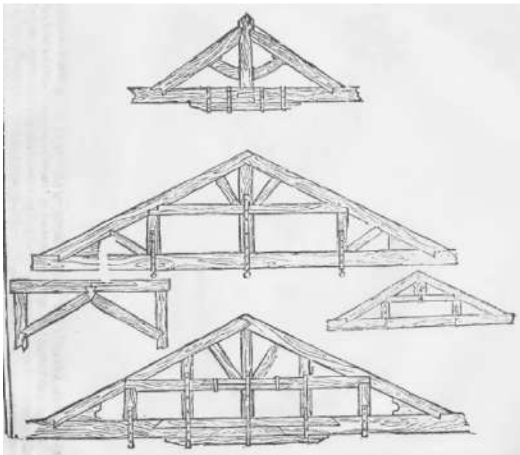


Figure 141: Trussed roofs drawn by Serlio (1545) at p. 197

Figure 142: Roof drawn by Du Cerceau (1576-9), vue 81

These drawings might have been the vehicle for transfer of technological knowledge from continental Europe to Scotland. However, Hanke (2006) argues that, considering the extensive use of simple common rafter roofs up to mid-seventeenth century in Scotland, it is reasonable to think that up to then Scottish wrights did not have access to European carpentry treatises or decided to disregard them and follow the traditional building methods they were comfortable with. He is right in stating that even the complex open structures devised for Edinburgh Tron church (Figure 128) and Parliament Hall (Figure 129) do not resemble any other known roof structure built or drawn - they are very different even from the English hammer-beam roofs - and thus owe little to foreign influences. Besides Hanke's and Newland's contribution (2010), however, little research has been carried out on the role of architects and wrights in the roof design process and on the influence of contemporary treatises, travels in other countries or acquaintances with foreign professionals. In particular, no investigation has been carried out to understand how these aspects change from the second half of seventeenth century, when Scottish architecture sees an important development driven by the early modern architects Sir W. Bruce and Mr. J. Smith (section 3.1.2).

3.3 Tracing the historic development of seventeenth- and eighteenth-century timber roof structures in Scotland based on our findings

3.3.1 Structural arrangements

As we have seen in the previous section, in Medieval times large spans (>8m) are covered in Scotland by hammer-beam roofs and open purlin structures in line with the English tradition (Figure 143). These structures have been extensively researched because they are visible and quite spectacular. Nevertheless, they represent an exception rather than the rule, because most Medieval Scottish buildings are characterized by reduced spans (<8m), which do not require the use of such complex roof structures, and by decorated ceilings, behind which the roof structures are hidden. These buildings are in fact covered with stone vaults or simple common rafter roofs (Figure 143), as highlighted by Hanke (2006) and confirmed by our surveys: the 15 pre-1670 roofs we have surveyed are all common rafter roofs (Figure 51).

However, things change by the end of seventeenth century, when classical and baroque architecture are introduced in Scotland by the architects Sir W. Bruce and Mr J. Smith: Scottish wrights are forced to develop roof structures able to span increasingly wider spans with shallow pitches and hipped arrangements, whilst supporting heavy plaster ceilings (Figure 143). Eventually, a completely different structure is imported from abroad: the trussed roof (Figure 143). Our surveys have allowed understanding how Scottish wrights face this challenge and how roofs evolve from mid-seventeenth century, which had not been investigated so far.

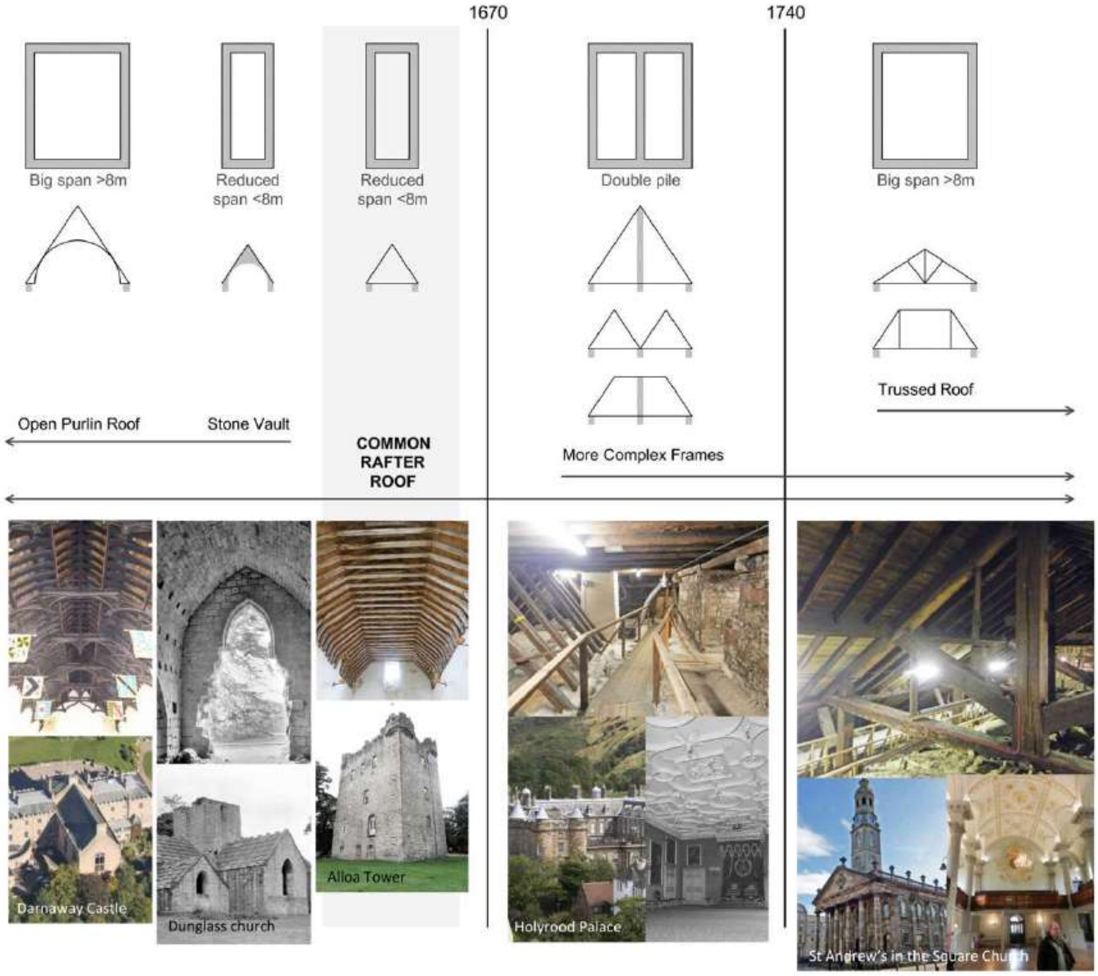


Figure 143: The development of Scottish timber roof structures (Serafini and Gonzalez Longo, 2015b). From left to right: Darnaway Castle, 1387 (RCAHMS DP 161383, 2013, RCAHMS DP 222837, 2015); Dunglass Church, 1423 (RCAHMS SC 1164646, Undated, RCAHMS SC 1171792, Undated); Alloa Tower, 1497 or older; Holyrood Palace, 1670s (RCAHMS SC 1209320, 1922); St Andrew's in the Square Church, 1751-3

3.3.1.1 Common rafter roofs

Our surveys and archival research (Appendix A) confirm Hanke's (2006) statement that up to late seventeenth century Scottish roofs are of simple common rafter form (Figure 51), with no subdivision between load-bearing and non load-bearing rafters and no longitudinal members other than the sarking boards. This is remarkable considering the wider European context, where these features are introduced much earlier, from twelfth century (section 3.2.1). The reason for this extensive use of simple common rafter roofs lies in the development of Scottish architecture of the time (section 3.1) and in the timber trade with North Europe (section 3.2.2), as highlighted by Hanke (2006) and Newland (2011). However, our surveys have allowed identifying certain variations in the structural arrangements of these common rafter roofs that denote a technological development starting from the end of seventeenth century, as discussed below.

The oldest surviving Scottish common rafter roofs are open roofs, exposed to view: the thirteenth century Glasgow Cathedral (Oldriev, 1916) (Figure 108), the fifteenth century Alloa Tower (Ruddock, 1995) (Figure 113) and Tullibardine Chapel (Fawcett, 2002) (Figure 131). However, painted timber and then plaster ceilings soon become fashionable and roof structures are hidden above them: one of the earliest examples is Guthrie Aisle (1464) (Fawcett, 2002), whose painted timber ceiling has been removed and is now exposed at Guthrie Castle.

The 22 common rafter roof structures we have surveyed from the period between the end of sixteenth century and 1700 (Figure 51) are all hidden behind decorated ceilings. The spans are generally less than 7m and the pitches are quite steep (50°-60°). The typical arrangement can be seen in Figure 144: they are simple gabled roofs composed of rafter couples, spaced 30-60cm apart, each connected transversally by one or two collar beams and longitudinally by sarking boards (Figure 129, Figure 130). The timbers have uniform square/round scantlings of 10/15cm. The rafters are often simply sitting on the wall-head or on a sole piece tenoned into an ashlar post extended downwards on the masonry (Figure 129, Figure 130) - the ‘Scottish rafter foot’ (Ruddock, 1995) discussed in detail in section 3.3.2.2. No wall-plates, tie-beams, struts or longitudinal elements are used, with the exception of headers supporting the rafter ends above windows and dormers.

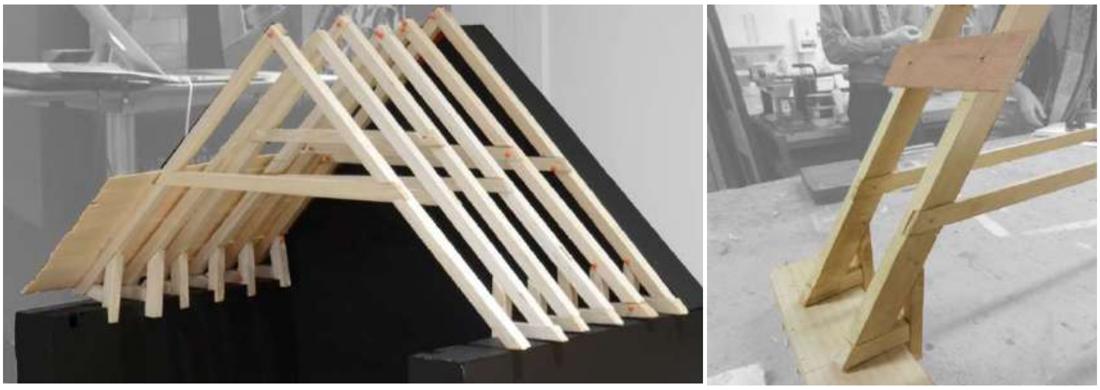


Figure 144: Maquettes of Scottish common rafter roofs produced by the attendees of the workshop "Traditional Scottish Timber Frames" held by the author at Glasgow City Heritage Trust on 19/04/2016 (left) and by the Master students of Edinburgh University during a workshop held by the author on 12/02/2015 (right)

During the eighteenth century common rafter roofs are still used, but some innovations are introduced: they retain the basic structural arrangement composed of common rafter couples connected solely by collars and sarking boards, but they are characterized by wider spans (the maximum is 9.8m reached by Duff House, 1737), shallower pitches (the minimum is 34° reached again by Duff House, 1737), different roof geometries (intersected roofs, hipped roofs, M roofs, etc) and the use of wall-plates and tie-beams, discussed in detail in section 3.3.2.2. Moreover, some roofs we have surveyed testify the introduction of other features that modify their structural arrangement even more significantly: this is why they have been grouped separately, as 'complex frames'.

Figure 145: The common rafter roof of Culross Palace (1597-1610): sections (left), the rafter foot (centre), the ceiling underneath (right)

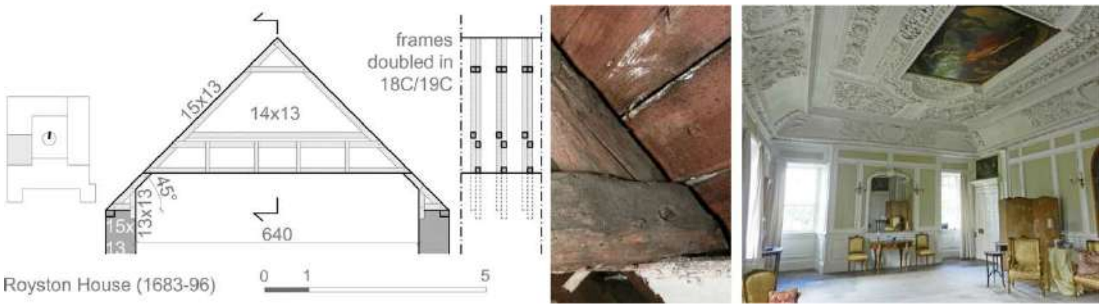


Figure 146: The common rafter roof in the West range of Royston House (1683-96): sections (left), the joint between rafter and collar (centre), the ceiling underneath (right)

3.3.1.2 Complex frames

From 1670s onwards, common rafter roofs had to adapt to the new architecture introduced in Scotland by the architects Sir W. Bruce and Mr J. Smith. Shallower roofs, more in keeping with the requirements of the new facades of buildings such as Holyrood Palace (1671-9) and Melville House (1697-1703), were needed. M-roofs, platform roofs and hipped roofs - known in Scotland as 'Italian roofs' (Innocent, 1971) -, emerged and substituted the high pitched gables of medieval Scottish buildings (Figure 147). The spans became increasingly wide (>8m). Scottish wrights already had the technical knowledge to cover big spans, as proved by Darnaway Castle (Figure 107) and Edinburgh Castle (Figure 109). However, by late seventeenth century heavy plaster ceilings had become fashionable and roof structures were also responsible for supporting them. Roof structures took some time to become efficient enough to do this. At first, intermediate supports were necessary.

Holyrood Palace (1671-9) is the earliest hipped platform roof we have surveyed (Figure 148). The internal structure is still a common rafter roof, since there is no subdivision between load-bearing and non load-bearing rafters, and there is still no longitudinal bracing other than the sarking boards. However, the roof geometry is innovative as it is hipped and spans above a double pile plan.

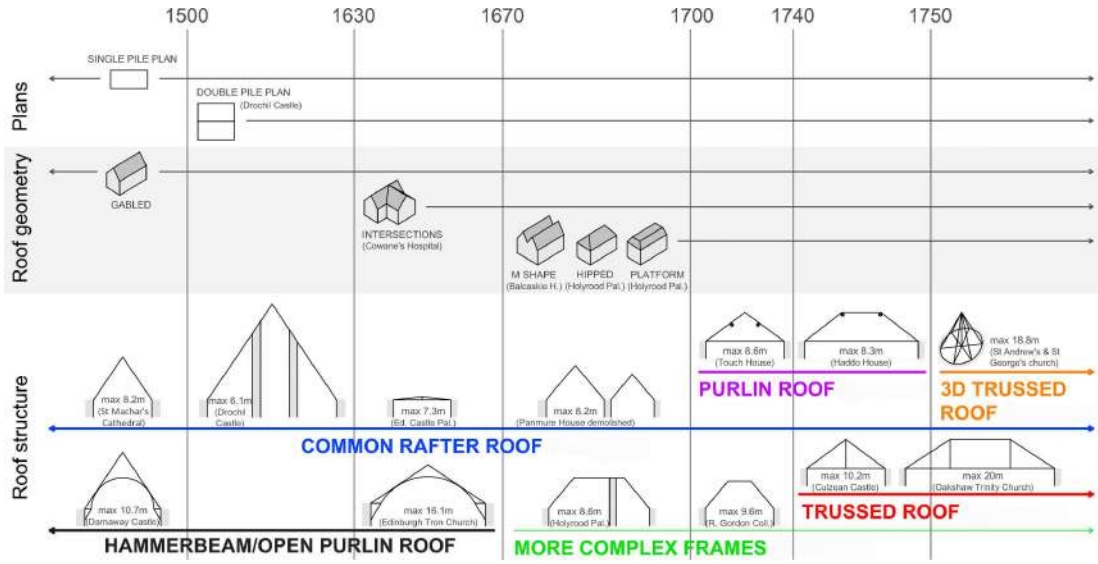


Figure 147: Timeline of the development of structural arrangements of Scottish timber roof structures; adapted from Serafini and Gonzalez Longo (2016)

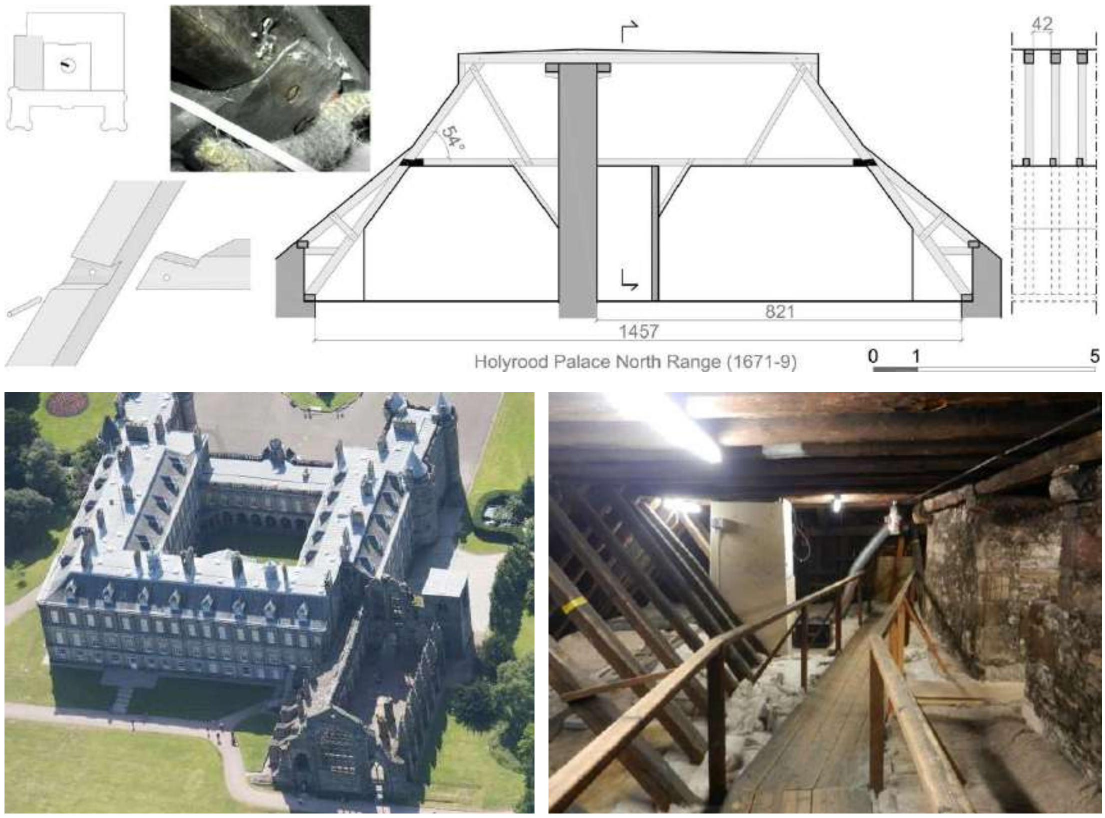


Figure 148: The roof of Holyrood Palace (1671-9): sections with tension-absorbing joints highlighted in black (top), bird's eye view at bottom left (Map data: Google), view of roof space (bottom right)

Double piles had already been introduced by late sixteenth century: Drochil Castle (1578) has one of the very first known double pile plans (Figure 147); the roof has not survived unfortunately, but from what remains we can hypothesize that it was gabled, probably with a common rafter structure spanning over the double pile, supported by the intermediate spine walls (Figure 149). This type of structure was used up to mid-eighteenth century, as testified by Tweeddale House in Edinburgh (1754-56). Sir W. Bruce did the same in Holyrood Palace, but introducing the hipped platform roof and other innovative features, such as tension absorbing joints (dovetail joints, highlighted in black in Figure 148).

Figure 149: Drochil Castle (1578): plan (Macgibbon and Ross, 1887-92) (left), bird's eye view (RCAHMS DP 143824, 2012) (centre), West facade (RCAHMS SC 937335, 1963) (right)

Joints will be discussed in detail in section 3.3.2.1. However, it is important to stress here that whilst dovetail joints were in use in North-West Europe already during early Middle Ages (Bláha, 2006, Corvol-Dessert et al., 2009, Eissing, 2009, Gogolin, 2008, Janse, 1989, Madsen, 2013, Suchý et al., 2008, Szabó and Kulin, 2005, Thelin and Linscott, 2008), they are used in Scotland for the first time in Holyrood Palace and their introduction is important because it testifies the awareness that timber elements can work in tension. In fact, up to late seventeenth century Scottish wrights understood timber elements as behaving in compression only: in structural terms open purlin roofs and common rafter roofs resemble barrel vaults, because all the timber elements are behaving in compression, just like voussoirs in stone arches (Hanke, 2006). The use of tension absorbing joints allowing timber elements to work as ties, in tension, is therefore an important innovation for Scottish roofs.

Holyrood's configuration with an intermediate spine wall might be seen as a consequence of the fact that the Palace had been extended in 1671-9 rather than built ex-novo. This is certainly true but buildings contemporary to Holyrood testify that intermediate spine walls were used even for the new-built. Kinross House (1679-93) and Melville House (1697-1703) (Figure 150), for example, are designed and built ex-novo but they are very similar to Holyrood in terms of roof design: they both employ hipped platform roofs with intermediate spine walls. This suggests that at the time Scottish wrights still did not have the ability to create shallow roofs over wide spans without intermediate supports.

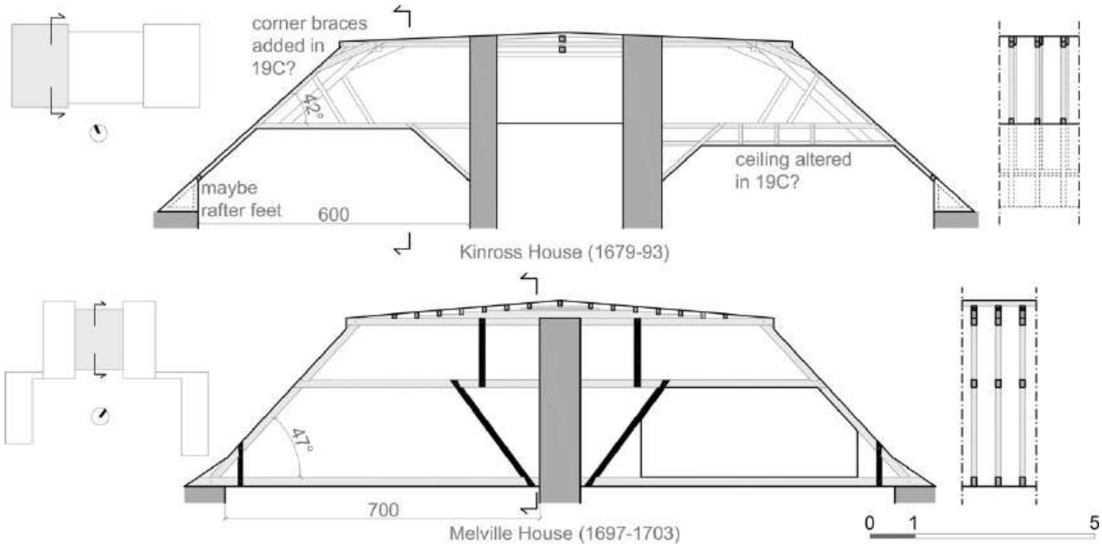


Figure 150: The roofs of Kinross House (1679-93) (top) and Melville House (1697-1703) (bottom)

Another innovative feature is introduced in Melville House's roof: the use of hanging posts and struts (highlighted in black in Figure 150). These tension-absorbing members, just like dovetail joints, were already in use in North-West Europe since early Middle Ages (section 3.2.1.2). Their use in Melville House suggests an awareness of the problem of beam deflection, and can be seen as an antecedent of king/queen-posts in trussed roofs, even though they do not show a full understanding of their role as they create additional load on the collar and upper beam. They later appear in the roofs of Yester House (1699-1748) (Figure 152), Stirling Castle Palace (after 1719) (Hanke, 2008), and Newhailes House (1730) (Figure 153). In some earlier roofs, such as Fountainhall House (early seventeenth century), Pinkie House (1613) and Abbeystrand Buildings (1630), they seem to be later additions, judging from the timber dressing and the joints.

The roofs of Holyrood Palace, Kinross House and Melville House achieve a shallow external geometry, but fail in attaining an undisturbed big span inside, as they still rely on intermediate spine walls as support. Roof structures had to evolve a bit further to be able to get rid of these walls. It was eventually necessary to import from elsewhere a completely different structural type: the truss.

The introduction of the trussed system in Scotland is slow and gradual: many eighteenth-century roofs still show a common rafter form. A good example is Tweeddale House’s roof (Figure 151). The house is built in sixteenth century as a small rectangular single pile mansion, with a projecting stair tower, and around 1600 it is extended to the North, transforming it into a double pile (Gifford, 1984a). Throughout the seventeenth century it is renovated several times and in 1750-6 the 4th

Marquess of Tweeddale commissions its reconstruction to John and Robert Adam (Gifford, 1984a). Deacon Thomas Dunlop, who had previously done other works for the Marquess (NRS CS96/2243, 1736-47, NLS MS14665, 1735-53), is the wright and contractor (NLS MS14665/64, 1750-6). The roof is completely dismantled and rebuilt. Some repair works are carried out later in 1779-82 (NLS MS14680, 1779-82) and in 1791 the house is extended to the West (Figure 151) (Gifford, 1984a).

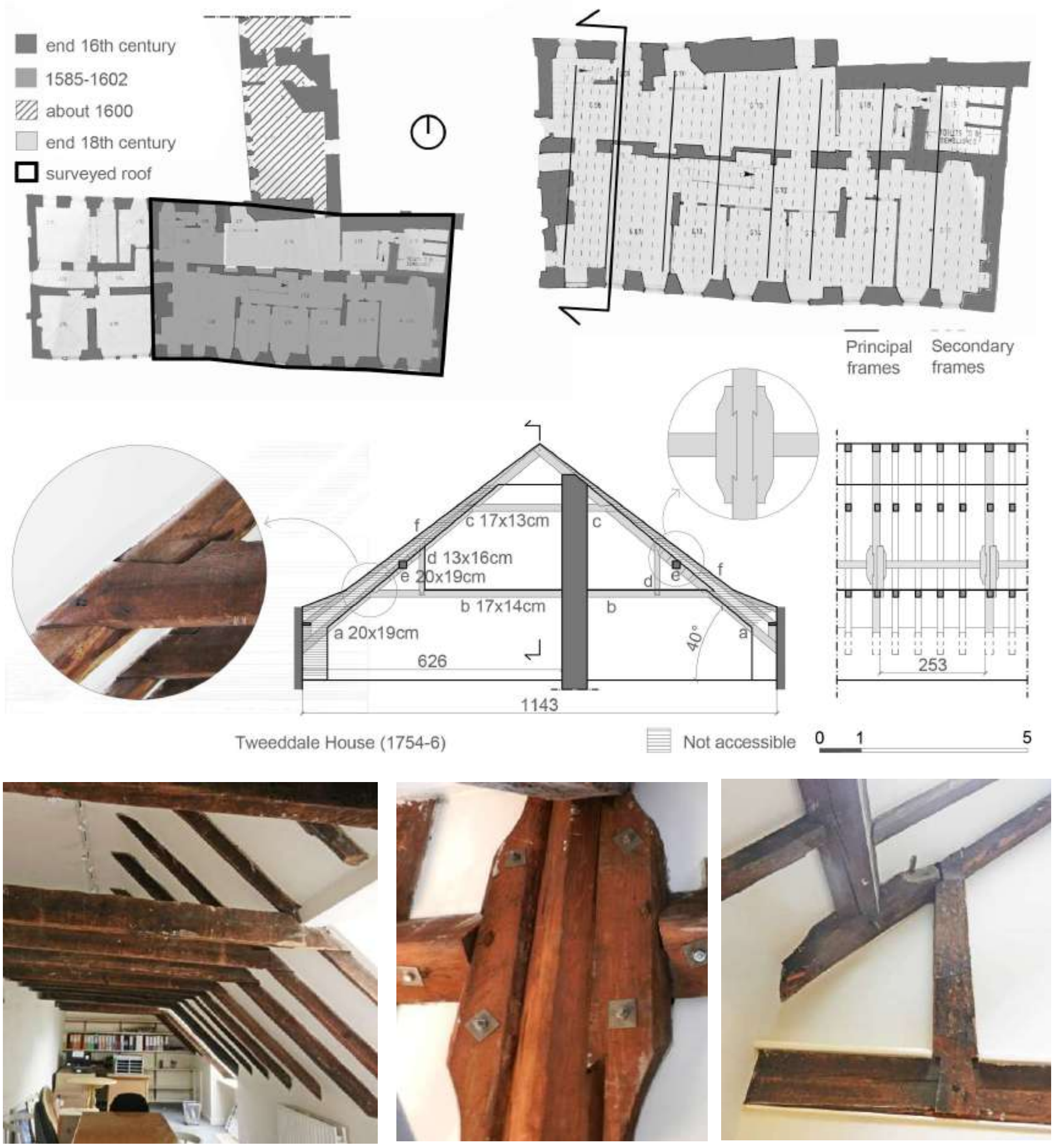


Figure 151: The roof of Tweeddale house (1750-6): reference plans and sections (top), general view from inside (bottom left), cleats reinforcing the rafters' section where the purlins abut (bottom centre), vertical struts supporting the collars (bottom right)

Although only partly visible today, we can appreciate that the structure is the one reconstructed by Dunlop in 1750-6, except for the additional rafters ('f' in Figure 151) later added on top of it, perhaps as part of the 1779/82 works. Tweeddale’s roof retains many features of seventeenth-century common rafter roofs: the pitch is steep (40°) compared to contemporary roofs, such as Oakshaw Trinity church (1754-6) (34°); the frames are very closely spaced (50cm max); neither tie-beams nor wall-plates are employed; though the span is quite wide (11.4m), due to its double pile configuration, the spine wall reduces it to 6.2m, just like in Holyrood Palace (1671-9) (Figure 148).

On the other hand, some features of the roof anticipate the emerging trussed system: vertical tension-absorbing struts ('e' in Figure 151) appear in some frames to give additional support to the collars. More interestingly, there is a subdivision between primary and secondary frames/rafters and the use of butt-purlins as additional longitudinal stiffening elements ('c' in Figure 151). The butt-purlins are tenoned in cleats ('d' in Figure 151) that are in turn dovetailed on the sides of the primary rafters to reinforce their section where the purlins abut. The rafters of the secondary frames are supported by the purlins.

Butt-purlins are actually introduced earlier, together with the subdivision of frames/rafters into principal and common ones, in the roof covering the central hall of Yester House (1729-48), where the primary frames (‘a’ in Figure 152) are spaced about 2.5m apart and connected by butt-purlins (‘b’ in Figure 152), which in turn support the common rafters (‘c’ in Figure 152); an arrangement which significantly reduces the amount of timber needed. The timbers’ scantlings and dressing are also different from previous roofs: Holyrood’s rafters are bigger compared to previous roofs (21x18cm - height x base), but Yester House’s rafters are even bigger and more rectangular (27x17cm – height x base) and some of their faces are hewn rather than axed.

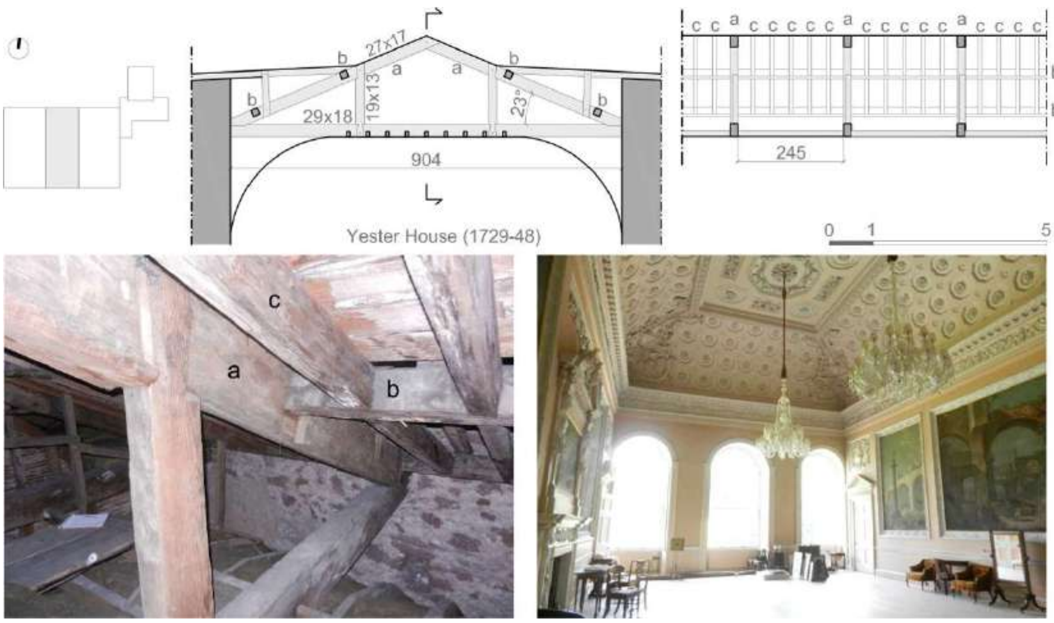


Figure 152: The roof of Yester House (1729-48): sections (top), connection with the lateral walls (bottom left), ceiling underneath (bottom right)

Because of the low pitch, the principal rafters and butt-purlins, as well as the tentative triangulation, Yester House's roof is in structural terms very close to trussed roofs. The same is true for Newhailes House (1730) and Robert Gordon's College (1731-2) (Figure 153), that employ king-posts and struts to counteract the deflection of the raised tie-beam. While in Newhailes the post is designed to work in compression, and the struts in tension, in R. Gordon's it is the other way around. However, both roofs leave the lower part of the rafters unsupported and subject to high bending stresses.

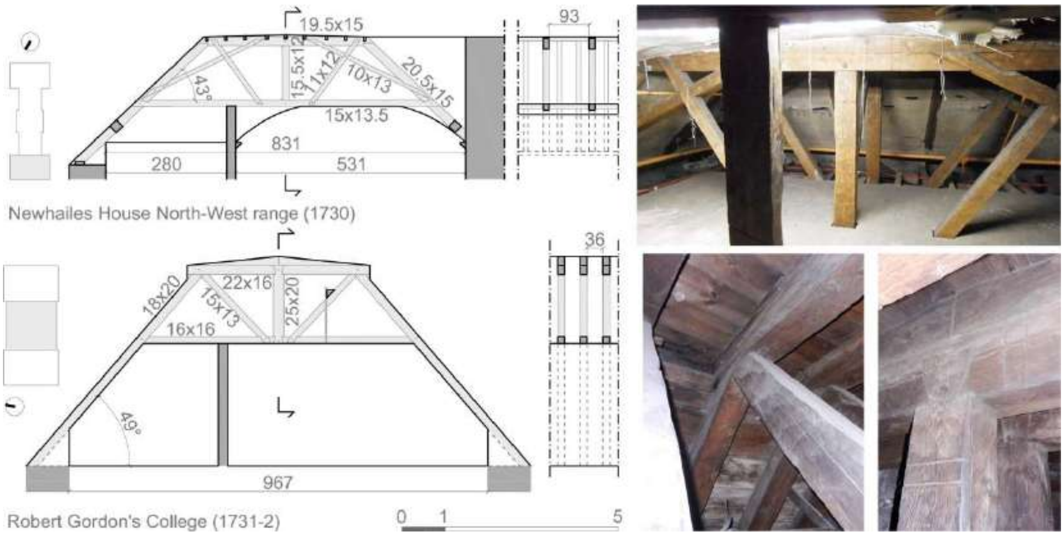


Figure 153: The roofs of Newhailes House (1730) (top) and Robert Gordon's College (1731-2) (bottom)

3.3.1.3 Trussed roofs

In the second half of the eighteenth century trussed roofs are introduced in Scotland (Figure 147): our surveys suggest that from 1750s/60s king-post trusses start being used to cover reduced spans - as in Fort George Museum and Staff blocks (1762-4) (Figure 154) - and princess-post/queen-post trusses to cover bigger spans - as in Fort George Chapel (1763) (Figure 155) and Oakshaw Trinity church (1754-6) (Figure 156). The earliest Scottish trussed roof we have surveyed is the one in Hopetoun House (1721-48) (Figure 157).

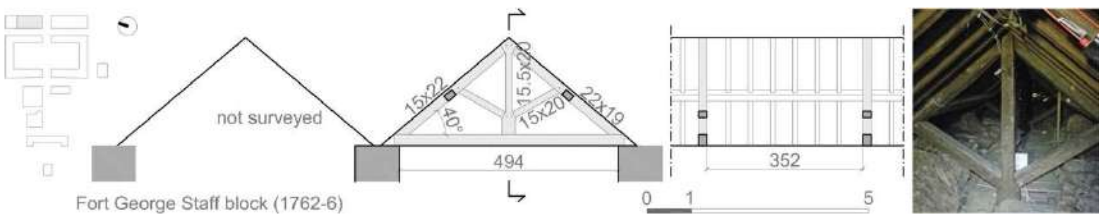


Figure 154: The king-post trusses in the staff block of Fort George (1762-6)

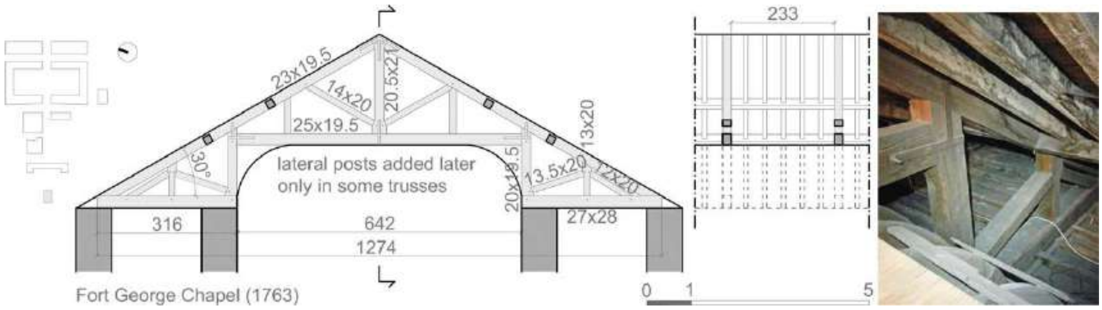


Figure 155: The princess-post trusses in the Chapel of Fort George (1763)

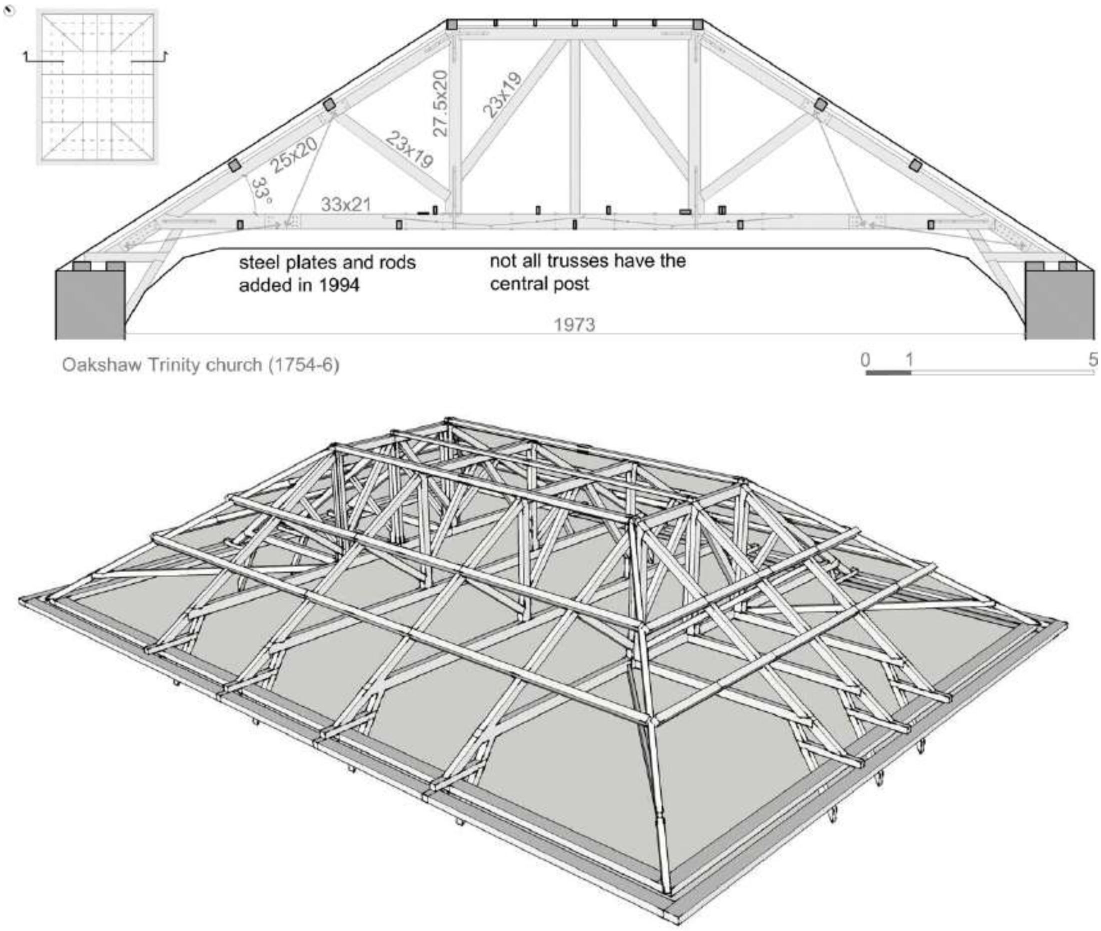


Figure 156: The queen-post trusses in Oakshaw Trinity church (1754-6)

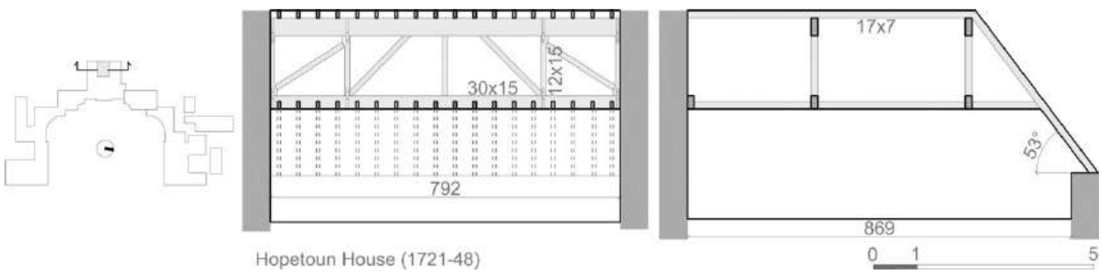


Figure 157: The trussed roof of Hopetoun House (1721-48)

The 14 Scottish trusses we have surveyed have quite different external geometries and internal arrangements, some developing veritable 3D structures, as in St Andrew's and St George's Church (1782-4) (section 4.1) or Glasgow Tron theatre (1793-4). The spans reach their maximum in Oakshaw Trinity church (1754-6) with 19.7m (Figure 156), and pitches vary between 44° and 27°. The characteristic Scottish sarking remains in use, even though butt-purlins are always present too.

The arrangerments of the earliest Scottish trusses show that architects and wrights had only a superficial understanding of how the trussed system works. In Hopetoun House (Figure 157), for example, the truss configures itself as a sort of bridge structure, with two horizontal beams connected by a series of vertical posts and slanted struts. The triangulation is interrupted in the central part, where the post seems to perform no structural function except for keeping apart the two horizontal beams, which can actually be harmful in case of deflection of the upper beam.

The same happens in Oakshaw Trinity church (Figure 156) where the central post is left unsupported and with no apparent function. Another problem of Oakshaw's roof is the asymmetry in the joints between posts and struts: one strut springs from a higher level than the other strut. The purpose was probably to avoid reducing excessively the section of the post by placing two mortice and tenon joints in the same place; however, this arrangement generates unnecessary bending moments in the post. The connection with the wall is also problematic, because the raised tie-beam produces high bending moments at the rafter ends and does not counteract effectively the transversal opening of the roof (as in Newhailes House and Robert Gordon's College, previously discussed). In fact, steel cables and plates have been added in 1994 to try to solve these problems.

The heterogeneity of arrangements of Scottish trusses indicates a transfer of technical knowledge from various sources, as well as a will to experiment and adapt the single solutions to the local tradition. The same had happened one century earlier in England (Valeriani, 2006). The trussed roof of Oakshaw Trinity church (1754-6) (Figure 156), for example, suggests an inspiration from Wren’s St Michael’s Paternoster Royal (1690) (Campbell, 2002), but the connection with the wall is somehow reminiscent of the traditional Scottish rafter foot, with the load transferred to a lower point downwards on the masonry. We will discuss other examples and try to understand which has been the role of architects and wrights in the development of Scottish roof carpentry in section 3.3.4.

3.3.1.4 Purlin roofs

Scottish wrights are acquainted with the purlin roof system at least since early Middle Ages, as testified by the thirteenth, fourteenth and fifteenth century roofs of Darnaway Castle, Stirling Castle, Edinburgh Castle, Holy Rude church in Stirling, and by the seventeenth-century roofs of Tron church and Parliament Hall in Edinburgh (discussed in section 3.2.1). However, the above-mentioned examples are all open roofs, exposed to view, whilst the ones we have surveyed are all hidden behind plaster ceilings. The only other known example of non-exposed Scottish purlin roof is that of Newark Castle (1597-99), whose arrangement is however not reported in detail (Hanke, 2012).

Melville House (1697/1703) is the earliest purlin roof we've surveyed (Figure 158), followed by Stirling Castle Palace (after 1719) (section 5.2.7), Hopetoun House (1721-48) (Figure 159), Haddo House (1732-6) and Touch House (1757-62) (section 5.2.8). Two of them support pitched roofs, of which one gabled (Stirling Castle Palace) and one hipped (Touch House), two others support platform roofs (Melville House, Haddo House) and one a shed roof (Hopetoun House). The purlins are always supported by masonry walls; additional timber struts are used in Touch House only. The common rafters of Stirling Castle Palace and Touch House are connected by collars and their top ends lean against a thin ridge beam. According to our surveys, ridge beams do not appear in any earlier roof in Scotland (the ones found in Balcaskie House and Gardyne's Land are clearly a later addition judging from their dressing and location). The only other examples we have found date from the second half of eighteenth century and include mainly trusses: Oakshaw Trinity church (1754-6), Auchinleck House (1755-62), St Andrew's and St George's church (1782-4), Glasgow Tron theatre (1793-4). The late eighteenth-century roof in Brunstane House is the only common rafter roof we have surveyed that employs a ridge purlin.

The limited number of surveyed examples and the heterogeneity of their arrangements and details makes it difficult to draw conclusions on their development. However, it is interesting to note that they are often coupled with other structural types in the same building: in Melville House part of the roof structure is composed of complex frames (Figure 150) and the same is true for Touch House, whilst in Hopetoun House part of the roof structure is covered with a truss (Figure 157) and in Stirling Castle Palace most of the roofs are common rafter roofs or complex frames (section 5.2.7). There is no apparent reason driving the choice of one structure or the other. This suggests that either the different timber structures have been constructed in different periods, or, if they appear to belong to the same period (as is the case of Melville House, Hopetoun House and Stirling Castle Palace), that wrights/architects were experimenting.

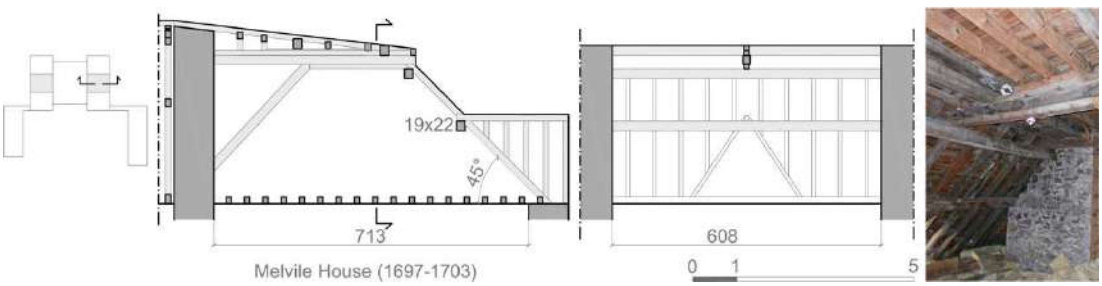


Figure 158: The purlin roof of Melville House (1697-1703)

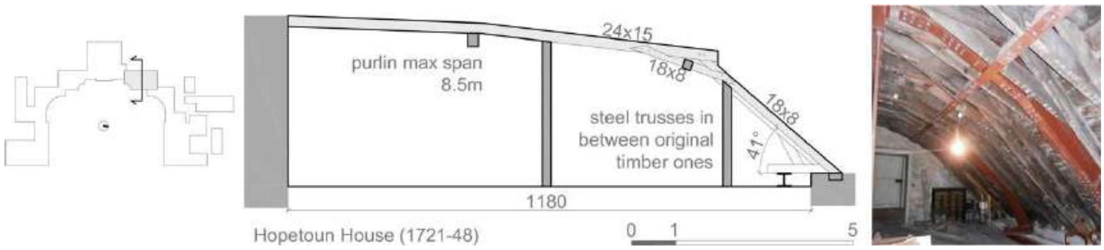


Figure 159: The purlin roof of Hopetoun House (1721-48)

3.3.2 Construction methods and details

3.3.2.1 Carpentry joints

The development of Scottish carpentry joints mirrors that of structural arrangements dicussed above. At first only mortice and tenon joints secured by roughly squared timber pegs (not flush to the surface of the elements) are used to connect all the elements: rafters, collars, sole pieces and ashlar posts (Figure 160 a, b). They are all joints with stopped mortices and stub tenons.

Contrary to what Hay (1976) affirms, lapped/halved joints are introduced already from 1630s (Figure 172) to secure collars to rafters: Malleny House (1635) is the first example (Figure 160 c). These joints are halfway in between lapped and halved joints, as part of the rafter and collar are halved, but the faces are not flush. Soon after, these joints start being secured with a metal nail (Figure 172), rather than a timber peg, and their profile is more refined, 'chamfered' (Figure 160 d).

During the latest part of seventeenth century, when hipped platform roofs and complex frames are introduced, lapped/halved joints start being used at the rafters' apex as well, although mostly secured with timber pegs (Figure 172): the first examples are Geilston House (1666) and Cockenzie House (1683). At the same time, the joints securing collars to rafters become dovetail joints secured with metal nails (Figure 172), as in Holyrood Palace (1671-8), Gardyne's Land (1675-90) (Figure 160 e), Kinross House (1679-93) and Touch House (end seventeenth century). The use of dovetail joints suggests awareness of the fact that timber elements are subject to tension forces, as previously discussed. However, when there are two collars there is no distinction between the upper one, generally working in compression, and the lower one, working more in tension; the joints are treated in the same way and evolve simultaneously from mortice and tenon to lapped/halved to dovetailed. This suggests little understanding of the structural purpose of dovetail joints.

With the introduction of the trussed roof in eighteenth century joints become more diversified. Mortice and tenon joints become common again, although they are now secured with timber round dowels (often two rather than one, rarely square as in Newhailes House) and sometimes timber wedges used to secure the tenon in place (Figure 160 g, Figure 172). Metal straps are seldom used

(Figure 160 f); in some cases they are a later addition, as testified by the Trades Hall truss where the metal straps have been added 50 years after the construction of the building (TDH 1/899, 1856) (Figure 225). In two cases only, the post is connected to the raised tie-beam with a lapped/halved joint rather than a mortice and tenon joint: Auchinleck House (1755-62) and Brodie Castle Stables (end eighteenth century). Double dovetail joints and notched joints are also introduced and used especially for struts (Figure 160 h, i, l, Figure 172). In the second part of the century joints become even more refined and specialised (Figure 160 m, n) (Figure 172).

Scarf joints are rarely used (Figure 172). The roof above King's Old Buildings in Stirling Castle (1557) is a very early example of the use of both the scarf joint and metal nails: the rafters are composed of two elements jointed with a very simple scarf joint secured by metal nails (Figure 160 o). Other scarf joints have been found in Kinross House (1679-93) (Figure 160 p), Duff House (1737), Oakshaw Trinity church (1754-6) (Figure 160 q) and St Andrew and St George's church (1782-4). They are all indented splayed scarf joints that do not develop specific resistance to tension forces.

a) Craigston Castle (1604-7): mortice and tenon joint secured by timber peg (rafter & collar)

b) Methven Castle (1678): mortice and tenon joint secured by timber peg (rafter & sole piece)

c) Malleny House (1635): lapped/halved joint secured by timber peg (rafter & collar)

d) Cowane Hospital (1637-48): chamfered lapped/halved joint secured by metal nail (rafter & collar)

e) Gardyne's Land (1675-90): dovetail joint secured by metal nails (rafter & collar)

f) Hopetoun House (1721-48): mortice and tenon joint with joggle secured by metal strap (post & upper beam)

g) Arniston House (1726-55): mortice and tenon joint secured by timber dowel and wedge (rafter & cut post)

h) Yester House (1729-48): notched mortice and tenon joint (rafter & tie-beam)

i) Yester House (1729-48): double dovetail joint secured by metal nail (tie-beam & strut)

l) Auchinleck House (1755-62): notched dovetail lapped joint secured by metal nails (collar & strut)

m) Drum tower of Culzean Castle (after 1791): mortice and tenon joints secured by metal straps and bolts (radial tie-beams & post)

n) Glasgow Tron theatre (1793-4): notched bridle or step joint (rafter & strut)

o) King's Old Buildings in Stirling Castle (1557): scarf joint secured by metal nails (rafters)

p) Kinross House (1679-93): scarf joint secured by metal nail (upper beams)

q) Oakshaw Trinity Church (1754-6): scarf joint secured by timber key and metal bolts (tie-beam)

Figure 160: A representative sample of different types of joints found in the surveyed Scottish roofs structures

Posts in trusses are normally reinforced at their ends by joggles (Figure 160 f, Figure 161 left, Figure 172), a distinctively English feature (Yeomans, 1992) used even in earlier roofs to reinforce joints (Munby et al., 1983) (Figure 161 centre). Scottish wrights could have copied this detail from English examples or from Italian treatises such as Serlio (1545) and Antonio da Sangallo (Munafò, 2002)

(Figure 161 right). The joggles at the top of the post sometimes take the form of a rounded 'bulb', as if to provide further support to the rafters while adding a decorative feature (Figure 163, Figure 172). The origin of this detail remains uncertain so far. Other examples such as Oakshaw Trinity church (1754-6), Glasgow Trades Hall (1791-4), Glasgow Tron Theatre (1793-4) and Brodie Castle Stables (end eighteenth century) show that notches, common in Italy and in the rest of Europe, were used too (Figure 162).

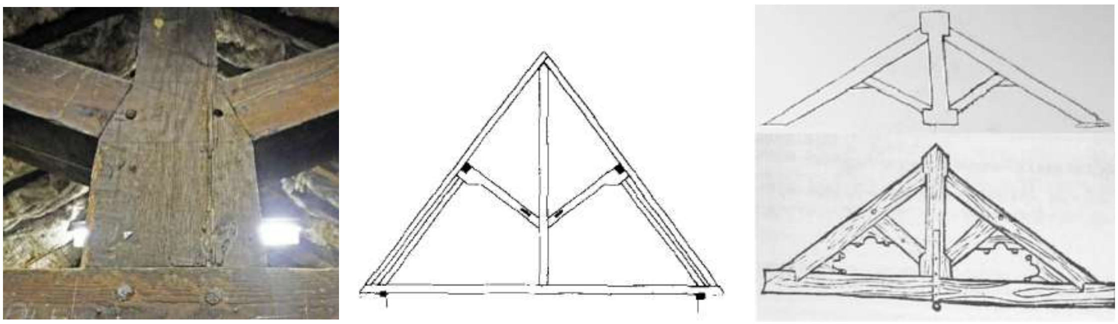


Figure 161: Joggles: the Ordnance Store of Fort George (1759-61) (left), the Chapel of Bishop's Palace in Chirchester (second half of thirteenth century) (Munby et al., 1983) (centre), truss drawn by Antonio da Sangallo il Giovane in his 1539 translation of Vitruvius' treatise (Munafò, 2002), Serlio (1545) (top right), truss drawn by Serlio (1545) (bottom right)

Figure 162: Notches: Glasgow Trades Hall (1791-4) (left), Brodie Castle Stables (end eighteenth century) (centre), Glasgow Tron Theatre (1793-4) (right)

Figure 163: Bulb shaped joggles: Aunchinleck House (1755) (left), Stirling Tolbooth (1785) (centre), Culzean Castle (end eighteenth century) (right) (Serafini and Gonzalez Longo, 2015a)

Another interesting feature is cleats, commonly used in Italy (Figure 164, Figure 165) and found in Scotland in different types of roof structures (Figure 172): the simple frame in Touch House (end seventeenth century) (Figure 169), the complex frame in Tweeddale House (Figure 151), the truss in Oakshaw Trinity church (1754-6) (Figure 166), the truss in Brodie Castle stables (end eighteenth century) (Figure 167) and the truss in Auchinleck House (1755-62) (Figure 168). These features respond to the same need expressed by joggles in posts: reinforce the mortice and tenon joint.

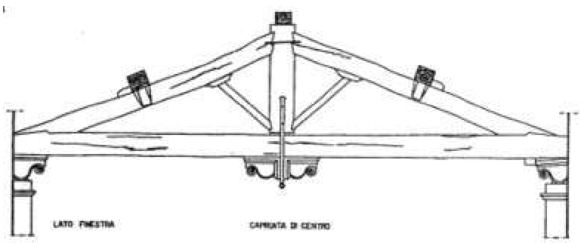


Figure 164: The roof of the church of Sant'Agata di Mugello in Scarperia (Tampone 2001)

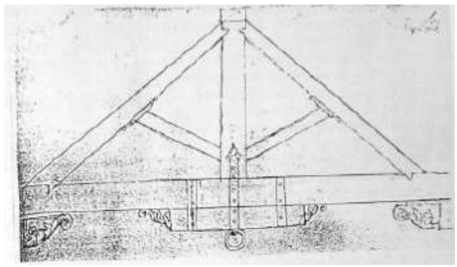


Figure 165: Truss drawn by Mariano di Jacopo (1449 in Munafò 2002)

Figure 166: Cleats used to reinforce the connection between tie-beams and longitudinal purlins in the trussed roof of Oakshaw Trinity church (1754-6)

Figure 167: Cleats used to reinforce the joint between struts and rafters in the trussed roof of Brodie Castle Stables (end eighteenth century)

Figure 168: Cleats used to reinforce the connection between collars and longitudinal purlins in the trussed roof of Auchinleck House (1755-62)

Figure 169: Cleats used to reinforce the connection between rafters and purlins in the common rafter roof of Touch House (end seventeenth century, but the purlins might be a later addition)

Redundant joints with a very particular shape have been found on collars and rafters in the roof of Blair Castle (Figure 170). This roof has probably been reconstructed after a siege in 1745 (personal comment by archivist Jane Anderson) and the redundant joints suggest the reuse of timbers perhaps from the previous roof. Several joints similar to the one in Figure 170 have been identified, but their shape has not been found anywhere else in literature. A thorough record of their dimensions and positions should be carried out in order to attempt a reconstruction of the original structure. Interesting redundant joints have been found in the North-West corner of Stirling Castle Palace too (Figure 171): these are chase mortice and tenon joints, used to enable the tenon to be slid into position when the morticed member is already fixed.

Figure 170: Redundant lapped/halved joints found in Blair Castle (1745)

Figure 171: Redundant chase mortice and tenon joints found in the North-West corner of Stirling Castle Palace (1719)

The sample of joints we have surveyed is certainly too limited to draw ultimate conclusions, but it allows making some considerations. It seems that Scottish carpentry joints remain quite simple up to end seventeenth century, just as structural arrangements. The introduction of dovetail joints only from the second half of seventeenth century (Figure 172) and the introduction of notched joints only from the first half of eighteenth century (Figure 172) is quite late compared to England and the rest of Europe: these joints are used since twelfth century in North France and Belgium (Corvol-Dessert et al., 2009), Germany (Eissing, 2009) and England (Fletcher and Spokes, 1964). The same is true for metal fasteners, commonly used in Scotland only since mid-seventeenth century (Figure 172) but used in Italy since roman times (Valeriani, 2003) and from late Middle Ages in the rest of North-West Europe: in North France and Belgium, for example, they are used since fifteenth century (Corvol-Dessert et al., 2009). There is the possibility that different types of joints and fasteners were used in earlier roofs, as suggested by the redundant joints we have found in Blair Castle (Figure 170).

Another interesting aspect that emerges is that Scottish wrights do not seem to fully understand the structural purpose of tension-absorbing joints: dovetail joints are used regardless of their position in upper or lower collars, mortice and tenon joints working in tension are seldom reinforced with metal straps and scarf joints remain quite simple, without indentations or specific arrangements to resist tension forces. This confirms the English and Scottish tradition to consider timber elements as working in compression and bending only (Hanke, 2006).

Finally, some eighteenth century features seem to indicate foreign influences: cleats and notches recall the Italian carpentry tradition, while joggles are a distinctive English characteristic. The origin of other details remains uncertain so far, but shows that eighteenth century Scottish roofs combine knowledge and skills from different sources.

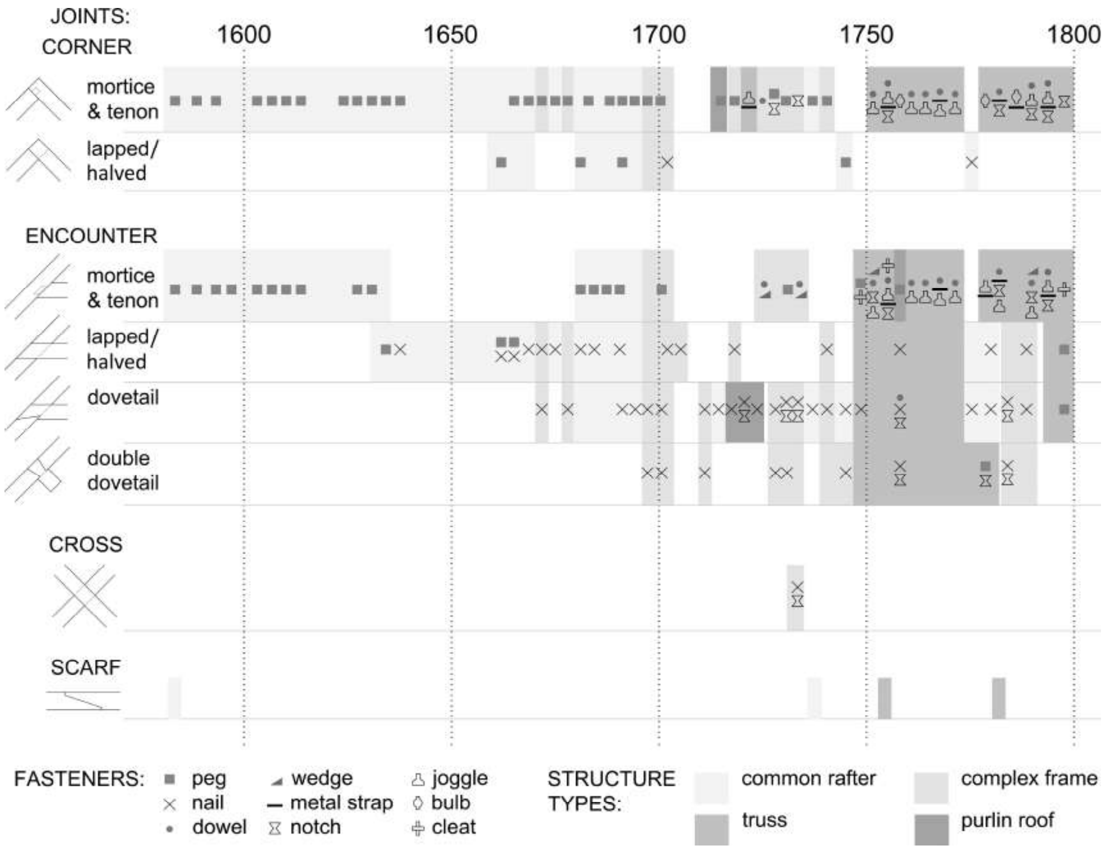


Figure 172: Timeline of types of joints and fasteners found in the surveyed Scottish roofs

3.3.2.2 The connection with the walls

The connection between the timber roof structure and the supporting walls is very important because it is the point where the loads are transmitted and where the horizontal thrust resulting from the roof needs to be neutralized. Unfortunately, in many cases it has been difficult to assess the exact geometry of this part of the structure because of accessibility issues (question marks in Figure 174). Our sample is however wide enough to start tracing a development and give indication of what the typical arrangements look like.

The connection with the lateral walls up to end of seventeenth century is characterized by a simple contact between the rafter ends and the wall-head (Figure 173 left) or by an arrangement known as the 'Scottish rafter foot' (Ruddock, 1995). We have found the latter to be of different dimensions (Figure 173 centre and right) but invariably composed of a sole piece, in which the rafter end is tenoned, and an ashlar post, in which the sole piece is tenoned. The ashlar post is always extended downwards on the masonry of about 10-15cm. All the joints are secured with roughly squared timber pegs. Rubble masonry is sometimes used to fill the space in-between one foot and the other (Figure 173 right). Hay (1976) states that the rubble infill is used from mid-seventeenth century, but we have found earlier examples too (Figure 174).

Figure 173: Connection with the lateral walls: simple contact between the rafter ends and the wall-head in Sailor's Walk (1670s) (left), rafter feet in Culross Palace (1597-1610) (centre) and Methven Castle (1678) (right)

As previously discussed, the missing wall-plate and the fact that the ashlar post is extended downwards on the masonry differentiate the Scottish rafter foot from the English one (Ruddock, 1995). Wall-plates are introduced in most European countries quite early, during the twelfth century (Bláha, 2006, Corvol-Dessert et al., 2009, Eissing, 2009, Gogolin, 2008, Janse, 1989, Madsen, 2013, Suchý et al., 2008, Szabó and Kulin, 2005, Thelin and Linscott, 2008). On the contrary the earliest Scottish roof with wall-plates we have surveyed is in Holyrood Palace (1671-8) (Figure 175). This is also one of the first Scottish roofs employing hip rafters instead of gable walls: wall-plates are probably introduced to reinforce the longitudinal connection and stability of the roof, previously provided by the gable walls. However, according to our surveys the use of wall-plates becomes common only from eighteenth century (Figure 174). Another interesting feature of Holyrood's roof is the use of sprocket rafters and raised wall-heads to protect the rafter ends: a feature which is not widespread in Scotland (Figure 174) as we have found it only in Stirling Castle Palace and as a later addition in Tweeddale House (Figure 151).

Tie-beams are introduced about 20 years later in Melville House (1697-1703) (Figure 176) and Yester House (1699-1729), reinforced by tension-absorbing ashlar posts and extended beyond the rafter end to create a bell-cast profile. Tie-beams are introduced at this time because the wider spans and thinner walls of late seventeenth century Scottish architecture (section 3.1.2) evidently call for a counteraction of the horizontal thrust more effective than that provided by the traditional rafter feet. In some cases there is a clear will to experiment different arrangements, in order to identify the most effective: the wright in Melville House (1697-1703), for example, uses traditional rafter feet in the corners of the house, tie-beams with tension absorbing ashlar posts in the central part (Figure 176) and wall-plates on the sides.

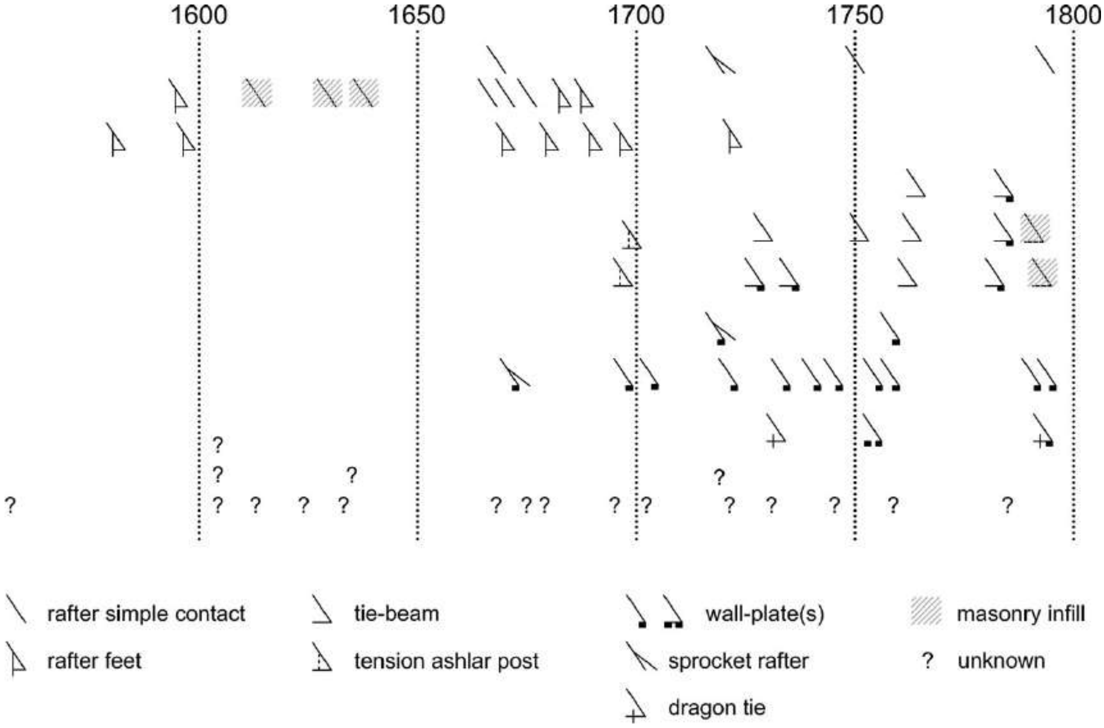


Figure 174: Timeline of different types of connections with the lateral walls found in the surveyed roofs

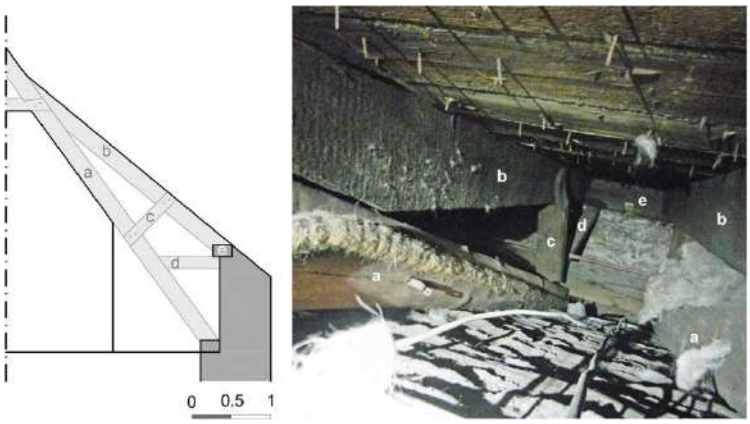


Figure 175: Connection with the wall in Holyrood Palace (1671-8): this is the first Scottish roof to employ wall-plates as well as sprocket rafters and a raised wall-head to protect the rafter ends and create a 'bell-cast' profile

Figure 176: Connection with the wall in Melville House (1697-1703): this is one of the first Scottish roofs to employ a tie-beam and a tension absobring ashlar post

According to our surveys the use of tie-beams becomes common only from mid-eighteenth century (Figure 174), either sitting on wall-plates or embedded in the masonry wall (Figure 177). Nonetheless, we have surveyed quite a few eighteenth century roofs without a tie-beam (Figure

174): even after 1700 raised tie-beams are often employed to increase the height of the room underneath, as in Stirling Castle Palace (after 1719), Blair Castle (1745), Auchinleck House (1755-62) and the previously discussed Newhailes House (1733-51) and Robert Gordon's College (1731-2). Generally rafter ends are left unsupported and become a very weak part of the structure because of the bending stresses concentrated there.

One interesting case is that of Oakshaw Trinity church (1754-6) (Figure 178) where the raised tie-beam is instead supported by a slanted brace springing from lower down on the masonry wall. This brace is kept in place by a sole piece, dovetailed and nailed to the brace. The arrangement is somehow reminiscent of the traditional rafter foot and is in line with the British tradition to bring the load of the roof structure to a lower point down on the masonry, as in hammer-beam roofs. Interesting is also the use of two wall-plates, which we have not found in other Scottish roofs. Another feature we have found in two roofs only (Haddo House 1732-6 and Glasgow Tron theatre 1793-4) is the dragon beam and tie, used to reinforce the corner of the structure (Figure 179).

Figure 177: Connection with the wall in St Andrew's in the Square church (1751-3): the tie-beam simply sits on the ashlar masonry

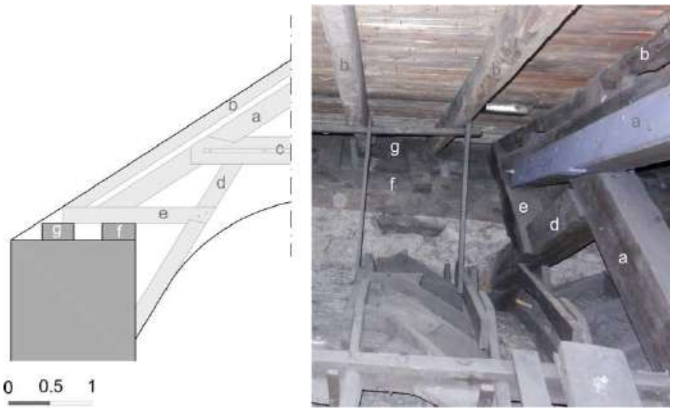


Figure 178: Connection with the wall in Oakshaw Trinity church (1754-6), somehow reminiscent of the traditional rafter foot: the tie-beam is raised and supported by a slanted brace springing from a point lower down on the masonry

Figure 179: Dragon ties in Haddo House (1732-6) (left) and Glasgow Tron theatre (1793-4) (right)

3.3.2.3 Sarking, roof coverings and pitches

One of the distinguishing characteristics of Scottish roof structures is the sarking: horizontal wooden boards (called deals) fixed on top of the rafters and forming a continuous surface which provides longitudinal rigidity and supports the roof covering. Similar wooden boards are used in England, North France and Belgium, Norway, Sweden, Greece, Albania, Italy (Bertolini Cestari et al., 2015, Corvol-Dessert et al., 2009, Janse, 1989, Pompejano et al., 2015, Thelin and Linscott, 2008, Tsakanika, 2007). The extensive use of sarking in Scottish roofs throughout the centuries up to today seems however to be unique: the sarking keeps being used despite the introduction of a foreign structural type, the truss, and is still used today. All the roofs we have surveyed employ the sarking.

The sarking deals we have found in the surveyed roofs are invariably sawn but have different dimensions ranging from 2 to 4cm in thickness and from 25 to 30cm in width. We have not been able to assess the length of the deals, because their ends are hidden behind the rafters (Figure 182). We know, however, that deals were produced in different dimensions and that lengths could vary from 8 to 20 feet (2.5m to 6.3m) (Newland, 2010, Thomson, 1991).

Hanke (2006) states that the sarking is generally composed of two layers of deals that run horizontally and vertically and comprise in-between a sort of fleece for insulation. He mentions as examples the roof in Lauder Parish Church, Black Castle, South Queensferry and Newbattle parish church, which we have not surveyed. The contract for the works in Panmure House (1666, demolished) analysed by Newland (2010) supports Hanke's statement as it specifies that the roof is to be 'double balked' with sarking. However, in all the roofs we have surveyed we have never found evidence suggesting the presence of two layers of deals. On the contrary, we could clearly see one layer of deals in 12 of the roofs we have surveyed, from both seventeenth and eighteenth century, either because the sarking was broken and the slates were exposed to view (Figure 180), or because there were intersecting roof structures from different periods and the sarking was partly continued inside the roof (Figure 182). The 'double balking' mentioned by Newland (2010) might refer to the thickness of the deals, rather than the number of layers.

According to our surveys, the deals are nailed to the rafters (Figure 181, Figure 182) with 1-2cm gap in between one deal and the other. A layer of tar/bitumen (Figure 180) or a modern waterproof sheet sometimes cover the deals outside. Pinkie House's roof (1613) does not have anything between the sarking boards and the slates, allowing for a natural ventilation of the roof space. Perhaps all early Scottish roofs employed this strategy.

We have been able to see how the sarking deals are nailed to the rafters only in a few cases (Figure 182, Figure 181). It is probable that in early seventeenth-century roofs wooden pegs were employed rather than metal nails, as for joints between elements and for the roofing material (Figure 183). It is not easy to determine when timber pegs are abandoned for metal nails, even because the original sarking and roofing material have often been replaced at a later date. However, we have found wooden pegs securing the slates to the sarking in the West wing of Kelburn Castle, dating to as late as 1722 (Figure 185). We have found them also in Tweeddale House (1750-6), but these might be a remnant of the earlier roof rather than an eighteenth century feature.

Figure 180: A broken sarking deal in Cockenzie House (1680-3) reveals the tar layer on top of the deals and the slates above

Figure 181: Nails on rafter feet of Cockenzie House (1680-3) left after the removal of the sarking boards

Figure 182: Sarking boards in the North range of Touch House (late seventeenth century)

Figure 183: Timber pegs used to secure the slates to the sarking deals in Pinkie House (1613)

The sarking supports the roofing material, which was chosen mainly based on the roof pitch. Figure 184 shows a timeline of the pitches in the surveyed roofs: there is an abrupt change at the end of seventeenth century, when pitches pass from being more than 50° to somewhere between 40° and 50°; by mid eighteenth century they are lower than 40° and at the end of the century they reach 30°. This change corresponds to the introduction of hipped and platform roofs, which start being covered not only in slates, as all previous roofs, but also in lead.

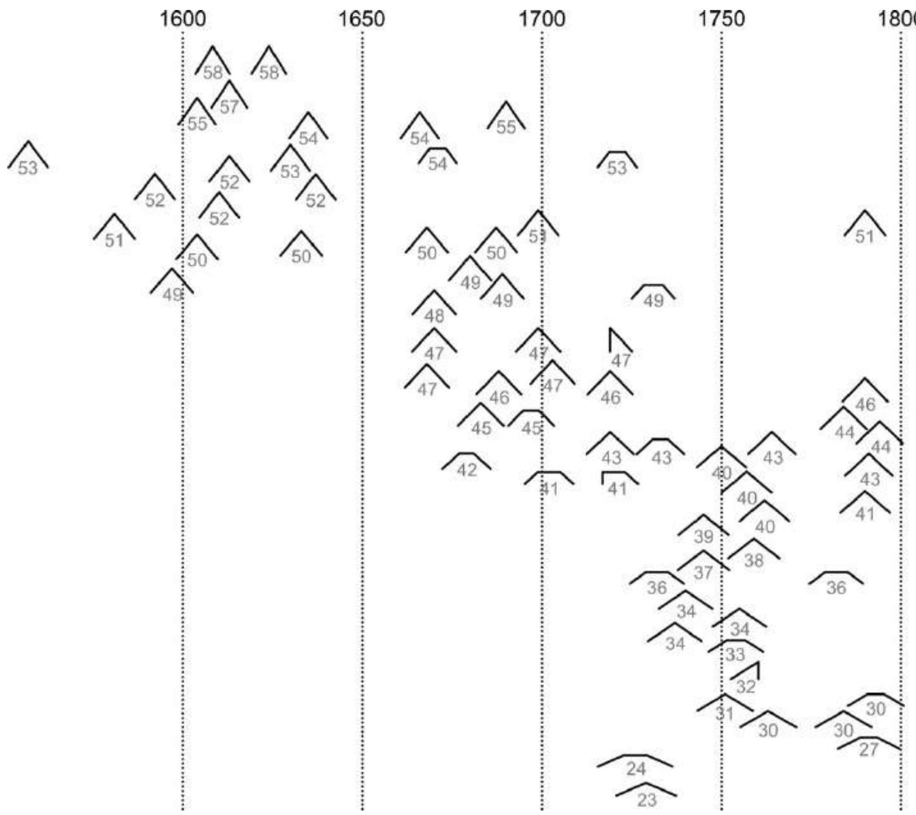


Figure 184: Timeline of the pitches of the surveyed roofs

There is documentary evidence that wooden shingles were used to cover high status buildings before the Reformation (Walker, 2006, Smith, 1870-2), while thatch was used mainly for vernacular architecture (Fenton and Walker, 1981); unfortunately not many examples have survived up to today. Seventeenth and eighteenth centuries are instead dominated by the use of grey/blue slates from Scotland and Wales (Hanke, 2006, Walker, 2006), as confirmed by our surveys (Figure 185) and various archival references (Brown, 1795, NRS E37/24, 1682, NLS MS14551/109, 1742-49, TCH account of materials, Undated). However, it is now very difficult to find roofs with the original slates. The owners of Methven Castle preserved some of the original slates, substituted in 1980s (Figure 186), but in most cases, as in Pinkie House, no records are available (Figure 187).

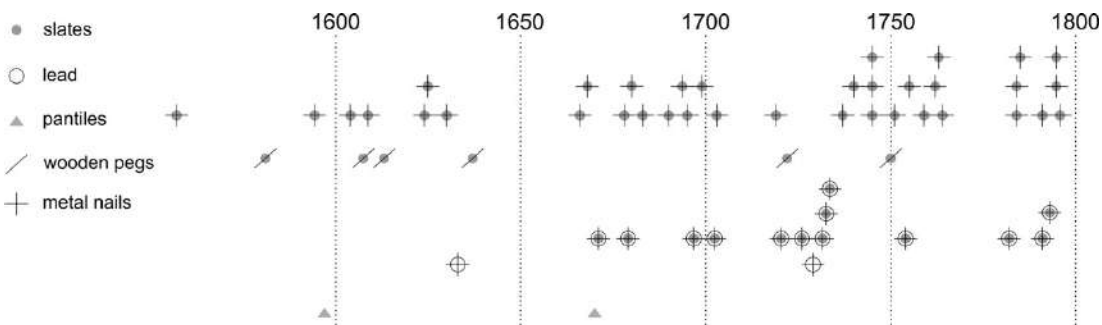


Figure 185: Timeline of the different roofing materials used in the surveyed roofs

Figure 186: An original slate of Methven Castle (1678) with its wooden peg and a piece of sarking

Figure 187: Slate roof at Pinkie House (1613)

George Heriot Hospital (1633-7) (Figure 188) is the first roof we have surveyed where lead is used for the overall covering and not only for the flashings. However, according to our surveys, the use of lead as overall covering material becomes common only from end seventeenth century (Figure 185). George Heriot is an interesting case also because lead is used here to cover a roof with a 50° pitch; in all the other surveyed roofs lead is used on flat parts, while slates cover the slopes, as in Holyrood Palace (1671-8), Kinross House (1679-93), Melville House (1697-1703).

We have also surveyed two roofs covered in pantiles: Culross Palace (1597-1610) (Figure 189) and Sailor's Walk (1670s) (Figure 185). Walker (2006) states that the original roof of Sailor's Walk was covered in slates. We can argue the same for Culross Palace. There is in fact documentary evidence that pantiles are imported from Denmark during late seventeenth century and start being produced in East Scotland at the beginning of eighteenth century (Shaw, 1990); considering that the construction of Culross Palace predates this of more than a century, it is highly probable that its original roofs were not covered in pantiles. Stone flags were also used during this period for low pitches, mainly in churches; we have not, however, surveyed any roof with this covering.

Figure 188: Lead roofs at George Heriot's Hospital (1633-37)

Figure 189: Pantile roofs at Culross Palace (1597-1610)

3.3.2.4 Timber dressing and scantlings

The tool marks we have found on seventeenth-century timbers (Figure 191) confirm Crone and Mills (2011)'s statement that up to eighteenth century Scottish roofs employ small squared heart baulks, shaped through scoring (Figure 190 d), hewing (Figure 190 a, b, f) and flattening all faces (Figure 190 e) (Bláha, 2013), often leaving bark on the corners (Figure 190 c). Such rough dressing results in uniform square/round scantligns rarely exceeding 15cm.

a) Culross Palace (1597-1610), axe marks on rafter

b) Balcaskie House (1668-74), axe marks on rafter

c) Pinkie House (1613), bark left on corners of collar

d) Duff House (1737), scoring marks on collar

e) Tweeddale House (1750-6), flattening marks on collar

f) Glasgow Trades Hall (1791-4), axe marks on strut

Figure 190: Tool marks on hewn timber found in the surveyed roofs

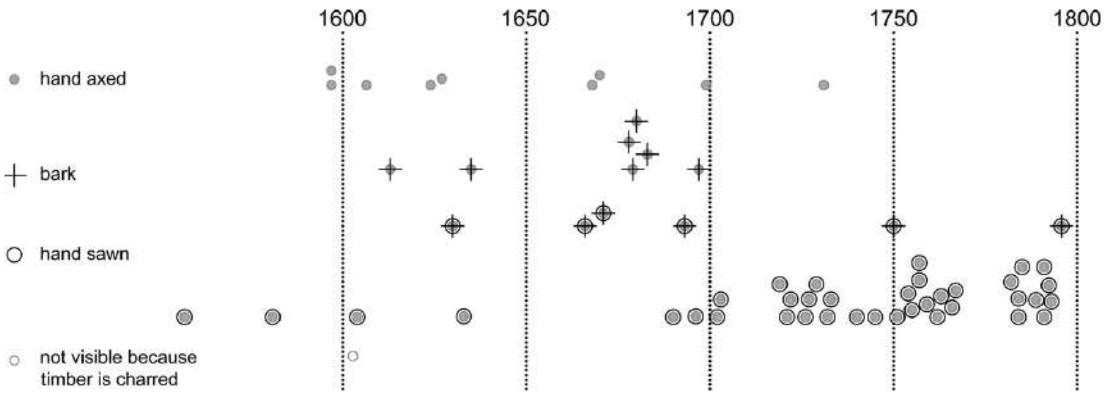


Figure 191: Timeline of the timber dressing found in the surveyed roofs

According to our surveys, the technique of scoring, hewing and flattening is used even during the eighteenth century (Figure 190 d, e, f), but combined with the use of pit and frame saws to further process the timber into two or more beams. This confirms Crone and Mills (2011)'s statement that saws are used sporadically before 1700, mostly in prestigious buildings, such as King's Old Buildings at Stirling Castle (1557) or Kelburn Castle (1581) (Figure 192 left and centre). On the contrary, from eighteenth century technological developments in sawmilling in Scottish ports encourage the import of big timber baulks to be further sectioned in smaller beams (Thomson, 1991): in fact we have found that eighteenth century timbers often have one or more sawn faces (Figure 192 right, Figure 191), and thus correspond to half balks (usually purlins or principal rafters) or a quarter of a balk (usually common rafters). The scantlings become more rectangular and their height increases, passing from 15cm to the double (*Figure 193*).

Figure 192: Saw marks on collars in King's Old Buildings at Stirling Castle (1557) (left), collars in Kelburn Castle (1581) (centre), struts in Newhailes House (1733-51) (right)

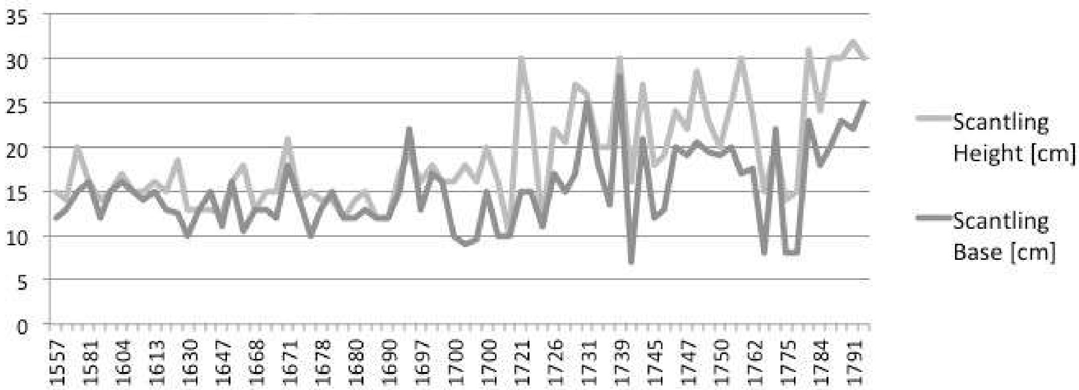


Figure 193: Timeline of the height and base of primary structural timber elements (rafters and purlins) in the surveyed roofs

Other tool marks we have found during our surveys are linked to the geometric tracing for the assembly of the structure. Medieval European carpenters made sketches and even scale models of roof structures; once the design was chosen, they reproduced the sketches full scale and proceeded with the 'staging' process, placing the timber elements on the ground to project the lines of the sketch on the timber surface and trace out on it all the work to be done (Corvol-Dessert et al., 2009). We do not know if Scottish wrights proceeded in the same way, but we have found some marks which show how the joints' geometry was traced on the timber elements (Figure 194).

Figure 194: Marks of geometric tracing in Craigston Castle (1604-7) (left), Oakshaw Trinity church (1754-6) (centre), Glasgow Trades Hall (1791-4) (right)

3.3.2.5 Carpenters' marks

Hanke (2006), Crone and Mills (2011) and Hay (1976) mention the use of Roman numerals as assembly marks in Scottish roofs. These were also used in North France and Belgium (Corvol-Dessert et al., 2009) and in Netherlands (Janse, 1989). Most of the roof structures we have surveyed are in fact numbered with Roman numerals: the members of each frame are marked with the same number, but in most cases the frames are not in sequence. As argued by Hay (1976), this should not be considered as a sign of later alteration because the numbers were used only to assemble the frames and not to place them in order on the wall-head. This is found also in twelfth- and thirteenth-century roofs in Belgium and North France (Corvol-Dessert et al., 2009). However, it does not explain why in some cases the same number is repeated more than once in different frames, in roofs whose homogeneity suggests no later addition or alteration, such as Stirling Castle Palace (after 1719).

The Roman numerals we have found can be grouped in two different categories: big Roman numerals occupying the whole section of the elements (Figure 195) and small Roman numerals (Figure 196). We cannot be sure which tools have been used to trace these marks but their appearance suggests the use of some kind of saw for the big ones and of some kind of chisel or knife for the small ones.

Figure 195: Big sawn roman numerals in Malleny House (1635) (left), Balcaskie House (1668-74) (centre), Brodie Castle Stables (end eighteenth century) (right)

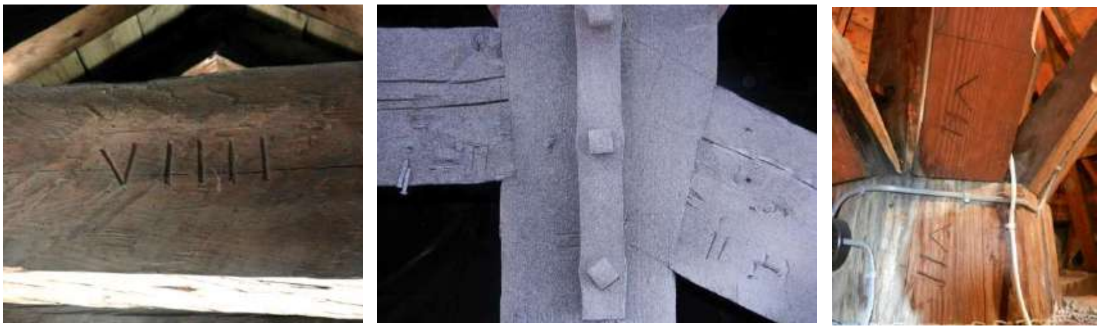


Figure 196: Small chiselled roman numerals in Duff House (1737) (left), Trades Hall (1791-4) (centre), Culzean Castle (after 1791) (right)

We have found the numbers expressed in different ways: number 4, for example, is sometimes marked as 'IIII', sometimes as 'IV' or even with the figure V turned upside down (Figure 197). The figure for 5, V, is sometimes incorporated with the figure for 10, X: number 15 can be 'X/' or 'X\' and the same is true for 25, 35, etc (Figure 197). Tens are normally expressed by multiplying the figure X: XX=20, XXX=30, XXXX=40; we have found the figure L only in Holyrood Palace, to express 40=LX (Figure 197). Another exception is number 11: in Cowane Hospital (1637-48) and Touch House (end seventeenth century) the X and I are incorporated and form a sort of asterisk (Figure 197).

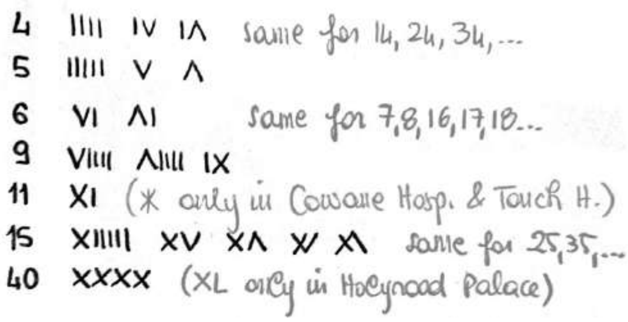


Figure 197: Roman numerals used in the surveyed roofs

The big sawn Roman numerals have been found in roof structures of all ages (Figure 198). On the contrary, the small chiselled Roman numerals have been found only in eighteenth-century roofs, starting from Duff House (1735) (Figure 198). They have also been found in the roof of Craigston Castle (1604-7), but they are clearly linked with eighteenth-century alterations; in fact the early seventeenth-century big sawn Roman numerals are visible too. The same is true for Blair Castle (1745), were both types of Roman numerals are used: this roof has probably been reconstructed after a siege in 1745 partly reusing the timber from the older roof (personal comment by archivist Jane Anderson), as suggested by the double carpentry marks and the numerous redundant joints found on site (Figure 170).

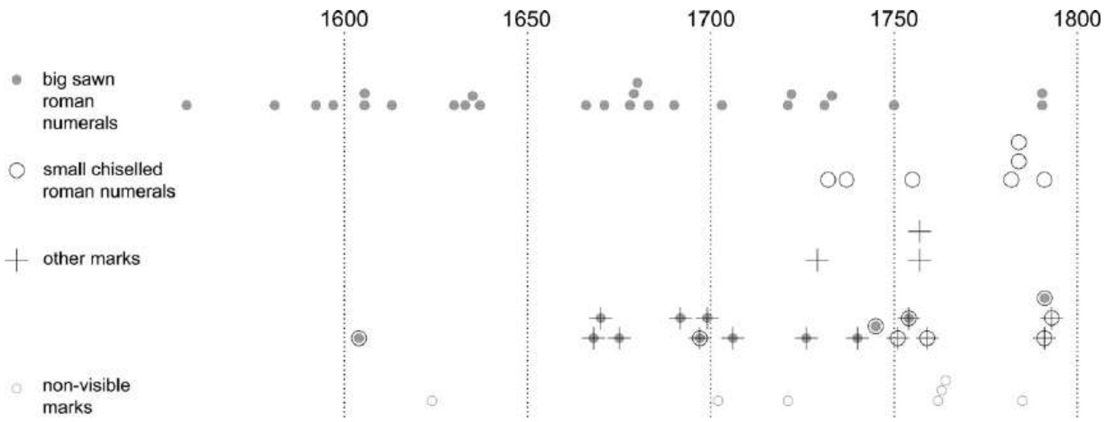


Figure 198: Timeline of types of carpentry marks used in the surveyed roofs

More intriguing is the case of Melville House (1697-1703), already mentioned by Hay (1976), where both types of Roman numerals are used, as well as other types of marks, including Arabic numerals (Figure 199). Some of the Roman and Arabic numerals are in order, but they are too sparse to be able to reconstruct a sequence. Moreover, many timber elements are marked with more than one numeral. This suggests that some of these marks are not assembly marks but perhaps identify the timber merchant, or the harbour of origin, or even the quality of the timber.

Figure 199: Carpentry marks in Melville House (1697-1703)

We have found marks different from Roman numerals in many other roofs we have surveyed (Figure 200), mostly from 1660 onwards (Figure 198). In most cases these marks are accompanied by Roman numerals which function as assembly marks within the single frames/trusses. Most of them have a 'runic' appearance (Figure 200 b, c, d, e, f, g, h, i, m, n, o), resembling marks found in other North-West European countries, such as Sweden (Figure 201 left). Only a few cases include Arabic numerals and lettering (Figure 200 a, q, Figure 198), which are rare in North-West Europe as well (Corvol-Dessert et al., 2009). In two eighteenth-century roofs (Figure 200 p) we have found Roman numerals combined with small semi-circles, used in Netherlands too (Figure 201 right). The marks in the Ordnance Store of Fort George are also the only ones found which stretch over a joint (Figure 200 p). Circles have been found on a common rafter in St Andrew's in the Square church (Figure 200 l): similar marks were used in North France (Figure 201 centre) and Denmark (Madsen, 2013). Some of them seem to have survived only in part, as if they stretched over a bigger section of timber.


a) Geilston House (1666), collar


b) Balcaskie House (1668-74), rafter


c) Sailor's Walk (1670s), rafter


d) Holyrood Palace (1671-8), upper beam

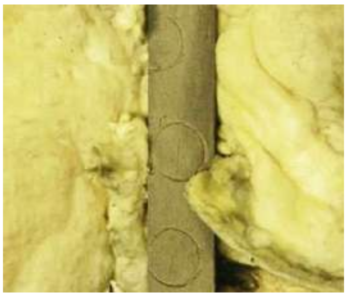

e) Gardyne's Land (1675-90), rafter


f) Stirling Castle Palace (after 1719), rafter


g) Arniston House (1726-55), rafter


h) Yester House (1729-48), upper beam


i) Oakshaw Trinity church (1754-6), rafter


l) St Andrew's in the Square church (1751-3), common rafter


m) St Andrew's in the Square church (1751-3), sarking


n) St Andrew's in the Square church (1751-3), strut


o) Touch House (1757-62), purlin


p) Fort George Ordnance Store (1759-61), rafter and collar


q) Glasgow Trades Hall (1791-4), strut

Figure 200: A representative sample of different types of carpentry marks found in the surveyed roofs

Only for a few of the buildings we have surveyed we know where the timber was sourced:

- Holyrood Palace (1671-8): Norwegian timber was used (NRS E36/30, 1671-1678, EUL LAII87/7, 1686); Holyrood marks (Figure 200 d) are compatible with Norway's (Janse, 1989).
- Gardyne's Land (1675-90): a timber element has been identified as Scandinavian oak by dendrochronologists (Crone, 2001); marks found in Norway (Janse, 1989) and Sweden (Figure 201) are compatible with the ones found in Gardyne's Land (Figure 200 e).
- Touch House (1757-62): we know that Norwegian and Russian timber was used (TCH account by Paterson, 1757, TCH account by Deas & Co, 1757-8); the marks on the common rafters are compatible with Norwegian ones (Janse, 1989) whilst the ones found on the primary structural elements (Figure 200 o) are very different, in both shape and dressing: these might be Russian, although no literature reference can support this hypothesis.
- Fort George Ordnance Store (1759-61): Baltic timber has been identified by dendrochonologists (Crone and Mills, 2008); marks found in Netherlands (Figure 201 right) are compatible with the ones found in Fort George (Figure 200 p).

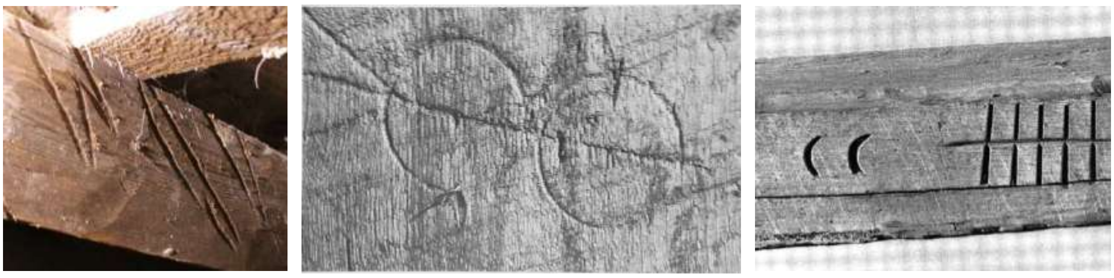


Figure 201: Carpentry marks in Falsterbo church in Sweden (picture by Karl Magnus Melin) (left), in Saint Pierre Cathedral in Beauvais (after 1573) (Corvol-Dessert et al., 2009) (centre), in Bovenkarspel Herv. church in Netherlands (1540) (Janse, 1989) (right)

In conclusion, carpentry marks found in seventeenth- and eighteenth-century Scottish roofs seem to reflect not only local practice but also the intense timber trade with Scandinavian and Baltic regions. If correctly interpreted these marks could provide invaluable information related to the date, origin and quality of the timber, as proved by a research on nineteenth-century Baltic marks (Vandenabeele et al., 2016). Due to the sparseness of literature on the subject, it is still very difficult to interpret these marks; more research is needed in order to fully exploit their potential.

3.3.3 The material

3.3.3.1 Timber Species

The species has been identified visually in all of the reference buildings - except for Maybole Castle (early seventeenth century) whose roof timbers are all covered by a thick layer of char -, and microscopically in the eight case studies. The reference buildings have been found to be made invariably of softwood except for the old tower at Kelburn Castle (1581), where the timbers have been identified as oak (*quercus sp.*) and only the sarking as softwood. The microscopic identification carried out in the case studies has revealed that most of this softwood is Scots Pine (*pinus sylvestris*), used in all structure types and for all types of structural elements: rafters, collars, beams, struts, purlins, sarking boards, pegs, etc (Figure 202). This confirms the dendrochronological studies carried out in Scotland up to today, which have identified pine in almost all post-1600 analysed structures (section 3.2.2).

The width of the rings in the extracted samples has been found to be quite variable, ranging from 3mm (Figure 202) to invisible macroscopically. Growth rings reflect climatic conditions in which the tree has grown: very narrow rings correspond to more severe temperatures. According to dendrochronologist Anne Crone this suggests that pine with narrow rings might be imported from Scandinavia or Russia, because in those countries the climate is more severe than in Scotland. As previously discussed, timber was imported in Scotland from Scandinavia and later the Baltic area, because it was of better quality than local Scottish timber and more accessible. Nevertheless, the rings' width does not seem to be a reliable criteria to estimate the timber provenance as many of the samples with wider rings have been extracted from elements that have probably been imported rather than being local Scottish; the hypothesis is made based on the presence of unusual carpentry marks on the timbers, discussed in the previous section.

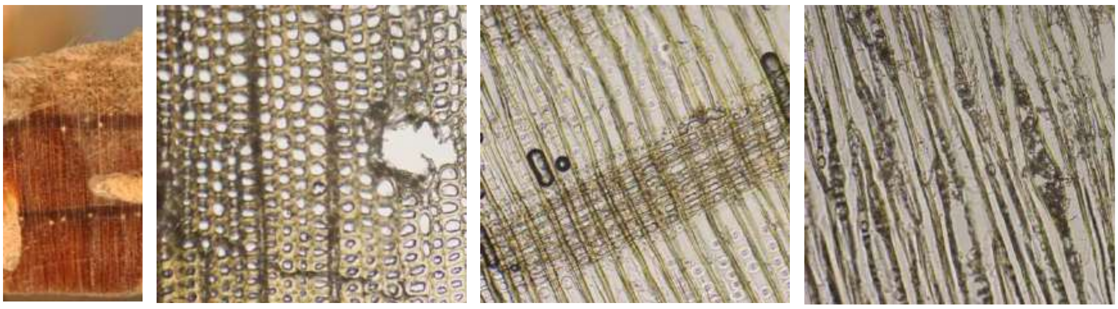


Figure 202: Sample of Scots pine extracted from a sarking board of the roof in Cockenzie House (1680-3): transversal section macro (left); transversal section X100 (centre left); radial Section X100 (centre right); tangential section X100 (right)

We have identified only two other species besides Scots pine: oak (*quercus sp.*) and spruce (*picea abies*). Oak has been used for rafters and collars in the roof of the King's Old Buildings in Stirling Castle (1557), pegs (securing both joints between rafters and collars and slates to the sarking) in Pinkie House (1613), pegs (securing joints between rafters and upper beams) in Holyrood Palace (1671-8) (Figure 203), purlins in the North-West corner of Stirling Castle Palace (after 1719) and pegs (securing joints between posts and collars and upper beams) in Newhailes House (1733-51). This is not surprising considering the early date of the buildings (the purlins in the North-West corner of Stirling Castle Palace have probably been reused from an earlier structure) and/or their high status. As discussed in section 2.2.2, oak, due to its strength and resilience, was considered the most valuable of timber and used whenever possible for high status buildings (Newland 2010). Local oak was used before sixteenth century, then it started being imported from Norway; oak imports were however restricted due to Norwegian governmental policies, and this is why oak is found mainly in very early roofs or high status buildings.

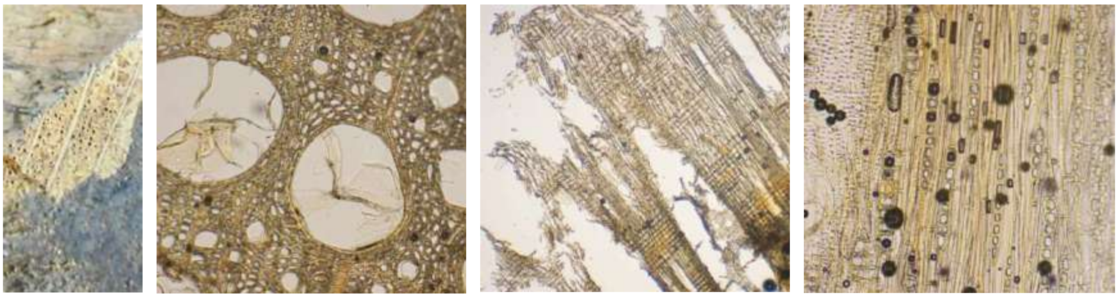


Figure 203: Sample of oak extracted from a peg securing the joint between a rafter and an upper beam in the roof of the North range of Holyrood Palace (1671-9): transversal section macro (left); transversal section X50 (centre left); radial Section X50 (centre right); tangential section X100 (right)

A spruce post has been found in the roof of the North-West wing of Newhailes House (1733-51) (Figure 204), testifying that this species was sometimes used for structural purposes as well. The post in this roof structure is behaving mainly in compression and is thus not highly stressed: this might be the reason why the use of spruce has been considered adequate for this element. All other elements are instead working in tension or bending and are in fact made of Scots pine, while the pegs are made of oak, more durable than pine and less subject to insect attack. The use of different species for different structural purposes in this roof is unique amongst the surveyed roofs and suggests that the wright had a very good knowledge of the material.

Figure 204: Sample of spruce extracted from a post of the roof in Newhailes House (1733-51): transversal section X100 (left); radial Section X100 (centre); tangential section X100 (right)

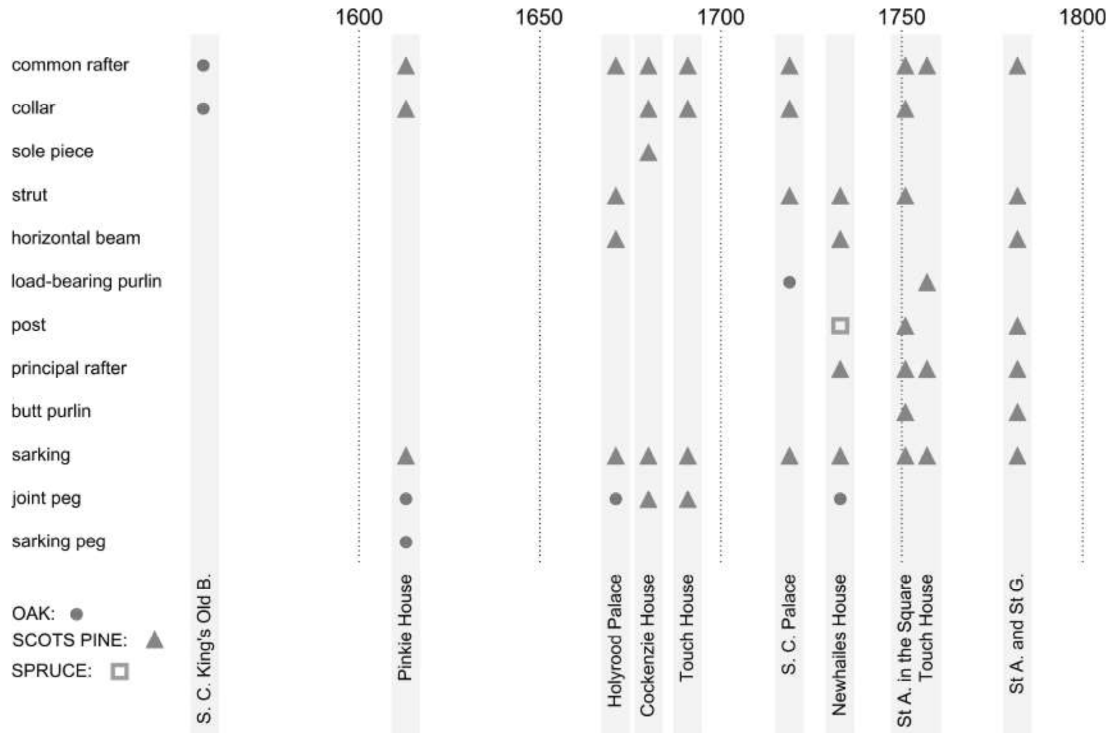


Figure 205: Timeline of the timber species identified microscopically in the case studies investigated

3.3.3.2 Timber Quality

Scottish roofs appear to be composed of timbers of variable quality (Figure 206). This is a consequence of the availability of material and funds and of the knowledge of wrights. The timber was sometimes bought and supplied by wrights - as in Tweeddale House (1750-6) (Dunlop, 1750-1756) -, sometimes by architects - as in Holyrood Palace (1671-8) (NRS E36/30, 1671-1678) - and other times by clients - as in George Heriot's Hospital (1633-7) (Lockhart, 2003). Clients sometimes supplied timber from their own woods, as the Earl of Tweeddale in Yester House (NLS MS14551/24, Undated). It seems that wrights were consulted on the purchase of the material: Thomson (1991) reports that the architect James Baxter working at Gordon Castle in 1770s asked the wrights which was the best quality timber to decide where to buy it from – the wrights replied the Russian one.

In the second half of the eighteenth century timber starts being imported from Russia. Russian deals and balks were of very good quality because in Riga officials sorted and stamped timber balks by quality and length (Thomson, 1991). This was an innovative procedure that allowed to sell and buy products according to their quality in a more efficient way. Timber from Riga had in fact a reputation of being very rigid, regularly squared, very clear of knots, straight in the grain and very durable. VSG has confirmed this reputation in Touch House's purlin roof (1757-62), where the primary structural elements have been found to be of high quality (Figure 207); archival documents record that Riga logs have been used (TCH account by Deas & Co, 1757-8).

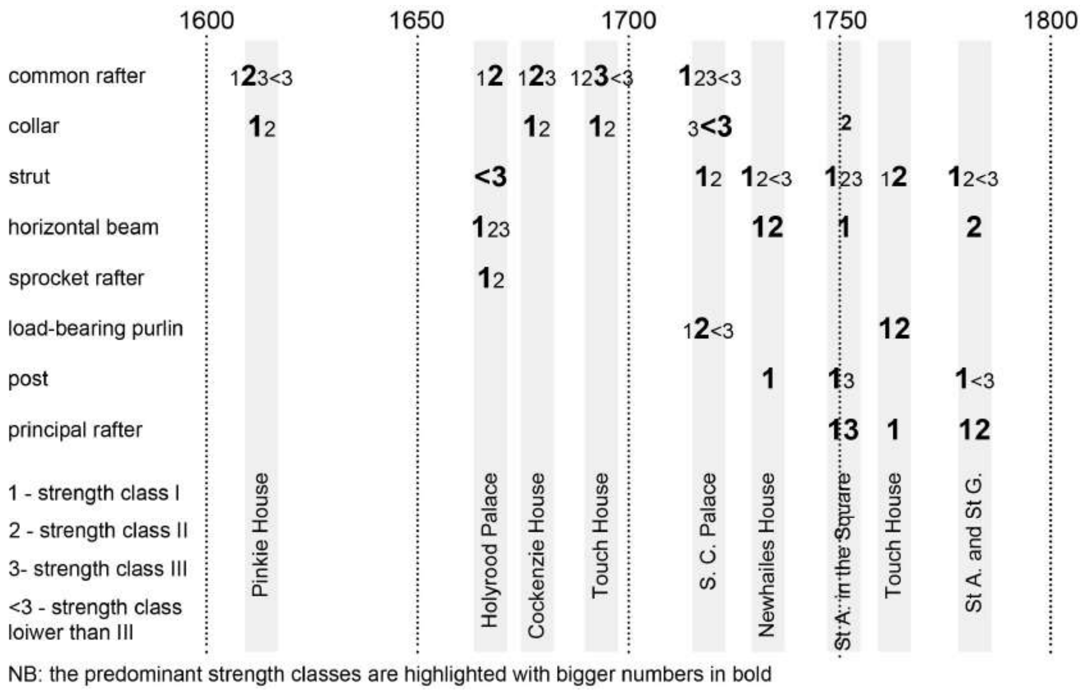


Figure 206: Timeline of the timber quality assessed in the case studies investigated

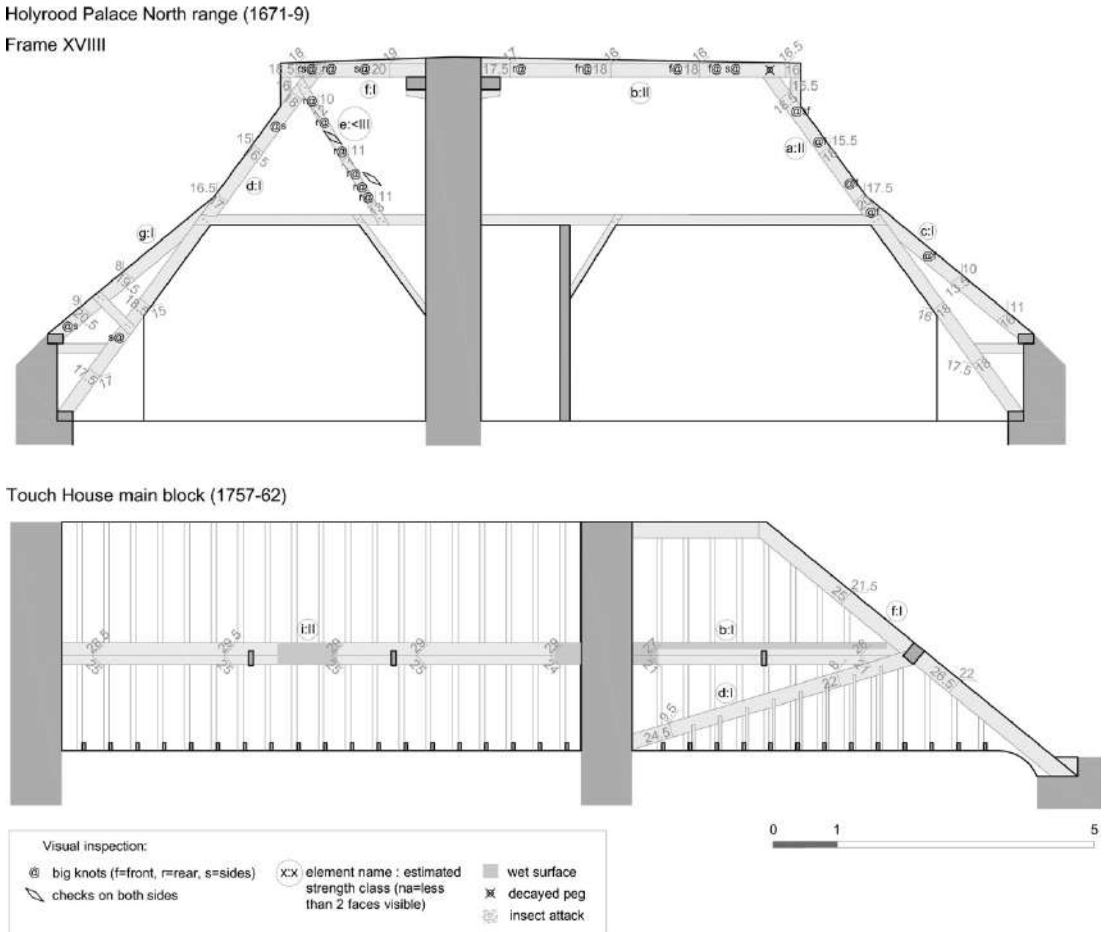


Figure 207: Part of the VSG results of the roofs of Holyrood Palace (top) and Touch House (bottom)

It is interesting however to note that often wrights tried to use the timber they had in the best way possible. Low quality timbers have been used in Holyrood Palace (1671-8), for example, for elements working in compression and thus less affected by defects, such as struts (Figure 207). Rafters in Stirling Castle Palace (after 1719) are sometimes of low quality but the defects are not placed in their critical section, suggesting that wrights were aware of their negative influence on the structural performance of the elements. Timbers in St Andrew's in the Square church (1751-3) do not seem to be distributed according to their quality, but this could be due to the lack of long elements that forced to use a low quality timber as a rafter. Moreover, as already noted, knots in St Andrew's roof are concentrated in elements charged in compression, suggesting that wrights were aware of the knots' negative influence on elements charged in bending and tension.

3.3.4 Wrights, architects and patrons

Figure 208 summarizes the development of Scottish roofs discussed in the previous sections. The end of seventeenth century sees important innovations with the introduction of hipped platform roofs, while different structural solutions are experimented and imported from elsewhere during the eighteenth century. We will now discuss who are the actors that made this development happen, what their relations were and which sources they might have taken inspiration from.

According to previous research, discussed in section 3.2.4, wrights become increasingly important during seventeenth century, working as main contractors (Dunbar, 1976, Newland, 2012b) and some even aspiring to the role of architect, as James Baine (1630-1704) (Newland, 2010). In eighteenth century wrights work as city developers in Edinburgh New Town (Lewis, 2006) and wright Allan Dreghorn (1706-65) becomes an established contractor and architect in Glasgow (Lewis, 2015). However, up to today Baine and Dreghorn are the only wrights whose work has been studied in detail. We do not know if they are an isolated case or if other wrights were following their example.

Based on our archival research (Appendix G) and on the artists' index of the Buildings of Scotland Collection (Cruft, 2005, Gifford, 1984b, 1988, 1992, 1996, 2002, 2007, 2012, McWilliam, 1978, Walker, 2000, Williamson, 1990) we have tracked down wrights involved in seventeenth- and eighteenth-century building works in Scotland, to start understanding who they were working with and if partnerships with other craftsmen and architects had been established. This information has been collected in the ADCRU Microsoft Access database and mapped using ArchGIS (Figure 209). Unfortunately some of the buildings included in Figure 209 are now ruinous (Bernera barracks, Linlithgow Palace, etc) and others could not be visited. Moreover, amongst the ones we have surveyed, some have been heavily altered (Winton House, Brunstane House, etc), leaving little or no trace of the roof structures built by the mentioned wrights. This has precluded a comparison between different structures designed and built by the same wright/architect.

Figure 208: Timeline summarizing the development of Scottish timber roof structures in terms of overall structural arrangements, construction methods and details and timber species and provenance

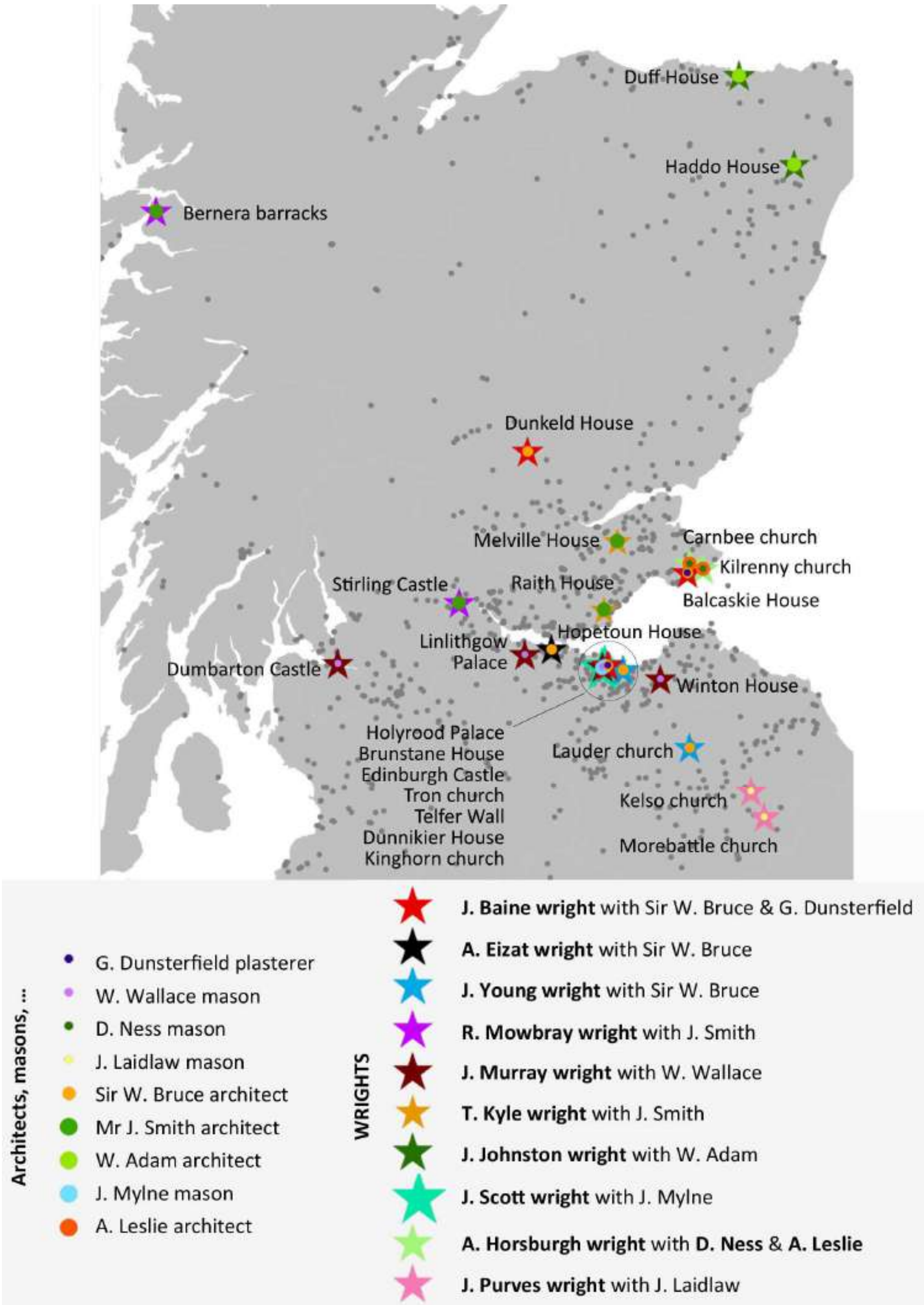


Figure 209: Working teams of wrights, architects, masons and other craftsmen identified during the research; only the teams which have worked together in more than one building have been included

The information collected has nevertheless allowed learning that during eighteenth century partnerships between masons and wrights bring to the design and construction of many churches: Kinglassie Parish church (1773/4) by J. Lawson wright and R. Baxter and R. Black masons, St Andrew's by the Green church (1750/1) by T. Thomson wright and W. Paull and A. Hunter masons, Kilmarnock old high kirk (1732/40) by W. Hunter wright and R. Hunter mason, Tibbermore church (1789) by J. Miller wright and A. Paterson mason, St Cuthbert's church (1771) by W. Watters wright and R. Weir mason. The fact that an architect was not involved in these projects suggests that either the wright or the mason, or both, were working as designers, following the example of Baine and Dreghorn.

In the following sections we will discuss some examples from both seventeenth and eighteenth century to understand what role the wrights, architects and patrons had in the design of the roof structures and which sources they possibly took inspiration from. Although the sample is not comprehensive and more research is certainly needed to draw ultimate conclusions, this work sheds some light on the competences, input and influences of the different actors involved and represents an important first step in the study of the design process of roof structures of the period.

3.3.4.1 James Baine, the Earl of Panmure and Tobias Bachop

James Baine (1630-1704) was one of the foremost wrights of his time: he worked as wright, plasterer, timber merchant and main contractor for the Crown and some of the most powerful members of the Scottish nobility. His career has been studied in detail by Newland (2007, 2010, 2011, 2012c, 2012b, 2012a) who has identified and analysed his work in twenty major building projects by reviewing a great amount of archival documents.

The only roof we have surveyed which might have been designed by Baine is the one at Holyrood Palace. Other wrights were involved in the building works at Holyrood (NRS E36/30, 1671-1678, NRS GD29/100, 1678, NRS GD29/94, 1679, EUL LAII87/1A, 1684-7), but Baine was the Royal Master Wright, therefore he must have had a major role in the design of the timber structures. Holyrood's roof is innovative for various reasons discussed in the previous section: it is the earliest hipped platform roof we have surveyed and it displays for the first time the use of tension absorbing joints. We know that Baine had invented a new flooring technique to bridge wide spans - the broken joists technique described by Newland (2012a) and used in Panmure House, Holyrood Palace and Brechin Castle -, therefore he could be the author of the innovative design of Holyrood's roof as well. On the other hand, Holyrood's roof is quite similar to the one at Kinross House and the point of contact between the two buildings is Sir W. Bruce, not Baine. This makes us think that the architect might have had an input in the design of the roof structures as well.

Brechin Castle is another building where Baine carried out major works. The seventeenth-century roof has not survived but it is mentioned in several archival documents studied by Newland (2010). Baine worked at Brechin between 1688 and 1694, carrying out repair and renovation works for the Earl of Panmure; these works included the dismantling of the roofs of the South and West ranges and their reconstruction with a wider span, since 3 feet were peeled off the supporting walls in order to widen the rooms (Newland, 2010). The roof structures are not described in the contracts, but they are commented on by the mason Tobias Bachop. Baine had carried out a series of works not agreed with the Earl, with the ambition to take in the role of architect. The Earl had refused to pay these works and had called in Bachop to assess Baine's work.

Bachop was highly critical of both the workmanship and the materials used by Baine: he stated that the roof was not stable because "*mostlie of old timber & werie few cupll feet & werie manie needless runroofs & too too long bridles but also too flat [...] so small & unsufficient timber not fit for such use [...] a great many of the feits wholly rotten [...] some of the toppings of the cuples as so shaft rotten & wailkie that the mortises have no strength*" (NRS GD45/18/1616/25, 1694 in Newland 2010). According to Bachop, the roof was too flat and made of inadequate timbers (reused, too small, rotten). Baine had inserted many dormers (*runroofs*), therefore many of the rafters did not reach the wall-head but were supported by purlins (*bridles)* ending on the neighbouring rafters; according to Bachop the *bridles* were too long and too many.

In his petition to the Earl Baine replied that he reused many timbers because he could not find suitable timber to buy, but that this was not a problem because old oak timbers look unpleasant but actually last longer than any other timber (NRS GD45/18/1616/21, 1694 in Newland 2010). He also stated that he would have preferred to use the same roof construction as in Panmure House, but the Earl had bound him to put only *upper backs* and not use *nether backs* fastened to the roof with *plum anglets* (NRS GD45/18/1616/21, 1694 in Newland 2010). Unfortunately Panmure House has long been demolished, thus its roof cannot help in understanding what these terms mean. *Back* is the first cut off a tree-trunk (Robinson, 1999); *upper* and *nether* (lower) probably refer to the position of these elements in the structure; a definition for *anglet* could not be found. The *backs* could be upper and lower collars and *anglet* an ashlar post (as suggested by Newland) to connect the lower collar. Perhaps the Earl did not want lower collars because he preferred a higher ceiling. Leaving aside these speculations, what is interesting is that, according to what Baine says, the patron had a say in the design of the roof structure, since he bound him to use only certain elements.

Even more interesting is the fact that a mason is called to assess the work of a wright and that he goes even beyond his task by describing the amount of timber needed to strengthen the roof: "*the supporting & rancing of the Roofe above the dyining roome, drawing roome & chamber will take 50 trees tuo pairt single & third pairt double & to Rance the Gallerie Garrets betwixt 12 & 16 trees tuo pairt single & a third part double"* (NRS GD45/18/1616/25, 1694 in Newland 2010). Thanks to this description he is later contracted by the Earl to re-work the roofs (Newland, 2010).

Bachop includes a sketch of the roof at the end of his comments on Baine's work (Figure 210); it could be either a survey of Baine's roof or his proposal of new design. Given the overall proportions and the four vertical elements it must be a longitudinal section. The four vertical elements could be four gable walls, but the timber structure in between is then difficult to explain. They could also be four rafter couples, with dormers in between; the small circles at the top of the vertical elements could be the collars - in this case the drawing would be missing the upper part and the other rafters. The drawing is difficult to interpret, but it suggests that timber work was not always a prerogative of wrights.

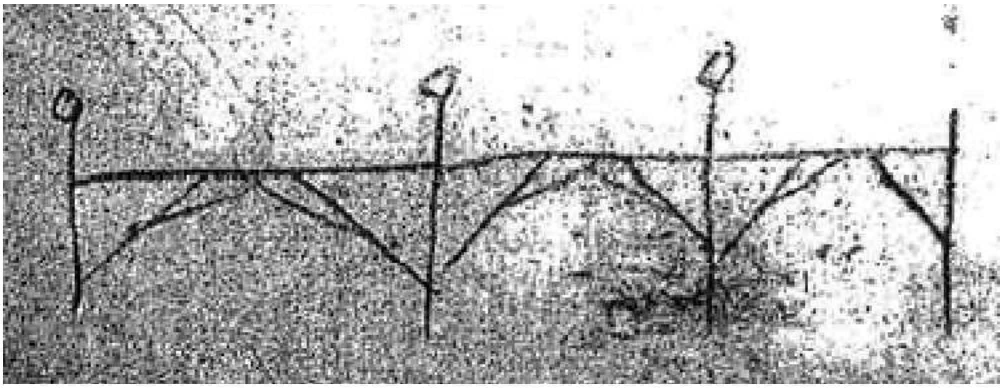


Figure 210: A sketch of Brechin's roof structure included in the assessment of James Baine's work drafted by Thomas Bachop in 1694 (Newland, 2010)

3.3.4.2 John Scott and James Gillespie Graham

The roof structure of the Chapel in George Heriot's Hospital (1628-84) illustrates well the impressive development that Scottish timber roof structures achieved during seventeenth and eighteenth centuries. At first it seems to be a simple common rafter roof, very similar to contemporary Scottish roofs: composed of closely spaced rafter couples (about 30cm space in-between), with two collars connecting each couple transversally and slanted braces supporting the ceiling (Figure 211). The rafters are connected longitudinally by the sarking boards only, forming a continuous surface on which lead sheets are fixed with metal nails. The connection with the supporting walls is not visible, unfortunately. The roof is quite steep (about 50°) but not excessively large (the span is 6.8m). The timbers are hand-axed softwoods connected with mortice and tenon joints secured by roughly squared timber pegs. Big roughly sawn roman numerals mark all the frames, though not in sequence.

Walking through the roof space, it becomes clear that something different happens in the central part of the Chapel: here the roof structure is supported by two additional low-pitched queen-post trusses, inserted in-between the original timbers (Figure 212). The timbers composing these trusses have much bigger scantlings and have been machine-sawn. They are connected again with mortice and tenon joints, but secured with iron straps. The tie-beams are composed of two elements, joined with a scarf joint. Small neatly chiselled roman numerals mark each piece of timber. Two longitudinal purlins sit on top of the trusses and support the upper collar beams of the original roof. Two other purlins hang from the trusses - supported by iron rods and plates - and support the rafters of the original roof, which have been cut.

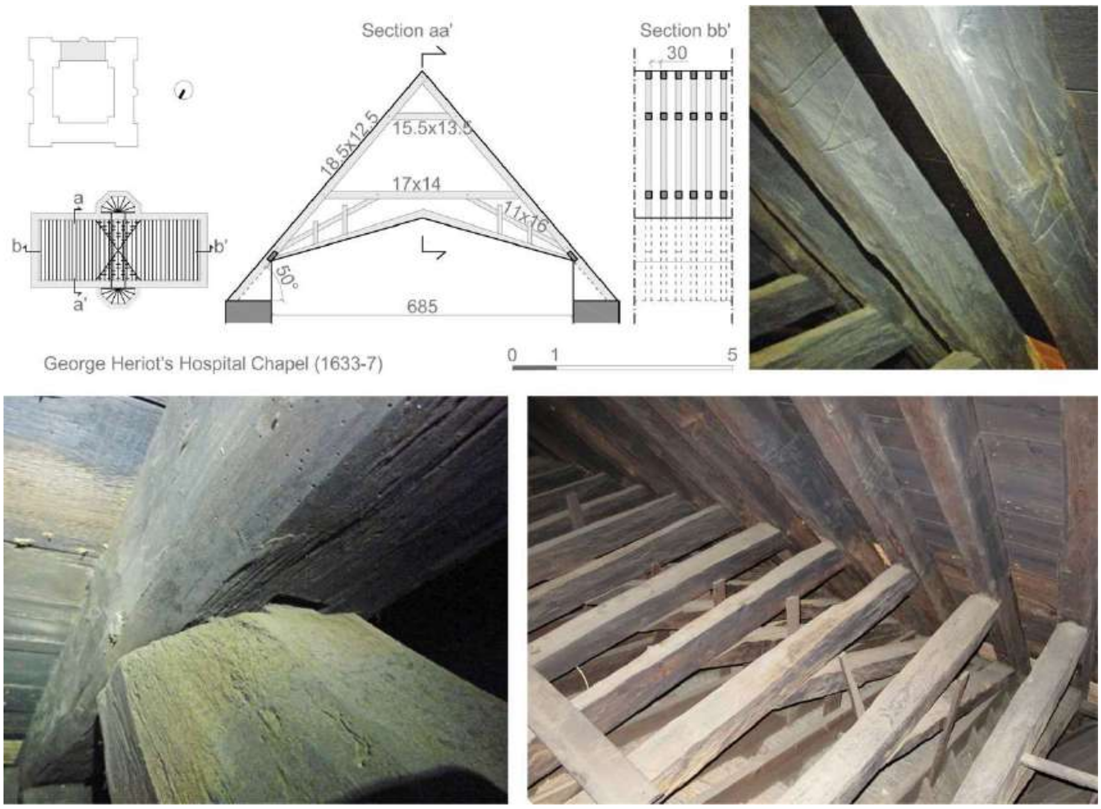


Figure 211: The common rafter roof covering the Chapel of George Heriot's Hospital (1633-7) (Serafini and Gonzalez Longo, 2015b)

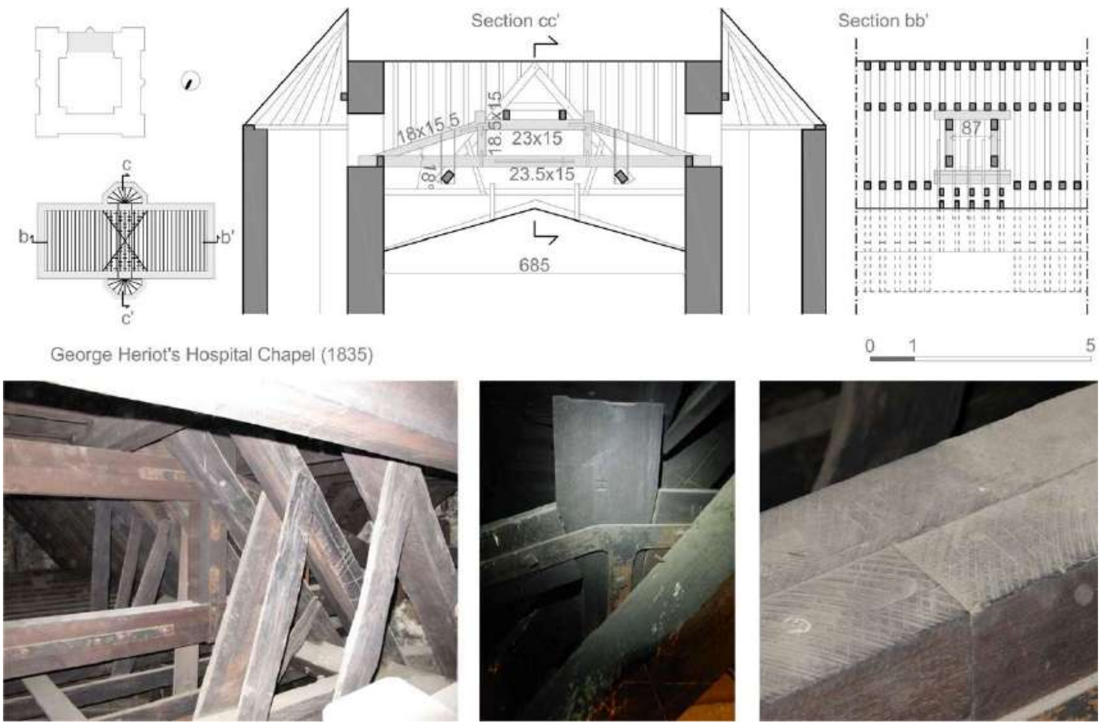


Figure 212: The trusses in the central part of the roof of George Heriot's Hospital Chapel (1835) (Serafini and Gonzalez Longo, 2015b)

Thanks to extensive archive material the original roof structure can be dated to 1633-7. Timber for works at George Heriot's Hospital was brought from Dalkeith, but large timber was imported from Norway (Lockhart, 2003). In December 1633 the mason John Ronald was paid for lintels for the wall-heads of the Chapel; in the same moment the Hospital's governors decided to cover the Chapel with lead and in 1635 the work was contracted to John Bland, an English plumber from Newcastle (Lockhart, 2003). In early 1637 the Hospital's Governors ran out of money and sent Bland back to Newcastle until they needed further lead work (Lockhart, 2003). This makes us think that by 1633 the Chapel walls had reached the roof level and that by 1637 the Chapel had been roofed with lead. However, the first wrights only appear in the Treasurer's accounts of 1638-9 with John Scott as leader of a 6 men team (NRS GD421/5/2, 1633-42).

John Scott (d. 1666) was Master Wright to Edinburgh from 27 January 1637 and Royal Master Wright from 9 June 1641. It is highly unlikely that the Chapel roof structure was built without wrights on-site, but it seems that Scott was not much involved in the design of the Hospital roofs since in 1648 he suggests to dismantle the pavilion roof of the South-West tower for structural reasons, saying that "*it was never his opinione that the said southwest torret should be built in the way that it now standis*" (Lockhart, 2003). Other roofs were platformed as well in those years: the roofs of the North towers in 1642, the North range before 1647, and the South East tower in 1649 (Lockhart, 2003). These alterations, just a few years after the original construction, suggest that Scott had not been much consulted on the roofs' design in the first place.

In that same period Scott was also busy at the Edinburgh Parliament Hall (1631-40) and Tron Church (1636-47) (Figure 128, Figure 129). The two arch-braced open purlin roofs show us that Scott knew very well how to design and construct complex roof structures. Nevertheless he chose to do something very simple in Heriot's Chapel, perhaps because the roof structure was never meant to be visible or because of economic constraints (the Hospital Governors often ran out of money). A further hypothesis is that the reliance on imported timber meant roof construction was rather dictated by standardised lengths; while 'ready-to-build' timber roof 'kits' from Norway would have certainly been a cheaper solution than paying Scott to design a complex roof, and would have allowed the Heriot's architect to bring in wrights only when construction started.

The Chapel interiors remained incomplete until Thomas Sandilands, one of Scott's apprentices, was contracted in 1680s to finish the work (NRS GD421/10/68, 1685). Sandiland's account of work unfortunately does not provide us with details to understand what he did. In this period plaster ceilings were gradually substituting timber ones, but the latter were still in use. The Chapel's roof structure with its slanted braces would have easily accommodated a painted timber ceiling like the 1626 one in Provost Skene's House (Figure 213 a). Nothing as grand as this is mentioned anywhere though, thus it is more probable that a simple ceiling was installed until further funds were found.

In 1787 the chapel was refitted with a new ceiling, called 'adamesque'; Robert Adam might have been involved since he had been consulted previously for other matters (Lockhart, 2003). An undated drawing held in RCHAMS shows a decorated ceiling that matches evidence found in the roof space (Figure 213 b and c). The central part of the roof structure was altered at this time to allow for this new ceiling to be installed. The rafters were cut ('a' in Figure 213 centre and Figure 214), leaving exposed the mortice and tenon joints were the lower collars used to be (Figure 214 right). A purlin was inserted on each side to support the cut rafters ('b' in Figure 213 centre and Figure 214). The purlins were kept in place by a collar ('c' in Figure 213 centre and Figure 214) and two struts ('d' in Figure 213 centre and Figure 214) pushing on the lateral walls. Ceiling joists ('e' in Figure 213 centre and Figure 214) were placed beneath and connected to the rafters with timber struts ('f' in Figure 213 centre and Figure 214).

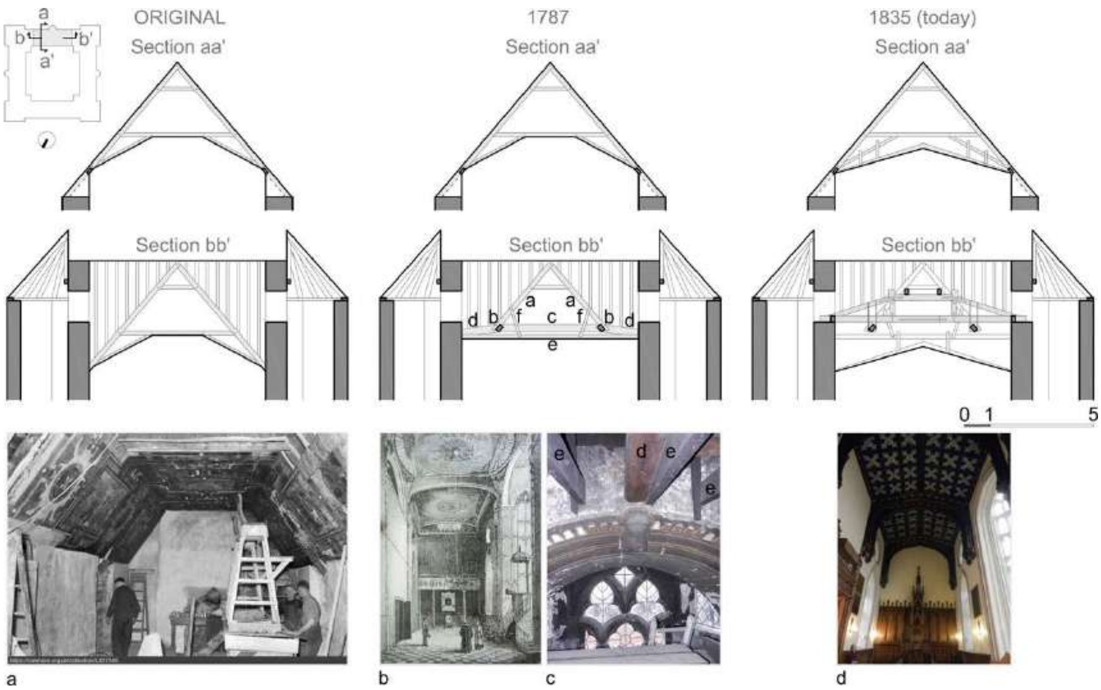


Figure 213: Alterations in time to the roof structure and ceiling of George Heriot’s Chapel: a) hypothesis of the original ceiling, that might have been similar to the 1626 one in Provost Skene’s House (RCAHMS SC 1327346, 1952); b) an undated drawing probably showing what the 1787 ceiling looked like (Lockhart, 2003); c) remains of the eighteenth century plaster decorations visible in the roof space; d) a view of the ceiling today, as renewed in 1835 (Serafini and Gonzalez Longo, 2015b)

In December 1833 the governors ordered to replace the whole plasterwork, considered unsafe: the work was carried out by architect James Gillespie Graham (Lockhart, 2003). Gillespie’s work is what we see today (Figure 213 d). He added two queen-post trusses to reinforce the central part of the roof structure, weakened by the late eighteenth-century interventions. The trusses are clearly of nineteenth-century dating because their pitch (18°) is much lower than that of earlier trusses: the truss above the Trades Hall in Glasgow (1791-4) is the shallowest with its 27° pitch. Moreover, the elements composing George Heriot's Chapel have been machine sawn - mechanical sawmills started being employed in Scotland only from early nineteenth century (Crone and Mills, 2011).

Figure 214: Alterations in time to the roof structure and ceiling of George Heriot's Chapel; the letters correspond to those in Figure 214 (Serafini and Gonzalez Longo, 2015b)

The use of trusses to cover a reduced span such as the one in George Heriot's Chapel is indicative of how well established the trussed system had become in Scotland by early nineteenth century. The following sections discuss how and by whom the trussed system has been introduced in Scotland.

3.3.4.3 John Robertson and Allan Dreghorn

St Andrew's in the Square church is one of a long series of public buildings designed by the wright and architect Allan Dreghorn (1706-65), who contributed to Glasgow's eighteenth-century flourishment (Lewis, 2015). The roof structure seems to be unaltered and can be confidently assumed to be contemporary to the construction of the church itself (1740-57). The records of the Burgh of Glasgow (Renwick, 1911) report in 16 October 1750 (p. 329): "*Considering that the stone work of the new church in Bells yeard is now done and that it is necessary the church to be rooffed, and to fall therto against the spring, they impower the magistrates, dean of guild and deacon conveener to agree with sufficient workmen to do the same and to furnish the timber thereto upon reasonable terms*". In 20 February 1753 Peter Smith is paid for slating the church (p. 361). All the payments made from 1753 onwards are for interiors, the steeple and lead. This brings to the conclusion that the roof structure was constructed between 1751 and 1753.

Since Dreghorn was a wright, it would be reasonable to assume that he designed the roof structure himself; however, the records of the Burgh of Glasgow (Renwick, 1911) report that in October 1758 (p. 532-533) the wright John Robertson is paid by the client for three different plans and estimates for the roof of the church, which he made in 1751. This does not necessarily rule out an input by Dreghorn in the design of the roof structure but it suggests that, since Dreghorn was acting as architect, another wright was contracted for the timber work. It also reveals that the client wanted to have his say not only in the cost but also in the design of the roof structure.

As previously discussed, the roof of St Andrew's in the Square church is amongst the earliest trussed roofs extant in Scotland. This raises the question of how Robertson and Dreghorn came in contact with the trussed system. We know that the architect and craftsmen had been asked by the client to follow the model of St Martin's in the Fields, the church designed and built by the architect J. Gibbs in London about 20 years earlier. The roof of Gibb's church is a trussed roof (Figure 215, Figure 216). However, if we compare it with the roof of St Andrew's in the Square church (Figure 217), it is easy to note that St Andrew's structure is a lot simpler. The structure drawn by Gibbs in his Book of Architecture (1728) (Figure 215) is actually a double structure, with more closely spaced trusses and thus employing a greater quantity of timber. The trusses covering the portico are simpler (Figure 216), but still quite different from the ones in St Andrew's in the Square.

Another roof drawn by Gibbs in his Book of Architecture (1728) is more similar to the one of St Andrew's in the Square: that of Marybole Chapel (Figure 218). It might be that Robertson took inspiration from Gibbs' book to draw three different roofs, since he was asked to make three different plans and estimates, and that the client eventually chose the one that employed less timber and was therefore cheaper.

Unfortunately not much is known about Robertson, so it is not possible to say with more confidence if he copied the structure from Gibb's book or another book or came in contact with the trussed system while travelling. However, it is interesting to note that this roof looks like a truss but is not actually behaving as a truss, because of the design of some construction details. The joint between the central post and the raised tie-beam is in fact a simple mortice and tenon joint secured by two timber dowels: such joint can resist very limited tension forces, thus it cannot counteract the deflection of the raised tie-beam, as in a truss. The post is simply sitting on the raised tie-beam and working in compression, as proven by the fact that the joint between the post and the raised tie-beam does not show any signs of distress/opening. In fact the raised tie-beam is supported by the lateral posts and their slanted struts, so it can support the post. What is interesting is that the top of the post is inserted in between the two rafters, as in a truss: the detail would make sense if the post was meant to work as a tie and needed support from the rafters, rather than the other way around.

Clearly, the joint between the post and the rafters has been copied without understanding its meaning. The same detail and misunderstanding has been found in the roofs of Fort George Ordnance Store (1759-61), Fort George Museum block and Staff block (1762-4) and Tron theatre (1793-4). This suggests that many architects and wrights still had a superficial understanding of the trussed system during the eighteenth century, as argued by Yeomans (1984, 1986b, 1992). According to Yeomans, English architects and carpenters did not fully understand the trussed system because they copied trusses from treatises rather than seeing built examples. Carpenters’ manuals of the time had in mind those supervising the work rather than the workmen carrying out the works, so no construction details were included and the structures suggested were often unsafe and difficult to build. The same could be true for Scottish architects and wrights. Other examples of Scottish roofs built during the second half of eighteenth century, discussed below, support this hypothesis.

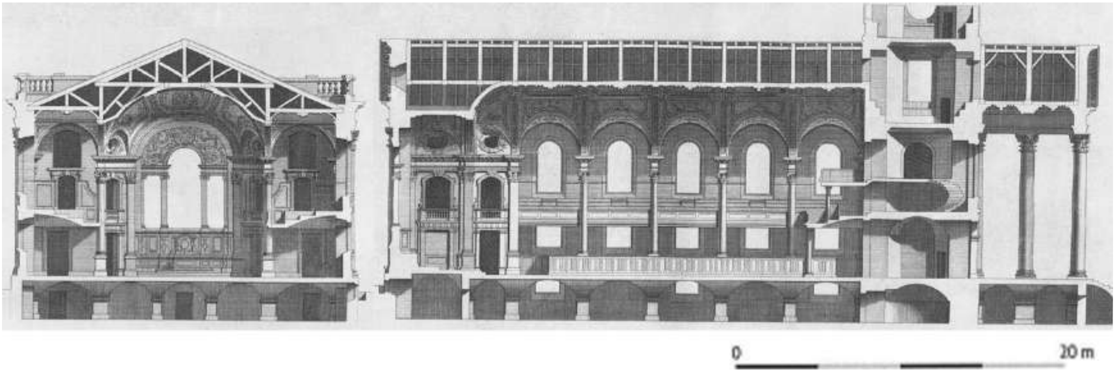


Figure 215: The roof of St Martin's in the fields church as drawn by James Gibbs (1728)

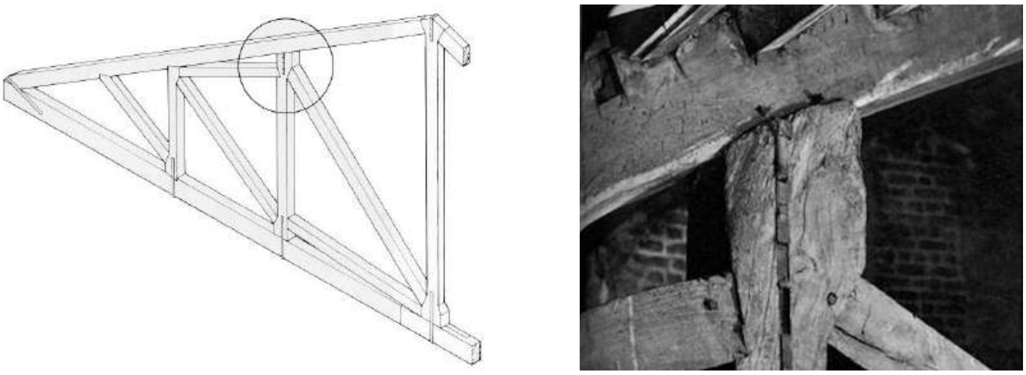


Figure 216: The roof of the portico of St Martin's in the fields church as built (Yeomans, 1987)

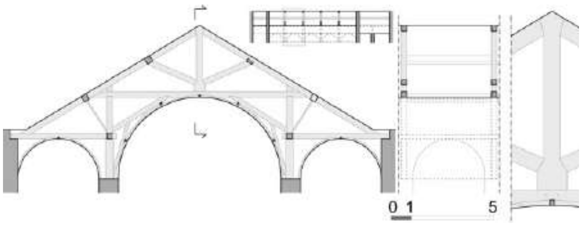


Figure 217: The roof of St Andrew's in the Square church (1751-3)

Figure 218: The roof of Marybole Chapel (Gibbs, 1728)

3.3.4.4 Thomas Dunlop, the Adams and the Marquis of Tweeddale

Tweeddale House's roof is an interesting example of 'complex frame' (Figure 151) built in in 1750-6, during the renovation works carried out by the architects John and Robert Adam (Gifford, 1984a). The Adams were also working at Yester House for the Marquis of Tweeddale at the time (Dunbar, 1972) and this could explain why the wright Thomas Dunlop had a wider commission in the building, as wright and masonry contractor (NLS MS14665/64, 1750-6). Dunlop had been apprentice to John Montgomery in Mary's Chapel, the incorporation of masons and wrights, from 1700 to 1711 (ECA SL34/4/2, 1706-1774). He was probably one of the foremost wrights in Edinburgh at the time: he was Deacon of the incorporation and had eight apprentices through his life (ECA SL34/4/2, 1706-1774). Thus it would be reasonable to think that Tweeddale's roof structure was designed by Dunlop.

A letter written by John Adam to the Marquis (NLS MS14551/126, 1753) suggests, however, that in the case of Tweeddale House the decisions were taken chorally by the architects, wright and mason (Mack), according to specific instructions given by the client: "*we went to your lord's house along with Mess.rs Mack and Dunlop, & concerted every thing with them on the spot, in terms of what your lord directed, so that they are now going on. We are also making out for them Memorandums of the several things with drawings of the particular parts so as they may committ no mistake*".

The Marquis of Tweeddale is known for intervening directly in the design of the roof of another of his houses: Yester House. In a contract between the Marquis and William Adam (NLS MS14551/109, 1742-49), the client asks the architect to change the present M roof (called *happer*) into a platform roof, and gives instructions even for the covering material: "*the present roofe of Yester house being done after the forme commonly called a Happer roof which lodges a great quantity of snow in the winter season to the great prejudice of the said roofe And the said noble marques being designed to alter the same from a Happer roofe to a Plattform to lye betwixt the ridges of the present roof […] The east part of the said house all which to be said with sufficient beams of firr wood and sarking deals and to be covered with lead sufficiently cast and laid with the usual rolls and overlaps at eight pound weight each foot […] As also the said noble marques designing to roofe the middle part of the said house viz- that over the great hall and garden room bounded betwixt the forementioned two principall walls with a pediment roofe to be covered with blue siaillie"*.

Wemyss (2014) underlines the important role that Scottish noblemen had in the design of their houses. The case of the Marquis of Tweeddale suggests that some clients had a say not only in the design of the overall appearance and decoration of their houses, but also in the choice of the construction techniques and materials.

The archival documents related to the works at Tweeddale House reveal another interesting aspect. In the accounts (NLS MS14665/64, 1750-6), both the words 'wright' and 'carpenter' are used. 'Wright' is used more for a person's identification (e.g 'Thomas Dunlop wright'), whilst carpenter is used more to identify the work (e.g. 'carpenter work'). In seventeenth-century accounts of Scottish building works (NRS E36/30, 1671-1678, NRS E37/33, 1699-1703, EUL LAII87/6, 1684-6, NRS GD421/5/2, 1633-42) and in most early eighteenth century accounts as well (EUL LAII88/3, 1721-1805, Rock, 2016, TCH letter to Mr Seton, 1751) the word 'carpenter' does not appear; only 'wright' is used. The fact that 'carpenter' starts being used in Scotland from mid-eighteenth century suggests an English influence, probably prompted by the Union in 1707. This English influence can be traced also in arrangements and construction details of Scottish roofs dating from mid-eighteenth century (discussed in the previous sectios) and in the introduction of the trussed roof, discussed in the next section.

3.3.4.5 John Brown and the Adams

The first Scottish building designed with a trussed roof is the 1720's William Adam's New College Library in Glasgow (Hanke, 2008) (Figure 219). William draws a simple king-post truss whose post has joggles and is dovetailed in the tie-beam. Joggles are a distinctive English feature, although they are also shown by some Italian treatises. Since William did not visit London until 1727, it is likely that his reference was the copy of Serlio's treatise he owned (Rowan, 1990), whose illustration also shows the post dovetailed in the tie-beam (Figure 220). Unfortunately the building has now disappeared so it is not possible to know if his design was implemented. However, other buildings designed by William in the same period, such as Duff House (1735-40) and Arniston House (1726-33), do not have trussed roofs. This brings to the hypothesis that Adam's intention to build trusses clashed with the lack of familiarity of local wrights with the trussed system.

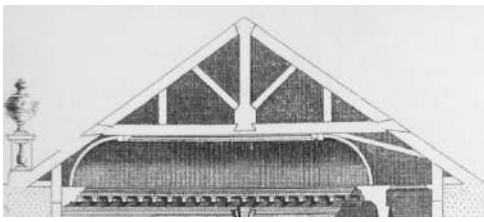


Figure 219: William Adam's design for the roof of Glasgow New College Library, 1720 (Adam, 1812)

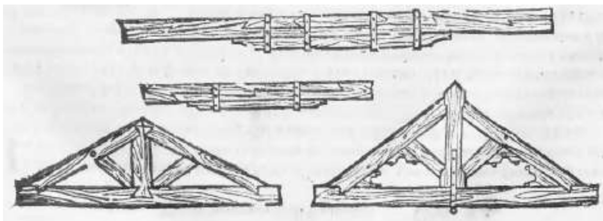


Figure 220: King-post trusses shown by Serlio (1545) at p. 197

Nevertheless, William does build a trussed roof in this period, in Hopetoun House (1721-48) (Figure 157). We do not know who was the wright working with him at Hopetoun, but the fact that he was able to build a truss while his Scottish colleagues still were not, suggests that he might have been a foreigner, or someone who had travelled. Perhaps William brought skilled English carpenters from his London trip for the very purpose of implementing innovative construction techniques, already used in England. Lewis (2006) noted that in 1760s-70s William's son Robert hired men in London whose names are found in Edinburgh New Town ten years later, thus it might be that William did the same 40 years earlier. Another possible source of information and inspiration could have been the new treatise by Price (1733), a copy of which William possessed in his library (Rowan, 1990).

Further considerations can be made by comparing Robert Adam's design for Glasgow Trades Hall (1791-4) with the structure built after his death in 1792 (Figure 221). Adam's design is chosen by the Trades Incorporations in 1791 through an invited competition between him, James Jaffray and John Craig (ML T-TH 1/1/7, 1787-98). The extra land required by Adam's design is never bought, so the design for a building about 33.5m long must be adapted to a plot only 30.5m long: if we compare Adam's drawings with the present structure (Figure 221) we can see the overall proportions distorted and the diameter of the dome dramatically decreased (Sutherland, 2005). This brings to the assumption that the set of plans used for the construction of the Hall, which has not survived, was not drawn by Adam, but by someone else, after his death in March 1792. This person might be the wright John Brown, appointed as contractor in May 1792, under the supervision of James and William Adam (ML T-TH 1/1/7, 1787-98).

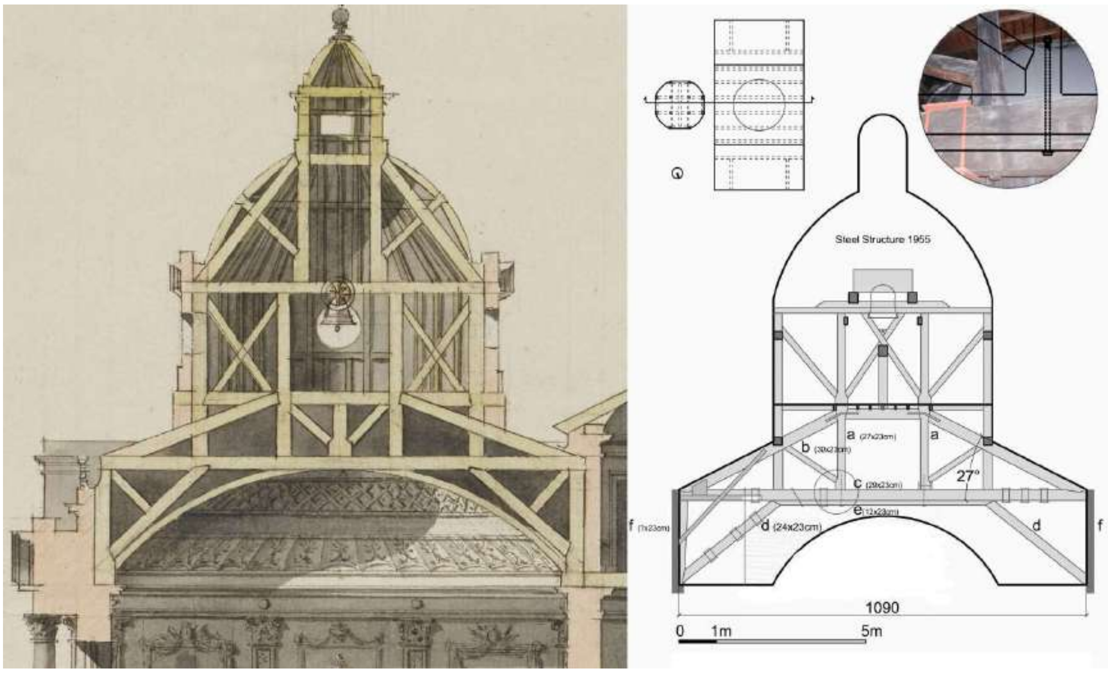


Figure 221: The roof of Glasgow Trades Hall, as designed by Robert Adam on the left (SM Adam 48/25, 1791), and as built on the right; the graphic scale relates to both drawings (Serafini and Gonzalez Longo, 2015a)

The built structure (Figure 221) is composed of 8 parallel queen-post trusses; the 4 middle ones support a drum, dome and lantern above, and leave space for the ceiling below. The span is not excessively wide (10.9m) but the structure is quite tall (10.5m below the lantern). The joints have joggles and iron straps so that the queen-posts ('a' in Figure 221) hang from the principals ('b' in Figure 221) and support the tie-beam ('c' in Figure 221). The bottom of the post is connected to the tie-beam with a system of cotters and folding wedges passing through the elements (Figure 221 top right): a detail developed in England at the beginning of the nineteenth century, according to Yeomans (1992); it could thereafter be one of the very first uses of this device. The trusses sit on a lower ‘arch’ system, formed by two slanted braces ('d' in Figure 221) and a horizontal beam ('e' in Figure 221). The slanted braces spring from the base of timber posts ('f' in Figure 221) that are partly (on the left) or completely (on the right) embedded in the walls. The tie-beams sit on these posts.

This is one of the two weak points of the structure. The lateral posts and the wall-heads behind them are unable to counteract the horizontal thrust coming from the truss above. The lower ‘arch’ system has partially opened in time and wooden wedges had to be inserted in the joints (Figure 222); the wall-head was reconstructed and steel rods, plates and brackets were added with the same purpose in 1990s (Figure 222). The other weak point is the insufficient longitudinal rigidity. Even though the sarking is still employed, the trusses do not rest on wall-plates and they only have a few purlins connecting one truss to the other. The transversal opening and longitudinal instability are probably the reasons why in 1950s both the dome structure and the ceiling had to be replaced (Figure 223, Figure 224).

The roof structure actually had problems even earlier than in 1950s: in 1856 the buildings’ committee discovered that some of the timbers of the roof had decayed and were unsafe, so architect Charles Wilson was asked to carry out 'considerable' repairs and alterations to secure the roof, which he did from September to November 1856 (Crawford, 1858). From Wilson's drawings we know he added some timber elements and some metal straps and rods (Figure 225).

Figure 222: Repair works to the roof structure of Glasgow Trades Hall (1791-4): a timber wedge inserted between a slanted brace and a horizontal beam (left); steel rods, plates and brackets added in 1990s (right)

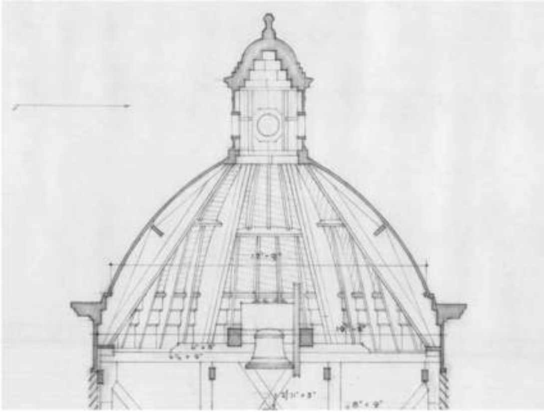



Figure 223: The original timber structure of the dome of Glasgow Trades Hall (1791-4) surveyed by W. Underwood in 1950s (ML Shanks 152/T6, 1955) (left) before the replacement in steel (right)


Figure 224: The ceiling of Glasgow Trades Hall (1791-4): an undated picture probably showing the original ceiling (ML T-TH 1/34/3, Undated) (left) and the present ceiling, installed by W. Underwood in 1950s (right)

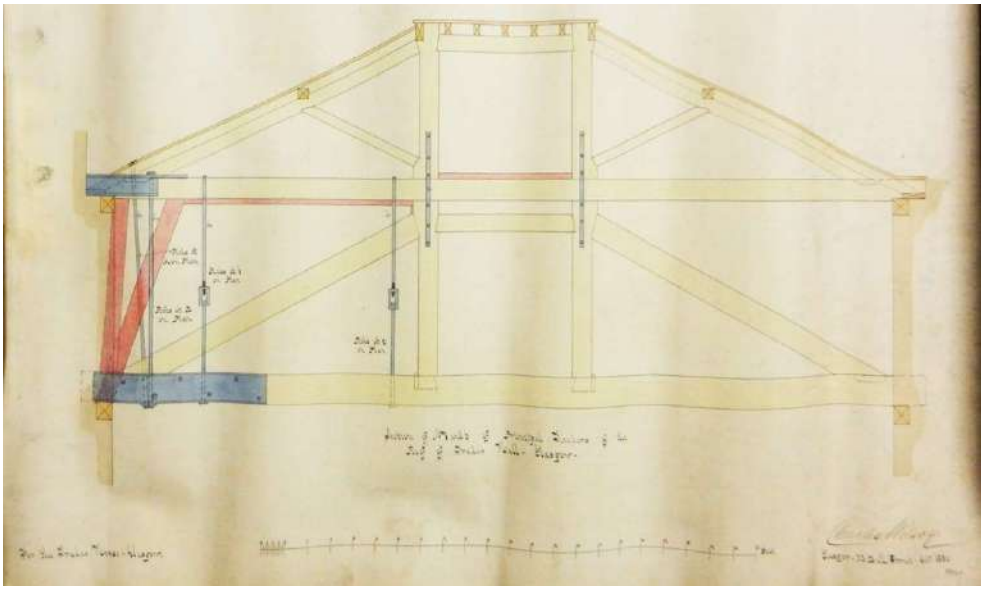


Figure 225: Strengthening of the roof of Glasgow Trades Hall (1791-4): drawing by Charles Wilson architect dated 1856 showing in yellow the original structure, in red new timber elements added by C. Wilson, in blue metal work added by C. Wilson (TDH 1/899, 1856)

The Trades Hall roof as built clearly has some faults, but it shows a better understanding of the trussed system than the structure drawn by Robert Adam (Figure 221). The latter shows an improper design of the joints, which causes the posts to behave in compression, enhancing the tie-beam deflection instead of counteracting it. Moreover, the small central post has no apparent structural function, the lateral walls are too thin to counteract the horizontal thrust produced by the very shallow pitch of the roof, and there is a questionable disposal of rainwater.

There is no evidence of who designed the built roof, whose dome is the very first in Glasgow. Little information could be found on John Brown, the wright/contractor at the Trades Hall, from whom no other building seems to remain. Brown was member of the Glasgow incorporation of wrights from 1790 until his death in 1816 (ML T-TH 9/4/2, 1731-1811, ML T-TH 9/4/3, 1811-70). His appointment as contractor for such a major work as the Trades Hall only one year after becoming a member of the incorporation suggests he was not at the beginning of his career but already had experience. Moreover, the fact that he built a complex dome structure, and perhaps modified Robert's design as well, suggests that he had confidence with the truss system. He might have been brought from London by the Adams, or from elsewhere where the trussed system was already known and used.

The brothers Adam were interested in construction details and in innovative roof structures, just like their father. This is testified by various drawings by Robert, John and James (two examples in Figure 226, Figure 227). Thanks to Rowan's research (1990), we know that William Adam possessed in his library not only Serlio's treatise, but also Vitruvius Pollio (1556), Palladio (1570), Scamozzi (1615), Price (1733) and Salmon (1767), who all show many examples of trussed roofs. His sons might have taken inspiration from these books, just as their father did. Robert and James also travelled to Italy and worked in London (Rykwert, 1985), so they might have seen built trusses too.

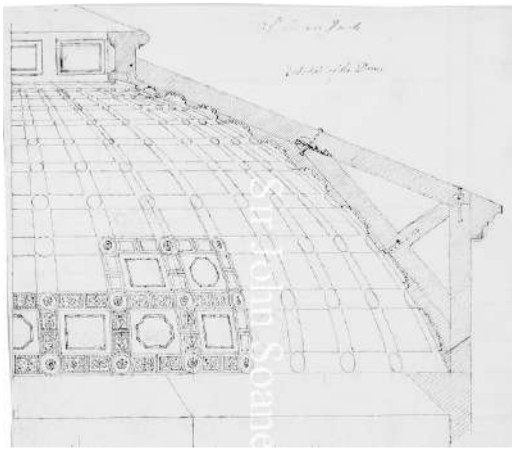


Figure 226: Design for the dome of Edinburgh Assembly Rooms and Musical Society by James Adam (SM Adam 7/225, 1755)

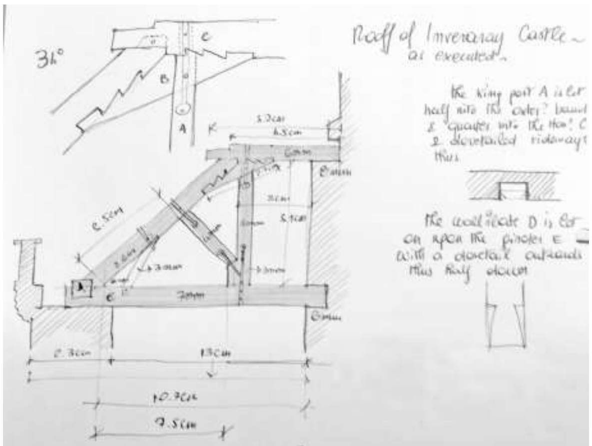


Figure 227: Design for the roof of Invereray Castle (copy of drawing found in John Adam's diary held at Blair Adam House)

These drawings show a superficial understanding of the trussed system, just like Robert's design for Glasgow Trades Hall. This brings to the hypothesis that, since the Adams aspired to build trusses, but they were unable to explain to Scottish wrights how to construct them, they probably sought foreign wrights who were more familiar with these structures and could satisfy their aspirations. And these foreign wrights eventually spread their knowledge to Scottish wrights too. This external influence, from England and/or beyond, necessary for the establishment of the trussed roof in Scotland, is also suggested by the heterogeneity of solutions and details used, previously discussed.

3.4 Conclusions

Our survey of 59 original seventeenth- and eighteenth-century Scottish timber roof structures has allowed identifying different structural typologies, dating them and tracing their development in terms of structural arrangements, construction methods and details, material, know-how and foreign influences. A distinctive Scottish school of roof carpentry has emerged, little influenced by England and Europe up to mid eighteenth century and retaining characteristic features even after.

We can confirm Hanke's (2006) statement that up to late seventeenth century the majority of Scottish roofs is of a simple common rafter form, hidden behind decorated ceilings. Our research also highlights an important development at the end of seventeenth century, when roofs evolve to cover wide spans with shallow pitches and hipped arrangements, whilst supporting heavy plaster ceilings. We noticed that the imported timber products and the know-how of wrights gradually change too. Our investigations also demonstrate that eventually a completely different structural type is imported from elsewhere: the Italian trussed roof, employed from 1740s. Interestingly, we found that some features are maintained and denote a distinctive Scottish tradition, while other details suggest foreign influences. This indicates a transfer of technological knowledge from various sources and a will to experiment and adapt the single solutions to the local tradition, a process in which, according to our research, wrights, architects and patrons all had an important role.

Our research on the work of the Adams architects, in particular, shows that they had an important role in the introduction of the trussed roof Scotland. Although they aspired to build trusses since 1721, when William Adam draws the first Scottish trussed roof, it seems that at first Scottish wrights were unable or unwilling to construct them, probably because they had limited knowledge on the structural behaviour of timber and on the strength and durability of different timber species, as highlighted by our surveys. Our conclusion is that the Adams were forced to bring wrights from abroad in order to implement their designs; this external influence is also suggested by the heterogeneity of solutions and details used in Scottish roofs and highlighted by our surveys.

4 Description of the case studies investigated

This chapter gives a detailed description of the eight case studies investigated (Figure 228), presenting for each of them the architectural and construction history - reconstructed through the literature review, archival research and visual inspection - and the present condition - assessed through visual inspection, VSG and in situ testing. The aim is to show how different assessment methods and tools have been combined together to determine the dating of the roof and evaluate its condition. The overall arrangement of the timber roof, as well as its construcition details and timber species, are described in detail. The accessibility and visibility of the roof structure, as well as the implementation of regular inspections and maintenance works resulting frrom questionnaires to the building owners/managers, are discussed. The measured air temperature/humidity and wood moisture content are then presented along with the results of the visual inspection and in situ testing in terms of present condition. Only the most significant features, documents and test results are here discussed; a thorough report can be found in Appendix F.

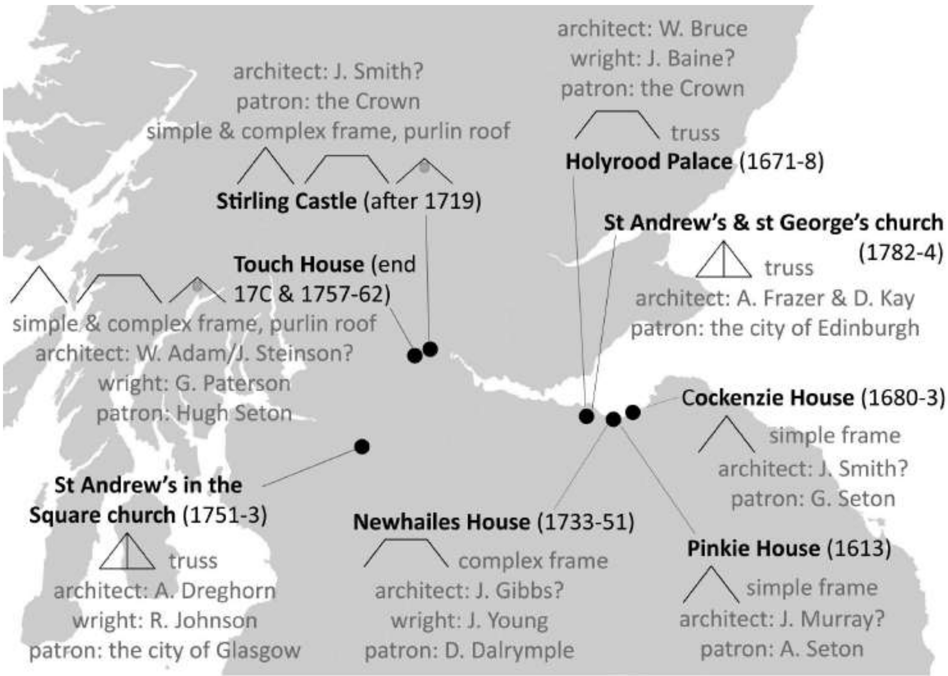


Figure 228: The location, date, structural typology, architect, wright and patron of the roofs of the 8 case studies investigated

4.1 St Andrew's & St George's church

4.1.1 Architecture and Construction

St Andrew's and St George's church is an elliptical church in Edinburgh with a portico topped by a 4-stage steeple on the South side. It was designed and built in 1782-4 by Captain Andrew Frazer, a royal engineer, and the architect David Kay, who might have executed Frazer's designs (Gifford, 1984a). The elliptical plan is one of the very first in Britain and the roof structure is one of the few 3D trusses we have surveyed. We carried out an initial assessment of the church roof (not the steeple) on 3rd July 2015 (accompanied by Dr Daniel Ridley Ellis) and detailed investigations on 3rd February (accompanied by PhD student Clara Gonzalez Manich) and 14th March 2016 (Figure 229).

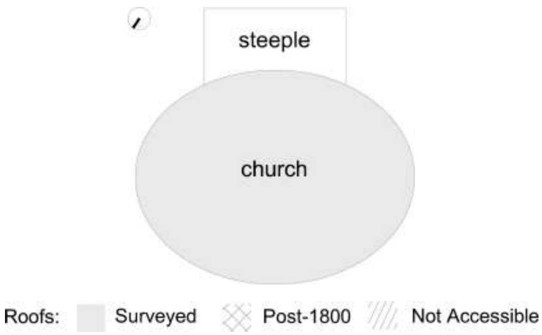


Figure 229: St Andrew's and St George's church (1782-4): plan (left) and view from South-East (right)

The roof is composed of two transversal trusses and radial trusses, linked together by two levels of butt-purlins that follow the elliptical plan (Figure 230). Longitudinal butt-purlins also link the centre top and bottom of the trusses. Sarking boards cover the whole surface of the roof and support lead (on the platform) and slates (on the slopes) secured with metal nails. The transversal trusses are queen trusses with additional central and lateral posts. Slanted struts spring from the posts and support the top of the neighbouriong posts, allowing them to work as ties. The span is almost 19m and the pitch 36°. The radial trusses mirror the arrangement of the transversal ones. The connection with the supporting walls is provided by a wall-plate, on which the tie-beam sits.

The timber elements are all hand sawn to rectangular sections. The rafters and tie-beams are whole logs with big sections (rafters have an average height of 31cm and base of 23cm), the posts and struts are half logs or quarters of logs. The joints are all mortice and tenon. Metal straps are used at the bottom of the posts (except for the posts on the far sides), at the top of the queen posts and between rafter ends and tie-beams (Figure 231 left), to secure the connections and allow them to work in tension. The posts are reinforced by joggles where the struts spring. The tie-beams of the transversal trusses are composed of two elements, joined with a simple scarf joint. Some timbers are numbered with small chiselled roman numerals (Figure 231 centre).

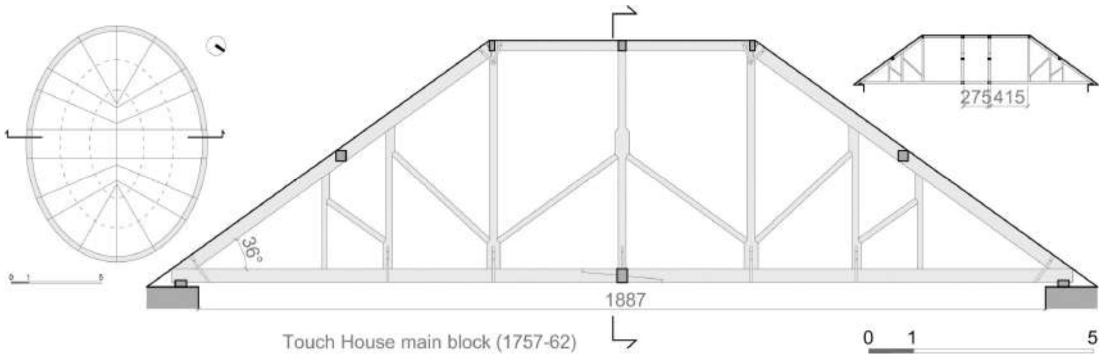


Figure 230: The roof of St Andrew and St George's church (1782-4)

All the timber elements, including the sarking, are made of *pinus sylvestris*. The timbers are of good quality, mostly belonging to Strength Class I and a few to Strength Class II. Three elements on the North side, however, have a Strength Class lower than III: a strut has a really big knot (Figure 231 right) and two posts have shakes all along their length.

Figure 231: The roof of St Andrew and St George's church: the connection with the wall (left), carpentry marks on a post (centre) and a big knot in a strut (right)

The structure is quite homogeneous and looks unaltered. The typology and details all suggest a dating contemporary to the church itself as they resemble other trussed roofs of the second half of the eighteenth century, such as the ones in Culzean Castle (1784 and 1791) or the Trades Hall in Glasgow (1791-4). Unfortunately no records could be found related to the construction works.

4.1.2 Current Condition

St Andrew's and St George's church is property of the Church of Scotland and is inspected regularly, on a yearly basis, although a program of works has not been implemented yet. The roof space is easily accessible, it is well lit and provided with a catwalk for inspections.

The air temperature and relative humidity have been found to be around 13° and 55% in February. These values are very near the optimal range identified by Ridout (2000) and correspond to an equilibrium moisture content of about 11% (Ross, 2010). The measured moisture contents varied from 8% to 15%, but none exceeded 18%, which would allow insects to live (Ridout, 2000); in fact there are no signs of biotic attack.

Some cracks have been identified close to the joint between a post and a strut (Figure 232), on two other posts and in the South rafter. However, the overall performance does not seem to be affected, probably also thanks to the strengthening works carried out in 2003-4, when a Vodafone plant was installed in the roof space: the joints between rafters, posts and upper beams have been strengthened with metal straps and bolts (Figure 233).

Figure 232: The roof of St Andrew and St George's church: compression cracks in a strut and in the joggle of a post

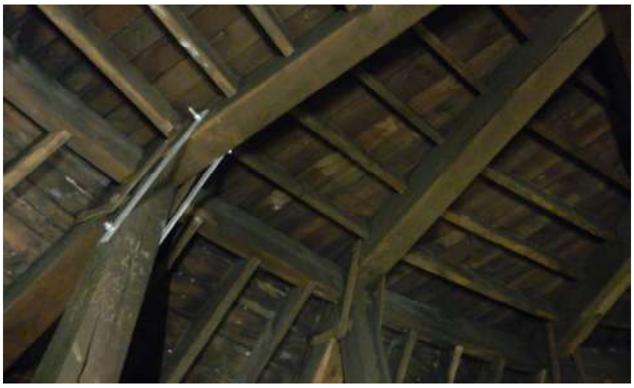


Figure 233: The roof of St Andrew and St George's church: strengthening of a joint between post and upper beam

4.2 St Andrew's in the Square church

4.2.1 Architecture and Construction

St Andrew's in the Square church is a rectangular 3-nave church in Glasgow with an entrance portico topped by a 5-stage steeple (Figure 234). It was designed and built by the wright and architect Allan Dreghorn between 1739 and 1756 (Renwick, 1911). The interiors have been altered during the end of the nineteenth century and the beginning of the twentieth century, but the original plasterwork survives unaltered. In 2000 major repair and restoration works were carried out, including a 4m deep excavation to create a basement café. We have surveyed the church roof (not the steeple): an initial assessment was carried out on 31st August 2015 and detailed investigations on 20th January and 16th February 2016 (Figure 234).

Figure 234: St Andrew's in the square church (1739-57): plan (left) and view from West (right)

The church roof is a double pitched roof sandwiched between two gable walls and supported by two transversal walls and four princess-post trusses, spaced more than 4m one from the other (Figure 235). The tie-beams are interrupted in the central part by the vaulted ceiling, but they are supported by the lateral columns. The posts sitting on these columns support the collars and rafters and have slanted struts on both sides. The trusses are connected longitudinally by two levels of butt-purlins and by sarking boards, on which slates are secured with metal nails. The overall span is 18.2m but it is reduced to 8.1 by the intermediate columns. The pitch is quite low (31°). The tie-beams sit in recesses in the lateral walls. The rafters join the tie-beams before these are supported by the walls, which causes shear stress in the tie-beam, but this does not seem to have created problems so far.

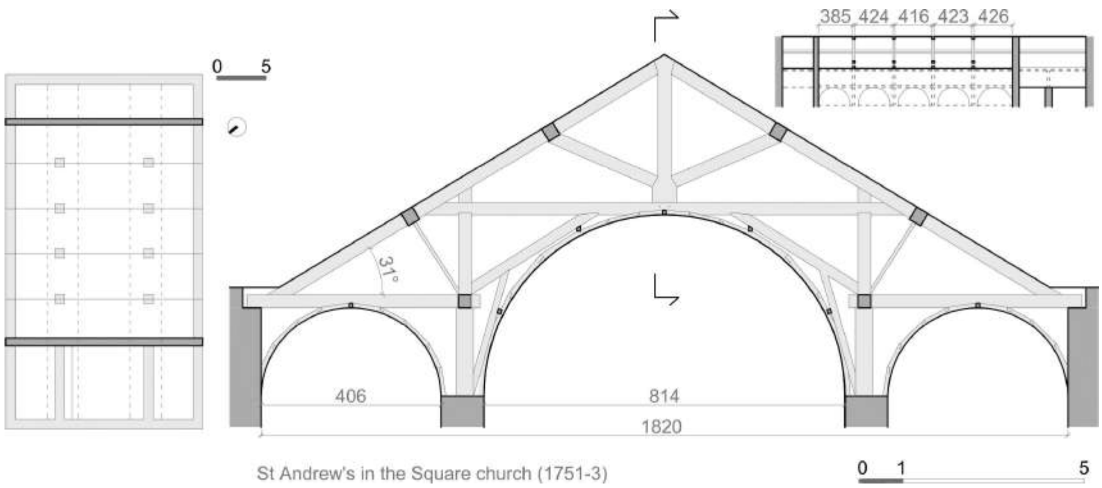


Figure 235: The roof of St Andrew's in the Square church (1751-3)

The timber elements are all whole logs, hand axed (Figure 236 left) and hand sawn to almost square sections, except for the thinner struts. The sections of the rafters are quite big (average height of 30cm and base 28cm). The joints are all mortice and tenon secured by timber dowels and reinforced by joggles in the central post, notched between lateral posts/struts and collar. The elements are all working in compression and bending, even the central post: in fact no metal straps are used anywhere. The trusses are numbered with small chiselled roman numerals, from I to IIII (from North-East to South-West). Some unusual carpentry marks have been found too (Figure 236 right).

Figure 236: The roof of St Andrew's in the Square church: the dressing of a butt-purlin (left) and unusual carpentry marks on a strut (right)

All the timber elements, including the sarking, are made of *pinus sylvestris*. Most of them have unusually narrow rings, not visible macroscopically (Figure 237). The quality of the timbers ranges from Strength Class I to III, and they do not seem to be distributed in the structure according to their quality. The presence of knots seems instead to be concentrated in less important elements, such as struts and posts, behaving in compression and therefore less affected by defects.

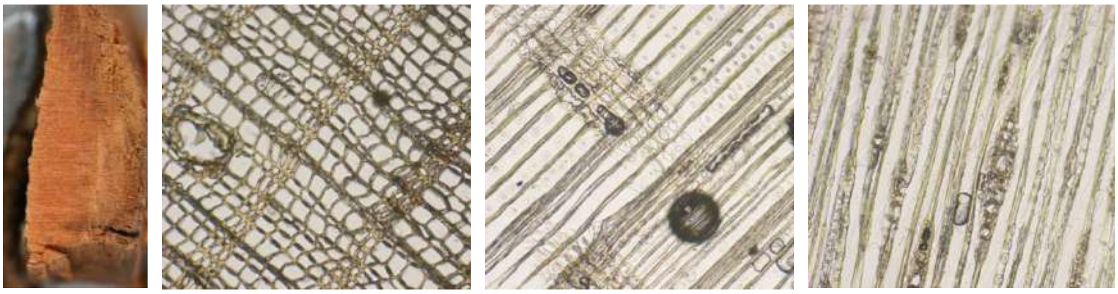


Figure 237: Sample of Scots pine extracted from a strut of the roof of St Andrew's in the Square Church: transversal section macro (left); transversal section X100 (centre left); radial section X100 (centre right); tangential section X100 (right)

The roof structure seems to be unaltered and can be confidently assumed to be contemporary to the construction of the church itself, as discussed in section 3.3.4.3. There are no accounts related to the purchase of the timber but the narrow rings of the pine samples and the unusual carpentry marks found suggest a Scandinavian/Baltic provenance.

4.2.2 Current Condition

The building is owned by Glasgow Building Preservation Trust and is inspected regularly, on a yearly basis, although a program of works has not been implemented yet. The roof structure is easily accessible, it is well lit and provided with a catwalk for inspections. The air temperature recorded in February was 13° with a relative humidity of 56%, very near the optimal range identified by Ridout (2000) and correspond to an equilibrium moisture content of about 11% (Ross, 2010). The measured moisture contents were a bit higher but none exceeded 18% (Ridout, 2000). In spite of this, there was evidence of insect attack on the corners of the rafters and collars, as well as fungi attack near the North-West gable, affecting the butt-purlins, common rafters and sarking (Figure 238). The cause seems to be water ingress and poor ventilation. Past insect attack has been treated in 1985 by Hunter and Clark Ltd with resin injections (Figure 239), which seem to have been effective, although quite invasive, whilst the fungi attack is currently being treated.

Figure 238: Fungi attack in the North-West gable of the roof of St Andrew's in the square church, affecting the butt-purlin, the common rafter and the sarking

Figure 239: Resin injections used in 1980s to treat insect attack in the roof of St Andrew's in the square church

There are also some cracks (Figure 240), open joints and rotations (Figure 241, Figure 242), but the overall performance and the plaster ceiling underneath do not seem to be affected, perhaps thanks to the strengthening interventions carried out in 1990s: steel brackets and rods strengthening the joints between posts and collars (Figure 242) and the joints rafter/collar and strut/collar (Figure 243).

Figure 240: Cracks in a butt-purlin of the roof of St Andrew's in the square church

Figure 241: A rotation of the principal rafter causing the opening of the joint with the central post in the roof of St Andrew's in the square church

Figure 242: Rotation of the central post causing the opening of the joint with the strut and steel strengthening interventions added in 1990s in the roof of St Andrew's in the square church

Figure 243: A joint between strut and collar with steel strengthening interventions added in 1990s in the roof of St Andrew's in the square church

4.3 Cockenzie House

4.3.1 Architecture and Construction

Cockenzie House is a seventeenth-century laird's house in Tranent (East Lothian). The oldest part is the 3 storeys (plus basement) central block shaded in grey in the plan in Figure 244. We have surveyed the roof above the 1680s central block: an initial survey was carried out on 10th November 2015 and detailed investigations on 22nd January 2016 and 5th February 2016. Due to accessibility and safety issues explained below, the tests have been carried out only partially.

Figure 244: Cockenzie House (1680-3): plan (left) and view from South-East of the central block (right)

The roof is hipped, supported by 4 transversal walls and rafter couples spaced 40cm, connected transversally by one, two or three collars and longitudinally by sarking boards, to which slates are secured with metal nails (Figure 245). Some of the original lower collars have been removed and others replaced and the ceiling has been lowered and is now supported by new collars. The span is 5.4m and the pitch 49°. The connection with the lateral walls is secured by Scottish rafter feet (Figure 246 centre left).

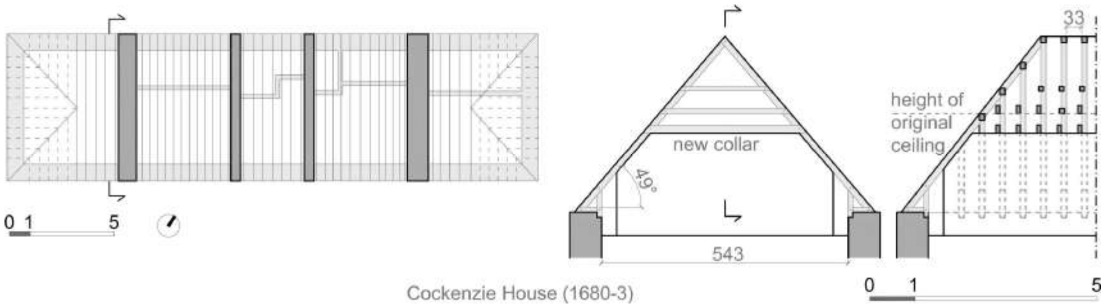


Figure 245: The roof of the central block of Cockenzie House (1680-3)

The timber elements are all whole logs roughly axed to almost square sections, leaving wanes on the corners. The sections are quite variable but small: the maximum height is 13cm and the maximum depth 11.5cm. The joints are mortise and tenon secured with timber pegs in the rafter feet, lapped and secured with timber pegs at the rafters' apex, lapped chamfered secured with metal nails between rafters and collars (Figure 246 right). Some timbers are numbered with roughly sawn roman numerals occupying the whole section of the members (Figure 246 centre right), not in sequence.

The timber elements are all made of *pinus sylvestris*, generally of good quality, belonging mainly to Strength Class I or II. The fact that good quality timber was chosen for Cockenzie House's roof supports the hypothesis that this was a high status building.

Rock suggests that, since the two inner transversal walls are thicker than the outer walls, the core of the house is of earlier date. The roof structure is nevertheless homogeneous in arrangement and construction details: if there was an earlier roof it must have been replaced when the house was extended in 1680-3. Some redundant joints have been found on timbers on site (Figure 246 left), and some timbers seem to have a more rough dressing, with some bark left on the corners. These timbers might have been reused from the earlier roof.

The dating of the roof structure to end seventeenth century rather than earlier is suggested by two details: the use of hip rafters and the use of lapped joints secured with metal nails (section 3.3). In fact, the first hip rafters can be found in the North range of Holyrood Palace (1671-9) and in Kinross House (1679-93) and the use of lapped joints secured with metal nails can be first seen in Cowane Hospital (1637-48). The dating of Cockenzie's roof to end seventeenth century is also endorsed by the comparison with similar roofs such as the one in the West range of Royston House (1683-96) or the ones in Methven Castle (1678).

Figure 246: The roof of Cockenzie House: redundant joint on a collar (left), rafter feet (centre left), big sawn roman numerals on a rafter (centre right), lap joint between collar and rafter secured by metal nail (right)

4.3.2 Current Condition

The roof structure of Cockenzie House is only partly visible and accessible, because the lower part is plastered and occupied by attic rooms. This hinders the inspection and maintenance of the connection with the lateral walls, which is a critical point. The rafter feet are visible only from the North-East roof and in a room in the South-West section of the House, where the plaster boards have been removed. Hatches give access to the upper part of the structure, but lighting and walking boards are not provided and some sections of the roof space are partly occupied by water tanks. The current tenants have occupied the building only since 2012 and are looking for funds to carry out the necessary maintenance and repair works.

The air temperature in January was 9°, with a relative humidity higher than 80%, even in the attic rooms. These values fall well out of the optimal range identified by Ridout (2000) and correspond to an equilibrium moisture content of about 17%, which is very high (Ross, 2010). Nevertheless, the measured moisture contents exceeded 18% in all measurement points except for one, and only 5 measurement points did not exceed 20% (Figure 247). The reasons are more than one: the attic rooms are not in use and so they remain unheated all year long; the sarking is broken in many areas allowing water ingress (Figure 248); the flashings probably have problems as well, since the masonry gables are wet, disintegrating into dust and falling on the timbers and ceiling underneath; some roof spaces are occupied by open-air water tanks (Figure 249). These problems have been identified in the thermographic images as well (Figure 250, Figure 251).

The recorded values of air relative humidity and wood moisture content are quite worrying also because they reduce the timbers' strength (Kasal and Lear, 2010). Considering that the timbers are quite slim and that they are carrying the additional load of the full water tanks it is surprising that no signs of distress or deformation have been found in the roof structure. There is active insect attack on a few rafters (Figure 252) and fungi attack was identified in a rafter foot (Figure 253), but no deflections, cracking or other types of failure have been identified. This does not rule out the possibility of a brittle failure, which is why it has been advised by a structural engineer to stop the surveys. This is why the assessment of Cockenzie's roof has been only partially completed.

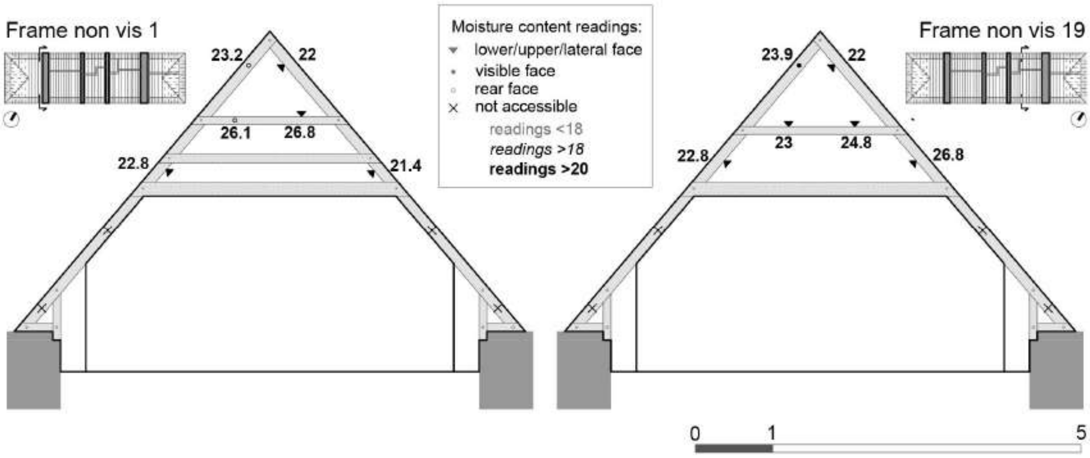


Figure 247: Moisture content readings in two frames of Cockenzie House

Figure 248: Broken sarking in the roof of Cockenzie House

Figure 249: Open-air water tanks in the roof of Cockenzie House

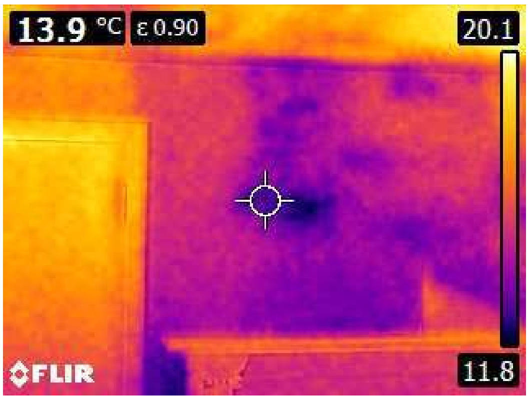


Figure 250: Thermal image showing humidity stains on the inner West gable of the attic of Cockenzie House

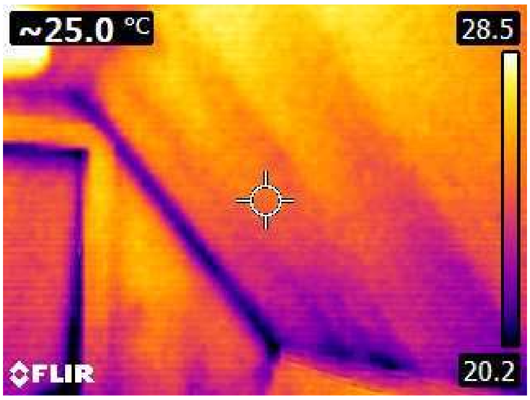


Figure 251: Thermal image showing lower temperatures in proximity of the flashings in the attic of Cockenzie House

Figure 252: Insect attack on a rafter in the roof of Cockenzie House

Figure 253: Fungi attack on a rafter foot in the roof of Cockenzie House

4.4 Holyrood Palace

4.4.1 Architecture and Construction

Holyrood Palace in Edinburgh was born as a monastery in the twelfth century. It became the Royal residence in sixteenth century, when James IV built a palace in the outer court of the Abbey, with a tower, a hall, a chapel and a gatehouse (Gifford, 1984a). What we see today is the result of the renovation works carried out by Sir William Bruce, Robert Mylne and Mr James Smith in 1670s (NRS GD29/94, 1679): they rebuilt the palace with a quadrangle form incorporating the sixteenth century tower to the North-West and mirroring it with another tower to the South-West (Figure 254). The West range is two storeys high and has a flat roof, whilst the other ranges are three storeys high and have hipped platform roofs (Figure 254). Continuous repairs and redecorations were carried out during the eighteenth and nineteenth centuries; in particular, Robert Reid rebuilt the South-West corner tower and refaced the entire South front in ashlar between 1824-34 (Gifford, 1984a).

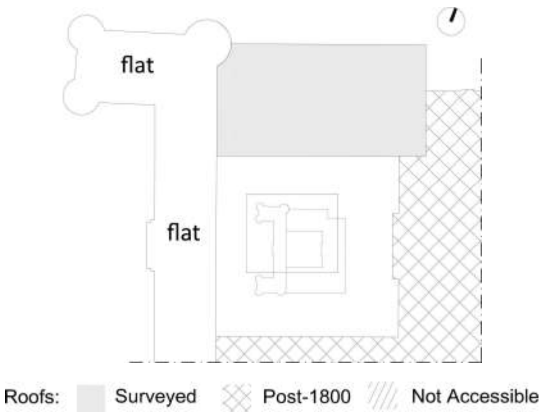


Figure 254: Holyrood Palace (mainly sixteenth century and 1671-9): plan (left) and view from West (right)

Amongst the non-flat roofs of the Palace, the North range is the only one retaining the original seventeenth-century structure. The arrangements and details of the roof structures of the other ranges, as well as various archival references, suggest a later date. Some damage caused by water ingress or fire is in fact recorded in letters of the Duke of Hamilton (Crae, Undated) and accounts of Mr J. Smith (EUL LAII87/1A, 1684-7), and replacements/repairs of roofs are mentioned in many eighteenth/nineteenth century works, although the extent and location are not always clear (Crae, Undated, EUL LAII88/3, 1721-1805, Historic Environment Scotland website - Holyrood Palace, 2016).

On the other hand, there are no records of major works carried out on the North range roof structure after its construction in 1670s. It seems that repair works here were limited to the sarking and slates/lead, which seem in fact to be of later date. Thus we have surveyed only the roof above the North range: an initial survey was carried out on 8th September 2014 and detailed investigations on 12th February 2016, 2nd June 2016, 15th June 2016 and 28th June 2016 (accompanied by Erasmus trainee Giulia Spigarelli during the last three dates).

The North range has a hipped platform roof supported by an intermediate longitudinal wall (Figure 255). The complex frames are composed of horizontal beams spaced 40cm that span transversally and sit on this intermediate wall; at their ends they are joined with the rafters with mortice and tenon joints secured by wooden pegs. The ceiling of the attic rooms is suppoprted by lower horizontal beams that span from the intermediate wall to the rafters, to which they are joined with dovetail lapped joints secured with metal nails. The rafters and upper beams are covered with sarking boards to which slates (on the slope) and lead (on the platform) are secured with metal nails. Slanted struts spring from the lower beams to provide additional support to the roof ridges. The dressing of some of these struts suggests that they have been replaced at a later date. Other slanted struts are used at a lower level to mirror the angle produced by the rafters in the ceiling of the attic rooms. The struts are secured with lapped joints and metal nails. The overall span is 14.6m, but it is reduced by the intermediate wall to 8.2m, and the pitch is 54°.

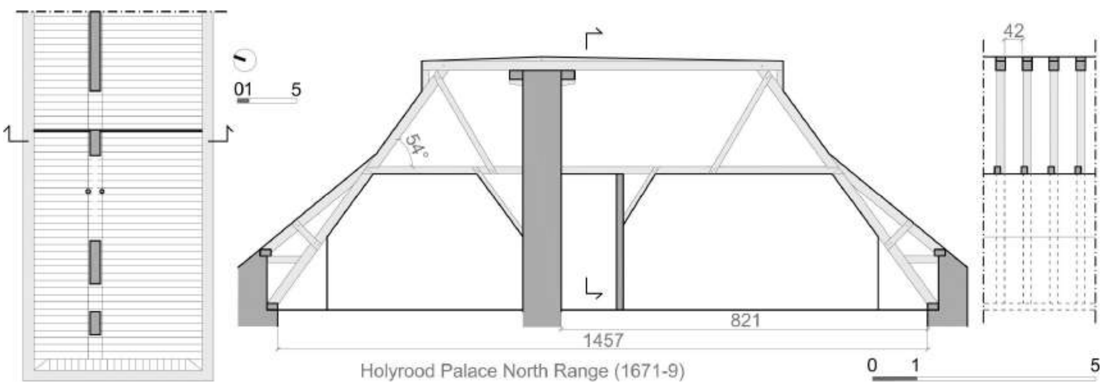


Figure 255: The roof of the North range of Holyrood Palace (1671-9)

Figure 256: The connection with the wall of the roof of the North range of Holyrood Palace seen from the roof space

Figure 257: Strengthening of the rafter ends and floor beams on the South side of the North range of Holyrood Palace

The rafter ends sit on a wall-plate and are protected by the wall-head which rises higher behind them and supports sprocket rafters (Figure 255, Figure 256). This arrangement is quite rare, as discussed in section 3.3.2.2. Some rafter ends on the South side have been partly replaced with prosthesis and strengthened with additional timbers bolted to their sides in order to be able to support the floor beams below (Figure 257).

All timber elements are hand axed whole logs (Figure 258). The sections are more rectangular and bigger than previous roofs (21x18cm - height x base), but they still retain some wane. The struts are smaller and more roughly dressed, with some bark on the corners. All frames are numbered with roughly sawn roman numerals occupying the whole section of the members (Figure 258 left), going from IIII (West) to XXXXX (East). This suggests that four other frames were previsouly in place on the Western side, but no evidence of alterations has been found. The rafters, upper beams, struts and sarking have been identified as *pinus sylvestris*, the pegs securing the joints between rafters and upper beams as *quercus sp*. The use of oak for the pegs highlights the high status of the building as in all other surveyed roof structures of this period pegs have been found to be of pinus sylvestris.

Figure 258: The roof of the North range of Holyrood Palace: the dressing and carpentry marks on two rafters (left), the joint between rafter and upper beam (centre), unusual carpentry marks on a rafter (right)

The dating of the North range roof structure to late seventeenth century is endorsed by the comparison with the roof structures of Kinross House (1679-93) and Melville House (1697-1703), which are very similar to Holyrood's in terms of both overall arrangements and details. The three structures are innovative because they employ tension absorbing joints (dovetail joints) and elements (struts, collars), as discussed in section 0.

The timber used for the renovation works in 1670s/80s was brought from Norway and Linlithgow Mill (NRS E36/30, 1671-1678, EUL LAII87/7, 1686). A few unusual carpentry marks found on site (Figure 258 centre and right) confirm this Scandinavian provenance. The work was carried out by wrights James Baine, Alexander Eizat and James Mcfarland, who also furnished part of the timber (NRS E36/30, 1671-1678, NRS GD29/100, 1678, NRS GD29/94, 1679, EUL LAII87/1A, 1684-7). Even though the roof structure is never mentioned it might have been designed by one of these three wrights, and being Baine the Royal Master Wright he is the number one candidate. James Mccleland and John Hamilton are mentioned too, but only during works in 1680s (EUL LAII87/6, 1684-6). A few timbers might have been reused from the previous roof, as suggested by an archival document (NLS MS14493/37, 1660) and redundant joints found on site (Figure 259).


Figure 259: Redundant joints in purlin on West side of the roof of the North range of Holyrood Palace

4.4.2 Current Condition

Holyrood Palace is property of the Crown but is in care of Historic Environment Scotland since 2000, thus inspections and maintenance works are carried out every 5 years in the roof. The roof structure of the North range is reasonably accessible and visible in all its parts. The lower part of the structure is plastered and occupied by attic rooms, but there are hatches at regular intervals.

The air temperature measured in the roof space varied from an average of 11° in February to an average of 19.5° in June, but the air relative humidity was always lower than 65% (average of 55% in February and of 54% in June). These values fall into the optimal range identified by Ridout (2000) and correspond to an equilibrium moisture content of about 9% in February and of 10% in June, when the moisture content readings were taken (Ross, 2010). Most of the measured moisture contents were quite higher, but only 6 out of a 119 were higher than 18% and only one was higher than 20%. In none of these points the micro-drill test has highlighted extensive material degradation, but traces of active insect attack have been found in other areas, suggesting that climatic conditions should be monitored regularly.

Most of the identified traces of insect and fungi attack are old and inactive; the roof has been treated in 1960s with insecticides (Figure 260) (personal comment of HES technician John Crae). However, traces of new bore dust in some areas suggest an active attack that should be monitored (Figure 261). In particular, the pegs securing many joints between rafters and upper beams are seriously degraded; some of them have almost disappeared. This can cause the disconnection and slip of these joints, which has already happened in some frames (Figure 262). Different kinds of fungi attack have been identified too, although the type and status (active or not) could not be identified (Figure 263).

Figure 260: Old insect attack treated with insecticides on a purlin of the roof of the North range of Holyrood Palace

Figure 261: New bore dust suggesting active attack on a strut of the roof of the North range of Holyrood Palace

Figure 262: A degraded peg causing the disconnection and slip of a joint between rafter and upper beam of the roof of the North range of Holyrood Palace

Figure 263: Fungi attack - status and type not identified - on a beam of the roof of the North range of Holyrood Palace

The timbers are of variable quality, ranging from Strength Class I to lower than Strength Class III. The latter are all struts whose main problem are deep drying fissures on both sides, which reduce the height of the resisting section. Nevertheless these elements are mainly charged in compression as their role is to counteract the natural tendency of the joint between rafter and upper beam to fall inwards, thus the effect of defects on their performance is limited (Cruz et al., 2015). It is interesting to note that the worst quality timbers have been used for compression purposes. Other elements fall into Strength Class III or II because of the deviated slope of grain or big knots, but most of these defects are not located in critical areas.

The micro-drill test has identified external and internal section loss in many elements, in particular struts, but also rafters and upper beams. Most of it is limited (>2cm total depth), but in a few cases it is extensive (Figure 264, Figure 265). This does not seem to have caused serious problems so far, probably due to the redundancy of the structure.

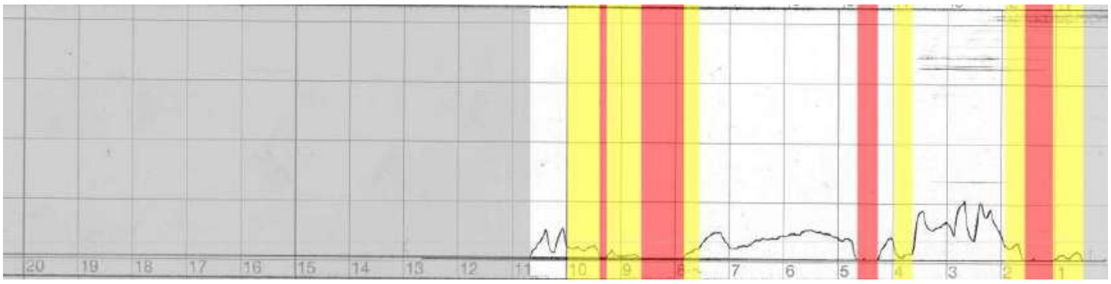


Figure 264: Micro-drill graph of point a in the North strut of frame 42 of the roof of the North range of Holyrood Palace identifying external and internal section loss

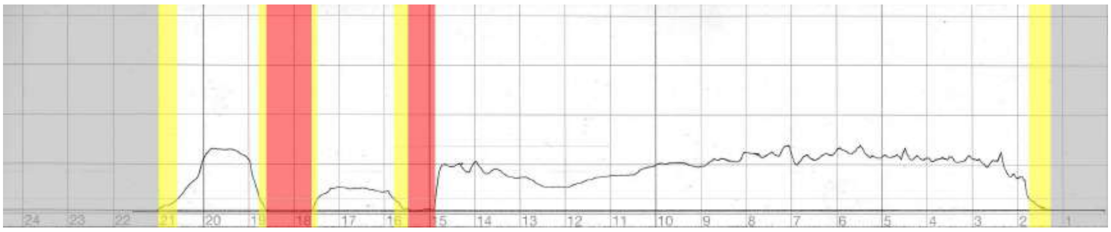


Figure 265: Micro-drill graph of point b in the South upper beam of frame 19 of the roof of the North range of Holyrood Palace identifying external and internal section loss

4.5 Newhailes House

4.5.1 Architecture and Construction

Newhailes House, previously called Broughton and Whitehill, is a 4-storeys oblong country house in Inveresk (East Lothian), whose architectural history has been recently unveiled by Rock (2016) (Figure 266). Rock affirms that James Smith did not build the house in 1686, as previously thought, but only after 1702, probably incorporating the ruins of a Chapel or previous manor house in the lower part of the North-West wing. The South-East wing, where the library is, was added in 1720 and the North-West wing, where the state apartments are, in 1733-51.

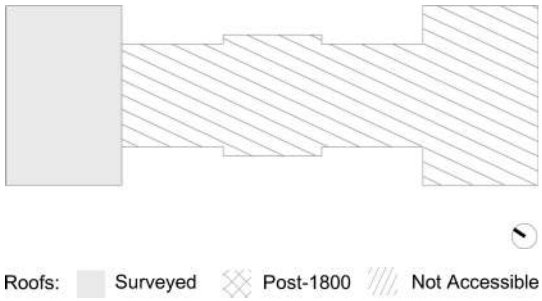


Figure 266: Newhailes House (1702-51): plan (left) and view from South-West (right)

The roof of the North-West wing is the only accessible one (Figure 266). We carried out an initial survey on 18th September 2014 and detailed investigations on 3rd June 2016 (accompanied by Erasmus trainee Giulia Spigarelli).

It is a particularly interesting roof as it is not similar to any other roof we have surveyed. It is a platform hipped roof supported by 8 complex frames, spaced about 1/1.3m one from the other (Figure 267). Each frame is composed of two rafters, an upper beam, a collar, a central post and two pairs of struts, crossing each other: two struts connect the rafter to the upper beam and two struts connect the upper beam to the collar. There is no tie-beam, to leave space for the partially vaulted ceiling underneath. The frames support common rafters, small purlins and the sarking, to which lead (on the platform) and slates (on the slopes) are secured with metal nails. The total span is 8.3m, reduced on the Southern side by an intermediate wall, and the pitch is 43°. The connection with the wall is not clearly visible but it seems that the rafters simply sit on a wall-plate (Figure 267).

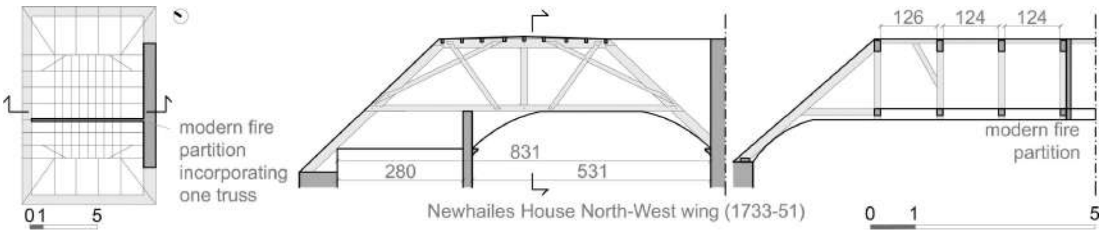


Figure 267: The roof of the North-West wing of Newhailes House (1733-51)

These complex frames could be regarded as the first Scottish trusses. They work in reverse if compared to normal king-post trusses: the struts that link the collar to the upper beam work in tension, pulling up the centre of the collar and allowing the post to work in compression, pushing up the centre of the upper beam. The struts that link the upper beam and the rafters help to counteract the opening of the rafters and to reinforce the joint between rafters and upper beams. The joints are designed according to the forces they have to counteract: dovetail lap joints for the struts and collar (secured with metal nails) (Figure 268 left), working in tension, and mortice and tenon joints for the post (secured with timber dowels and wedges), working in compression. The mortice and tenon joint at the top of the rafters is notched to prevent them from slipping downwards. The notched lapped cross joint between the struts is the only one we have found in Scotland.

The timber elements have varying scantlings and different dressing: the struts and posts are quarters of a log, with two hand axed faces and two hand sawn faces (Figure 268 centre); the rafters and horizontal beams are instead half logs, with 3 faces hand axed and one face hand sawn. The sections are all rectangular, with no wanes. The upper beams have a varying scantling, bigger in the central part, providing a slope for the disposal of rainwater. The frames are numbered with roughly sawn roman numerals occupying the whole section of the members, from I to VIII, although not in sequence (Figure 268 right).

The rafters, upper beams, struts and sarking are made of *pinus sylvestris*, one post is *picea abies* and a peg securing the joint between the post and the upper beam and collar is *quercus sp*. This is the only example of use of *picea abies* we have found in a Scottish roof. Spruce is in fact considered to be less strong than pine and was usually used for interiors rather than structural purposes. It is interesting to note though that it has been used here for an element working in compression that is not highly stressed. The use of oak for the pegs is unusual for eighteenth century roofs and shows an awareness of oak's durability compared to pine. It also suggests that the works had a good budget allowing to retrieve the required materials since oak was more difficult to source at that time.

Figure 268: The roof of the North-West wing of Newhailes House: a dovetail lap joint between struts and upper beam (left), the dressing of a strut (centre), carpentry mark on a post (right)

The timbers have been found to be generally of very good quality, belonging to Strength Class I or II, with only one strut belonging to Class III because of a very big knot. Thus it seems that not only the species were carefully chosen for this roof but the quality of the timbers as well. Whoever designed this roof structure had a good knowledge about timber species and structural behaviour.

Unfortunately there is no record of who was in charge of the timber works of the North-West wing. The wright John Young could be a good guess since he is mentioned in the accounts starting from 1710 up to 1723 (Rock, 2016). Unfortunately we have not surveyed other roofs that are known to have been designed by John Young so we cannot confirm the attribution by comparison.

4.5.2 Current Condition

Newhailes House is property of the National Trust for Scotland since 1997, thus inspections and maintenance works are carried out every five years. The roof space of the North-West wing is easily accessible from a door in the attic rooms; nevertheless, the timber structure is only partly visible, as the rafters and their connection with the lateral walls are partly hidden by remains of plaster (the roof space was probably part of the attic rooms originally), the collars are partly hidden under floor boards. The roof structures of the rest of the house are instead completely invisible as there are no hatches giving access to any of them. This impedes necessary inspection and maintenance works.

The air temperature was 19° in June and the relative humidity 55%. These values fall within the optimal ranges identifed by Ridout (2000) and correspond to an equilibrium moisture content of about 10% (Ross, 2010). The measured moisture contents were around 14/15%, but none exceeded 18%. There are in fact no signs of biotic attack or water ingress. The ventilation is however quite poor; one of the causes might be the recent replacement of some of the sarking with floor-boards (Figure 269). Recent works include also the replacement of some of the purlins, the insertion of a fire partition and floor-boards for inspections.

The structure shows no signs of distress or deformation either. The joints of the struts are slightly open (1 cm maximum) but this simply proves that they are working in tension (Figure 270). The posts, upper beams and collars are slightly rotated, but this is because the joints of the struts are all on the same side. The lower part of the rafters might have some problems since it is highly stressed and left unsupported, but unfortunately it is not visible.

Figure 269: Recently replaced purlins and sarking boards in the roof of the North-West wing of Newhailes House

Figure 270: Cross joint between struts with an opening of 1cm in the roof of the North-West wing of Newhailes House

4.6 Pinkie House

4.6.1 Architecture and Construction

Pinkie House is an L plan mansion in Musselburgh (East Lothian). It incorporates a late sixteenth century tower house and an earlier fortalice on the North side (McWilliam, 1978). Alexander Seton, Earl of Dumferline, renovated and extended the house in 1613: he added a pair of square pepperpots at the North end of the existing tower house and raised the projecting jamb 2 storeys higher; he also built a 3 storeys long wing to the South (Figure 271 right), decorated with a beautiful painted timber ceiling at the top floor (Figure 75 right). A West wing was added at the end of seventeenth century and extended around 1800 (Figure 271). The other buildings are of later date.

We have surveyed the roof above the old tower house to the North (3 in Figure 271), the roof above the long gallery (1 in Figure 271) and a small roof on the West side of the gallery (2 in Figure 271). These roofs have been accessed for an initial survey on 9th October 2014 (accompanied by PhD student Clara Gonzalez Manich). Detailed investigations have been carried out in the roof above the long gallery on 9th March 2016 (accompanied by PhD student Clara Gonzalez Manich), 31st March 2016 (accompanied by PhD student Bowen Qiu and professor A. Macdonald) and 2nd May 2016.

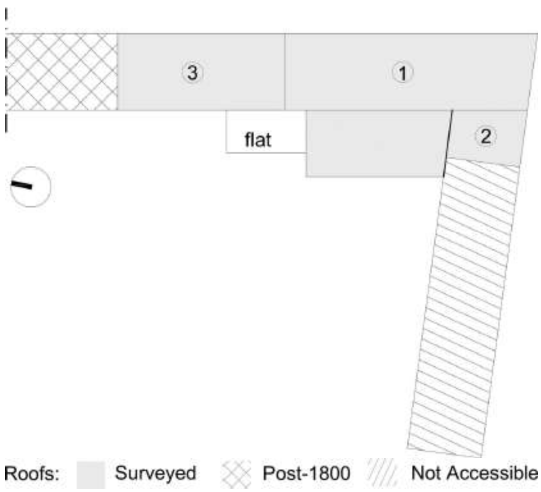


Figure 271: Pinkie House (mainly sixteenth century and 1613): plan (left) and view from East (right)

Unfortunately, as far as we know, no archival document related to the construction works carried out in 1613 remains; only the name of the patron is certain, Alexander Seton, while the design has been attributed to Sir James Murray (MacKechnie, 1994). The structural arrangement and construction details of the roof structures suggest a dating contemporary to the buildings themselves, the only exception being the small roof to the West of the long gallery (McWilliam, 1978): this roof is certainly contemporary to the one above the gallery since the arrangement and construction details are exactly the same (see form in Appendix F). This contradicts previous statements related to the dating of the West wing: its eastern section is of early seventeenth-century date rather than late seventeenth-century.

The roof above the long gallery is a double pitch roof sandwiched between two gable walls and supported by 50 frames (Figure 272). The frames are composed of rafter couples spaced 35cm, connected trasversally by three collars (the intermediate one is a later addition, as discussed below) and longitudinally by sarking boards. The lower collars support the original painted timber ceiling. The span in not eccessive (6m) but the pitch is quite steep (52°).

The connection with the wall is only partly visible, as it is mostly hidden by the ceiling and the insulation sheets. In an area on the South-West side the rafters simply sit on the wall-head (Figure 273 left). On the East side the space in between the rafters seems to be infilled with rubble masonry up to the start of the timber ceiling; this is confirmed by thermographic images which do not show any differences in temperature below the ceiling (Figure 273 right). In correspondance of windows and chimney stacks the rafter ends are supported by butt-purlins morticed in the rafters.

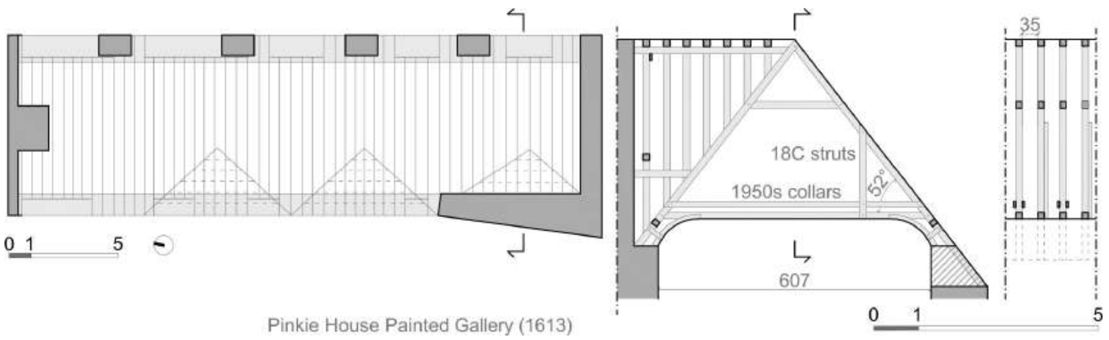


Figure 272: The roof of the long gallery at Pinkie House (1613)

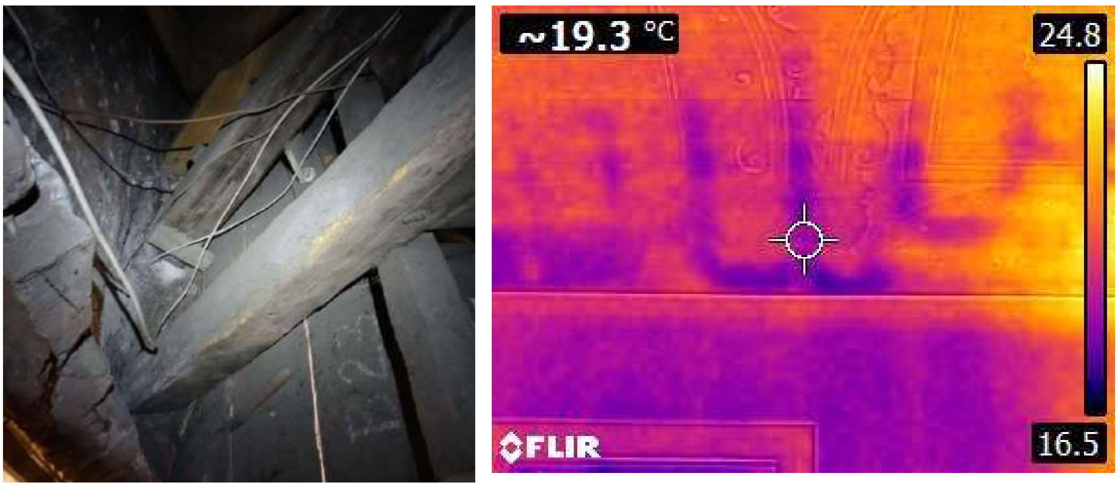


Figure 273: The roof of the long gallery at Pinkie House: the connection with the wall on the West side, with the rafters simply sitting on the wall-head (left), a thermographic image of the wall-head and ceiling on the East side, taken from the gallery below (right)

The timber elements are all whole logs roughly axed to a square section, leaving significant wanes and often some bark on the corners (Figure 274). The sections are quite variable but the height almost never exceeds 15cm and the base 14cm. All joints are mortice and tenon secured with timber pegs, used also to secure the slates to the sarking (Figure 274). The timbers are numbered with roughly sawn roman numerals occupying the whole section of the members (Figure 274). Similar arrangements and details can be found in contemporary roofs such as the one in Craigston Castle (1604) or Culross Palace (1597-1610).

The timber species has been microscopically identified as *pinus sylvestris* for rafters, collars and sarking, and *quercus sp*. for the pegs used for both the joints and the sarking. No unusual carpentry marks have been found. The quality of the timbers is variable, ranging from Strength Class I to lower than Class III. However, the lower class timbers are not many and even though one fourth of the rafters has defects in the central section, the most stressed, most of them are in class I or II.

Figure 274: The roof of the long gallery at Pinkie House: the dressing of the rafters (left), the oak pegs securing the slates to the sarking (centre left), carpentry marks on collars (centre right), mortice and tenon joint between rafter and collar secured with a timber peg (right)

Despite the good quality of the timber, the roof has been strengthened more than once. Some minor works are reported in eighteenth century, but not specified (NLS MS14716, 1768-78). Part of these works might have been the addition of vertical struts connecting the rafters and the lower collars on the East side. Judging from the dressing (sawn rather than axed), the scantling (more rectangular) and the metal nails (rather than wooden pegs) used to join these struts to rafters and collars, they are not part of the original construction. They were probably inserted to provide additional support to the lower collars, burdened by the weight of the timber ceiling underneath.

A report by HES technical officer WR Adams written in May 1954 (HES report by Adams, 1954), together with a drawing by Lorimer (Figure 275), describe and show the strengthening intervention carried out in 1950s to counteract the opening of the roof structure and the consequent cracking of the ceiling underneath. The problem had probably arisen because of the heating started in 1950s, when it became a private school. The structural strengthening intervention is still visible today and consists of two collar beams added on the two sides of the rafters of one frame every two (Figure 276). The collars are positioned above the original ones that still support the ceiling, thus the former only restrain the opening of the rafters and provide a support for a catwalk for inspections. In addition, some rafters have been reinforced in their lower end with additional timber elements bolted on their sides.

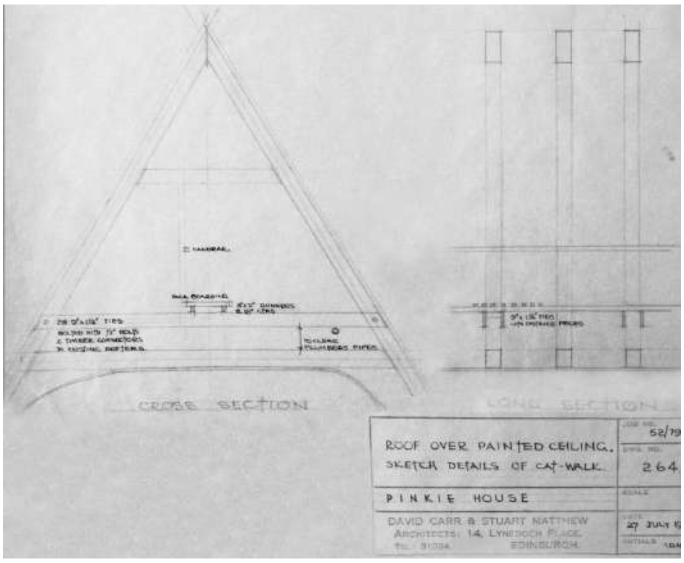


Figure 275: Drawing showing the strengthening intervention carried out in 1950s in the roof of the long gallery at Pinkie House (RCAHMS LOR/M/17/5, 1953)

Figure 276: Struts probably added in eighteenth century and double collars added in 1950s in the roof of the long gallery at Pinkie House

4.6.2 Current Condition

The building is property of Loretto School since 1950s and has a regular inspection regime in place, although a program of works has not been implemented yet. The roof structure of the long gallery is easily accessible and provided with a catwalk and lighting. The only part of the structure that is difficult to assess is the connection with the lateral walls, due to visibility issues discussed above.

The roof space seems to be well ventilated, thanks to the fact that nothing lies in between the sarking and the slates on the East side (the West side has been resarked with the addition of modern waterproof sheets), allowing air to pass in the 1-2cm gap between the sarking boards. In March the air temperature was 15° and the air relative humidity 50%, falling into the optimal range identified by Ridout (2000) and corresponding to an equilibrium moisture content of about 9.5% (Ross, 2010). All measured moisture contents were quite higher, but out of a total of 61 measurements only 17 exceeded 18% and only 1 exceeded 20%. Even though most timbers show diffuse insect exit holes, no fresh bore dust was found. The high moisture contents are evidently due to age (Ridout, 2000).

Some rafters and collars seem to have been treated against insect attacks, and portions of the timber sections have been removed. A letter dated July 1973 (Rentokil, 1973) held by HES details proposed chemical insecticidal treatment of the main roof space and provision of a thermal kilt by Rentokil (Ratsouris Scotland Ltd). It seems that this has been carried out and has been effective.

Since Pinkie's was the first roof where the ultrasonic and micro-drill tests were used some reference measurements were taken on reference frame I, even where the moisture content recorded was low. The micro-drill confirmed that the reduction of the resisting section caused by past biotic attack is in most cases concentrated in the sapwood and very limited (>1cm total depth). In one point only internal damage was identified (Figure 277) - probably a shake - and in one only extensive (>4cm total depth) external damage (Figure 278).

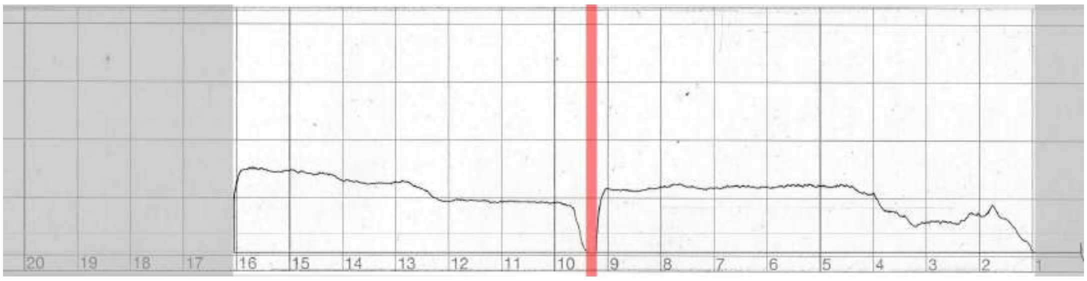


Figure 277: Micro-drill graph of measurement point 10 on frame I of the long gallery roof at Pinkie House

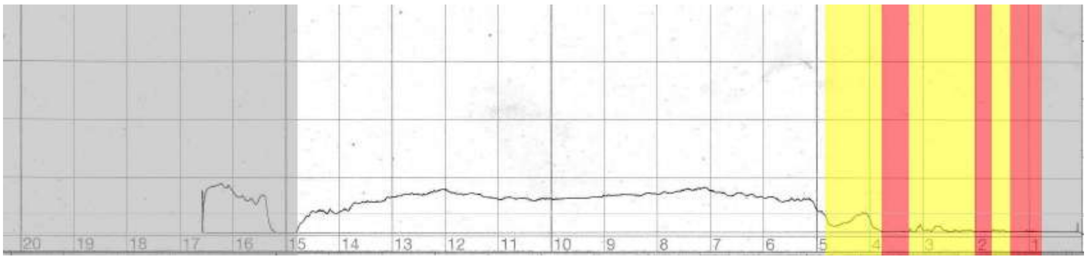


Figure 278: Micro-drill graph of measurement point 1 on frame XVII of the long gallery roof at Pinkie House

On the other hand more than half of the pegs securing the mortice and tenon joints between the rafters and the upper collars are deteriorated, some have almost disappeared (Figure 279). This has not created problems in the upper collar (charged in compression mainly), but it has created problems in the lower collars (charged in tension and bending): more than half of the visible joints have opened, and some of these failures are attributable to broken pegs (Figure 280). Other joints have failed because the part of the rafter covering the peg was too thin (Figure 281). These failed joints are probably the reason why in 1950s additional collars have been added. The strengthening intervention probably solved the problem as the ceiling has not been cracking since then.

A preliminary structural analysis based on all this information has been carried out by Professor Angus Macdonald (Macdonald, unpublished), who has concluded that the connection between the rafters and the lateral walls is the most critical point of the roof structure. The roof structure has in fact been found to be adequate for all conditions of support, but the factor of safety against strength failure has been found to be minimal if the connection at the wall-head is incapable of producing a significant horizontal reaction. Judging from what is visible from the roof space, the rafters simply sit on the wall-head and the space in between them is in-filled with rubble masonry. As suggested by professor Macdonald, although this arrangement is quite minimal, it is reasonable to assume that it develops a significant horizontal reaction since the overall condition of the roof structure is good. Moreover, the structural analysis has highlighted that the integrity of the joint between the lower collars and the rafters is critical to the overall structural functioning of the roof if no horizontal reaction is present at the wall-head. The fact that some of the connections have failed without causing significant distress to the overall roof is a further indication that the connection at the wall-head is providing a significant horizontal reaction.

Figure 279: A degraded peg in a mortice and tenon joint between rafter and upper collar in the roof of the long gallery at Pinkie House

Figure 280: A failed joint between rafter and lower collar with an opening of 8cm in the roof of the long gallery at Pinkie House; the peg is broken

Figure 281: A failed joint between rafter and lower collar with an opening of 4cm in the roof of the long gallery at Pinkie House; the rafter is broken

4.7 Stirling Castle

4.7.1 Architecture and Construction

The history of Stirling Castle dates back to at least the twelfth century (Gifford, 2002). However, the oldest surviving building inside the Castle is the fourteenth century North gate, followed by the sixteenth century Great Hall (1503), Palace (1530-55), King's Old Buidlings (1557) and Chapel Royal (1594). The remaining buildings and defences are of eighteenth- and nineteenth-century date. The West range of the palace was rebuilt in early seventeenth century, after part of it had collapsed, and the North and East wings of the King's Old Buidlings were rebuilt after a fire in 1855. However, besides these alterations, these buildings remain largely original. On the contrary, the Great Hall was greatly mutilated when converted into military barracks in the eighteenth century; the roof was lost and recently reconstructed. The Chapel Royal was also reroofed in nineteenth century; therefore we focused our surveys in the King's Old Buildings (Figure 282), Palace (Figure 283) and eighteenth century governor's house and regimental headquarters.

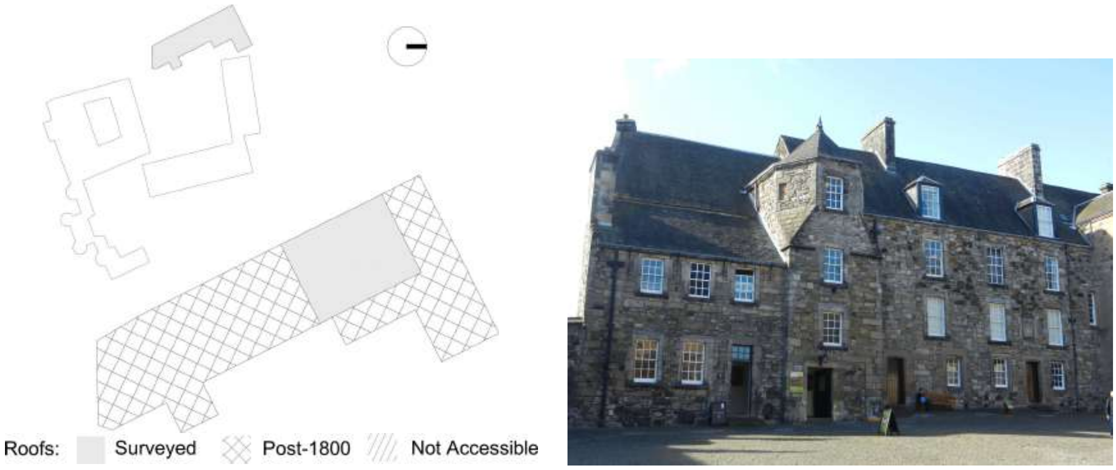


Figure 282: Stirling Castle King's Old Buildings (1557): plan (left) and view from East (right)

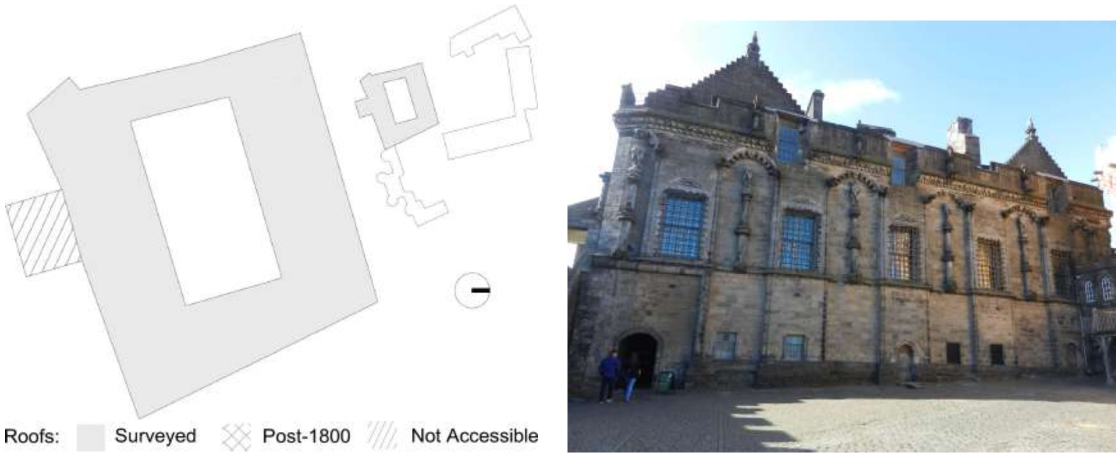


Figure 283: Stirling Castle Palace (1530-55): plan (left) and view from West (right)

We carried out an initial survey on 1st October 2014 and detailed investigations on 10th February, 7th April, 29th April (accompanied by PhD student Bowen Qiu), 20th May and 16th June 2016 (accompanied by Erasmus trainee Giulia Spigarelli on the last two dates). During the initial survey we found out that the governor's house and regimental headquarters have probably been reroofed at a later date, judging from the timber dressing and joints, therefore we have not proceeded with the measured survey in these buildings. The detailed investigations have been carried out in some roofs of the Palace and King's Old Buildings (Table 12). The measurements and tests have been carried out on 3 reference frames per roof and on additional critical elements identified during the visual inspection. The number of reference frames has been limited by constraints imposed by HES.

Table 12: Measurements and tests carried out in the roofs of Stirling Castle

STIRLING CASTLE	Timber Species Identif.	Air Temp. Humid.	Thermal camera - snake camera	Visual Strength Grading	Moisture Content Readings	Visual insp.	Rubber hammer	Ultrasonic test	Micro-drill
Palace North East Range	x	x	x	3 frames	3 frames & critical elements	all roof	3 frames & critical elements	45 points	45 points
Palace South West Range	x	x	x	3 frames	3 frames & critical elements	all roof	3 frames & critical elements	32 points	32 points
Palace North West Corner	x	x	x	all primary elements					
Palace West Range	x	x	x	3 frames					
King’s Old Buildings	x	x	x						

The roof structure we have surveyed in the King's Old Buildings is a double pitch roof sandwiched between two gable walls and supported by 18 frames (Figure 284). The frames are composed of rafter couples spaced 40cm, connected transversally by two collars and longitudinally by sarking boards. The lower collars support the ceiling of the attic rooms. The span in about 7m but the pitch is quite steep (53°). Unfortunately the connection with the wall is not visible.

The timber elements have almost square scantlings (15x12cm maximum), hand axed and hand sawn (Figure 285), with no wane. This refined dressing corresponds to the high status of the building: not many patrons could afford to hire sawyers before the eighteenth century, as discussed in section 3.2.3. The joints are all mortice and tenon secured by timber pegs (Figure 285). Big roughly sawn roman numerals occupy the whole section of the elements (Figure 285), although the numbers are not in sequence. The timber elements are all made of *quercus sp*.

The use of oak for the timber elements suggests an early date, since oak is very rarely used after 1600: we have not found it in any other seventeenth- or eighteenth-century roof (except for pegs in Pinkie House, Holyrood Palace, Newhailes House). The arrangement and details are also in line with the earliest Scottish roof structures we know of, such as the one in Alloa Tower (Ruddock, 1995) or in the late sixteenth-century North range at Pinkie House. Thus it seems reasonable to think that this is the original sixteenth century roof structure. One detail is interesting and has not been found in any other roof: the rafters are composed each of two elements joined together with a simple scarf joint secured with metal nails (Figure 285). This suggests that long oak timbers were not available at the moment of construction, which is in line with the scarcity of local and imported oak timbers that we know characterized Scotland from 1500 onwards (Newland, 2010). The use of metal nails is instead uncommon in such early roofs, as they were normally all made of timber, pegs included, but could be explained by the high shear stresses that these simple scarf joints had to endure.

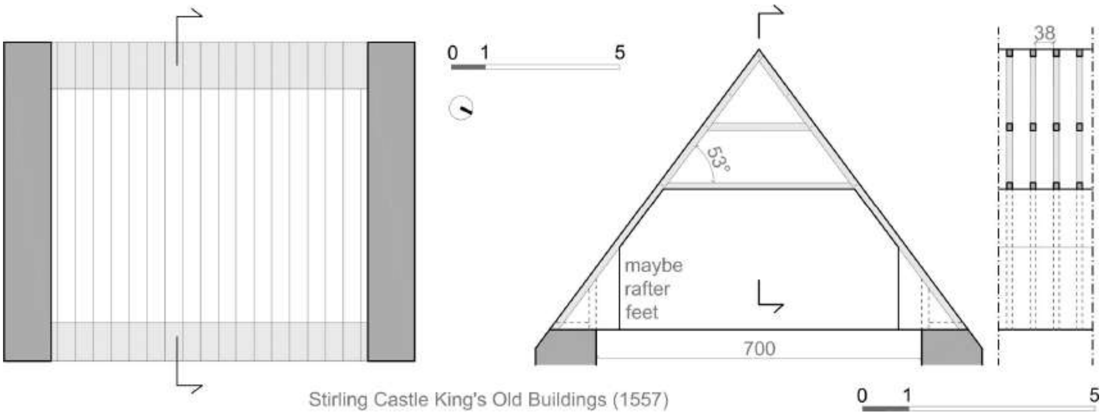


Figure 284: The roof of the King's Old Buildings (1557) at Stirling Castle

Figure 285: The roof of the King's Old Buildings: tool and carpentry marks on collars (left), mortice and tenon joint between rafter and upper collar (centre), scarf joints in rafters (right)

The Palace block, instead, clearly does not retain the original sixteenth century roof structure. The roof structures are all independent, sandwiched between two gable walls, except for the West range, which intersects both the purlin roof in the North-West corner and the common rafter roof in the South range. Although it is a composite roof, as it comprises common rafter roofs, complex frames and a purlin roof, the structures are quite homogeneous, suggesting that they belong to one single operation of re-roofing. Besides the purlin roof in the North-West corner, all the other roofs are composed of rafter couples spaced 40cm, connected trasversally by one or two collars and longitudinally by sarking boards (Figure 286). The spans range from 6.1m to 7.6m and the pitches from 43° to 47°. The rafters simply sit on the wall-heads (wall-plates have been identified only in the North-East range) and their lower ends are protected by sprocket rafters.

The timber elements are half logs, roughly squared with an axe and then sawn in half, with some wane. They have rectangular scantlings (18x8cm maximum). The collars are connected to the rafters with dovetail lap joints secured with metal nails (Figure 287 left); the rafters' apex is secured by simple lap joints with metal nails. Big roughly sawn roman numerals occupy the whole section of the elements (Figure 287 centre), although they are not in sequence. The timber was probably imported from Scandinavia or the Baltic area since many unusual marks have been found on site.

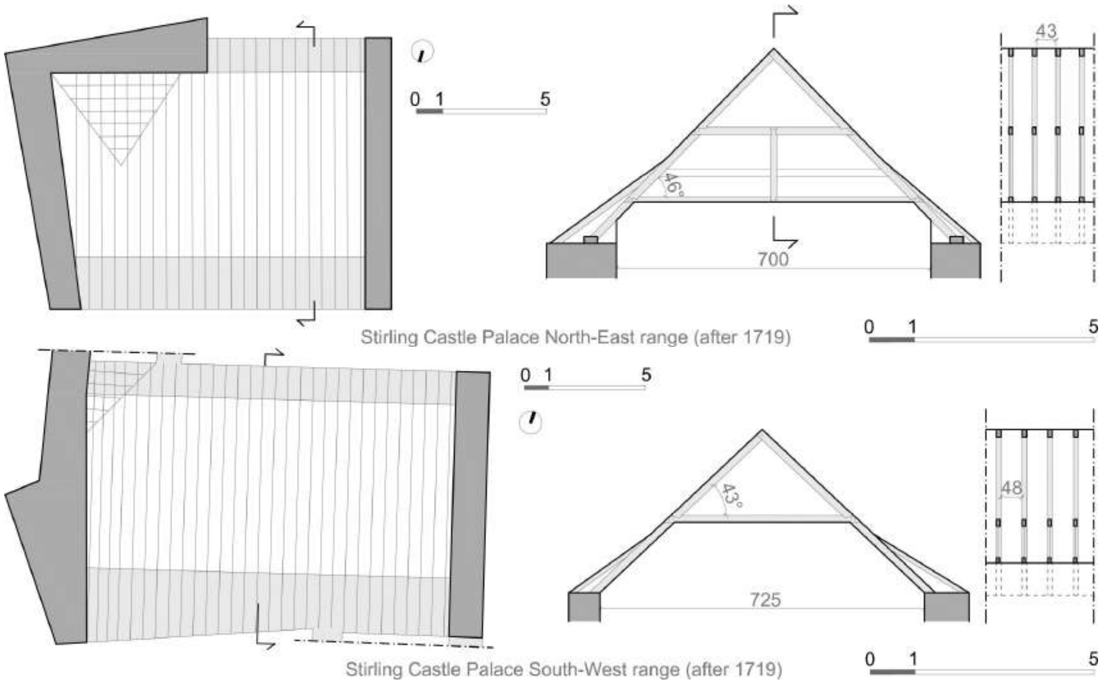


Figure 286: The roofs in the North-East (above) and South-West (below) ranges of Stirling Castle Palace (after 1719)

All the timber elements of the Palace roofs are made of *pinus sylvestris*, of variable quality, ranging from Strength Class I to lower than Strength Class III. Most of them are quite knotty, with shakes and a wavy grain (Figure 287 right). However, in most timbers these defects are not positioned in critical areas, which suggests that although high quality timber was not available or chosen for these roof structures, the wrights tried to use the timber they had in the best way possible.

Figure 287: The roofs of Stirling Castle Palace: dovetail lapped joint securing a collar to a rafter in the South-West range (left), carpentry marks on collars in the North-West range (centre), wavy grain and knots in a collar in the North-East range (right)

The timber species, dressing and details of the Palace roofs suggest a dating from 1700 onwards. The use of tension-absorbing elements (king-struts) in the North-East range (Figure 286 above) and the central part of the South range also suggest a late seventeenth- or eighteenth-century date, as discussed in section 3.2.1.2. The struts do not reach the rafters' apex and therefore fail in counteracting the collar's deflection; thus Hanke (2008) argues that they must predate the more mature king-post truss drawn by William ADam in 1721 (Figure 219). However, we have surveyed many eighteenth century roofs that refute Hanke's argument (section 3.2.1); moreover, the analysis of available archival documents suggests a different dating for the Palace roofs.

The archival documents record minor works carried out in 1671-87 (NRS E37/24, 1682, NRS GD29/92, 1671, EUL LAII87/1A, 1684-7), involving mainly re-sarking and pointing of the slates, and works carried out in 1699-1703, involving re-sarking, cutting of the rafter couples to insert windows and reinforcement of the rafters with additional timbers (NRS E37/33, 1699-1703). These reinforcement timbers are not visible today, suggesting that the existing roof structures are post-1703. Moreover, there are letters dated 1700-7 that report the efforts made to collect money to repair Stirling Castle (NRS GD124/15/216/2, 1701, NRS GD124/15/506/23, 1707, NRS GD124/15/567, 1707, NRS GD124/15/207/3, 1700) and a 1707 letter by J. Smith describing the 'dismail' condition in which the roofs of Stirling Castle are (NRS GD124/15/471, 1707). Finally, there is a survey by Thomas Moore dated 1719 which shows the roofs of the Palace with a different arrangement compared to what we see today (Figure 288). Considering that the roof of the King's Old Buildings in Moore's survey is instead very close to what we see today, it seems reasonable to think that the Palace roofs have been replaced after 1719. Unfortunately, as far as we know, there are no records of these works in the archives. Thus, it is only a hypothesis that the Royal Surveyor General J. Smith might be the responsible for the design of the new roof structures, considering that he had already employed tension-absorbing elements in both Melville House (1697-1703) and Yester House (1699-1715).

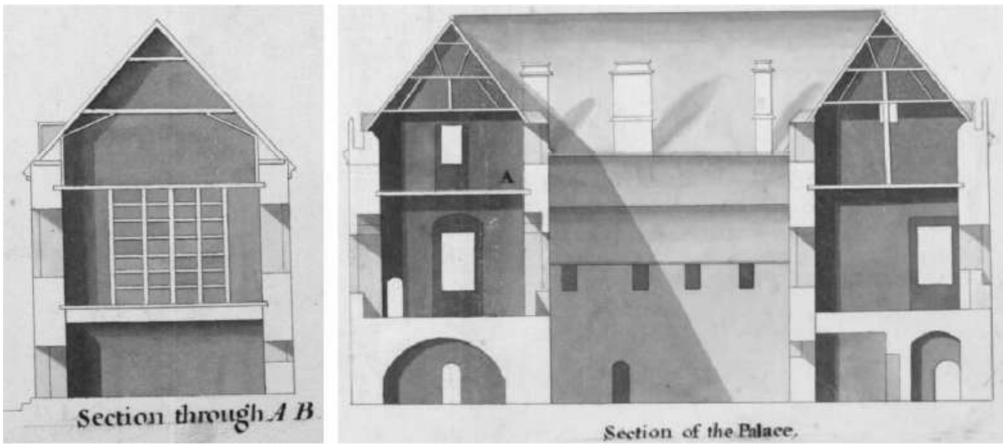


Figure 288: The roofs of Stirling Castle surveyed by Thomas Moore in 1719: the King's Old Building (NLS MS1646 Z.02/18b, 1719) and the Palace (NLS MS1646 Z.02/18b, 1719)

The North-West corner of the Palace is different from the rest of the quadrangle: it is covered with a purlin roof (Figure 289 left). The purlins are in oak and have redundant mortice and tenon joints with chase mortices (Figure 171), suggesting their reuse from another structure (perhaps the original roof). The common rafters are instead in pine and with similar scantlings and dressing to the rafters used in the other roofs of the Palace. This suggests a dating contemporary to the rest of the Palace roofs. The difference in type of structure can be explained by the fact that the longitudinal span covered in this corner is smaller than in the other ranges and therefore suitable for the use of four oak purlins that were readily available. The span is in fact reduced by a gable wall spanning North-South that is positioned only 3.7m East of the external gable. The East gable probably used to be the external one, as testified by a blocked mullion window (Figure 289 right).

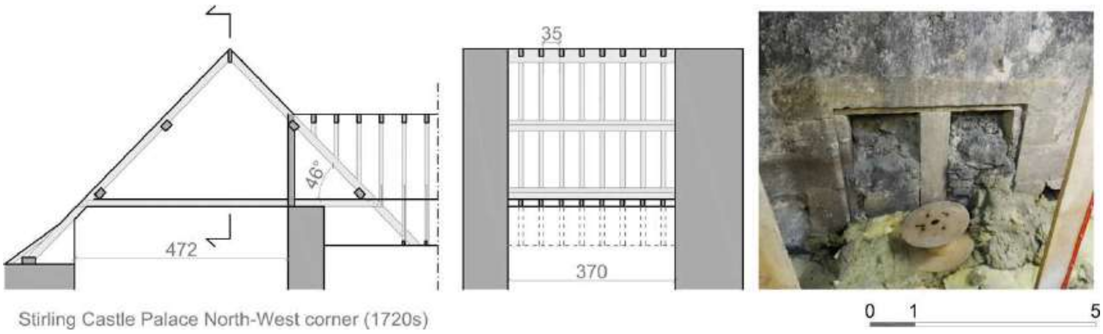


Figure 289: The roof of the North-West corner of Stirling Castle Palace (after 1719) with a picture of the blocked mullion window in the East gable

4.7.2 Current Condition

Stirling Castle is in care of Historic Environment Scotland. The roof spaces are easily accessible through hatches in the ceilings. The connection with the walls is however only partly visible and in the case of the King's Old Buildings completely invisible.

The air temperature measured in the roof spaces varied from an average of 12° in February to around 19° in June, but the air relative humidity was always lower than 67%. The West range of the Palace is the only one where the air temperature dropped to 10° in February with an air relative humidity of 73%. The West gable is in fact quite wet and the masonry is disintegrating to dust and falling on the timbers and ceiling underneath. The same is happening in the North-East range even though the values of air temperature and relative humidity were within the acceptable limits here.

The moisture content was measured in the North-East range in April (air temp. 17°, air humid. 61%) and in the South-West range in May (air temp. 18.3°, air humid. 53.7%). The corresponding equilibrium moisture content was of about 11% for the North-East range and 10% for the South-West range (Ross, 2010). All measured moisture contents were quite higher in the North-East range, whilst they were mostly near the equilibrium one in the South-West range. Only in 8 measurement points out of a total of 109 the hygrometer measured a moisture content higher than 18% and only in 3 points the moisture content was higher than 20%. Five of these points are on king-struts in the North-East range, the other three are on rafters in both ranges.

Traces of new bore dust suggesting an active insect attack have been found mainly in rafters in the North-East and West ranges (Figure 290Figure 291) and purlins in the North-West corner (Figure 27), where possible fungi attack has been identified as well (Figure 292). The South-West range showed instead traces of an old insect attack that had already been treated (Figure 293).

Figure 290: Insect attack on a rafter in the North-East range of Stirling Castle Palace

Figure 291: Insect attack on a purlin in the North-West corner of Stirling Castle Palace

Figure 292: Fungi attack on a purlin in the North-West corner of Stirling Castle Palace

Figure 293: Old insect attack on rafter in the South-East range of Stirling Castle Palace

The micro-drill test identified external and internal section loss in some rafters and collars. Most of it is limited (>2cm total depth), but in a few cases it is extensive (Figure 294, Figure 295). This does not seem to have caused serious problems so far, probably due to the redundancy of the structure. However, since traces of active attack have been identified, the condition of the structure should be closely monitored and the water ingress problems in the West range and the North-East range should be dealt with.

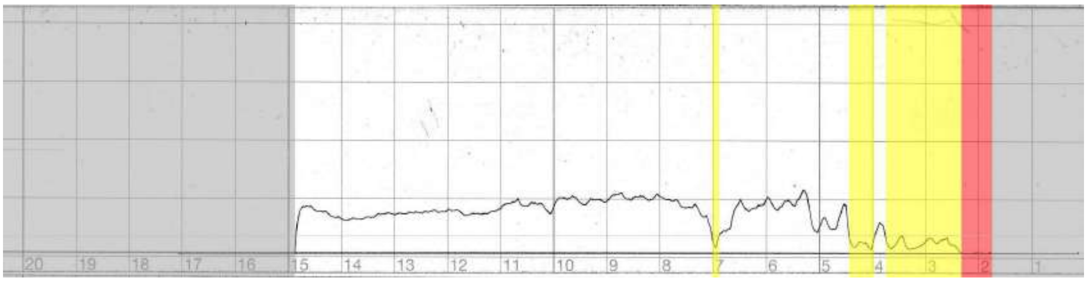


Figure 294: Micro-drill graph of point a' in the South rafter of frame 3 in the North-East range of Stirling Castle Palace identifying extensive external section loss and limited internal section loss

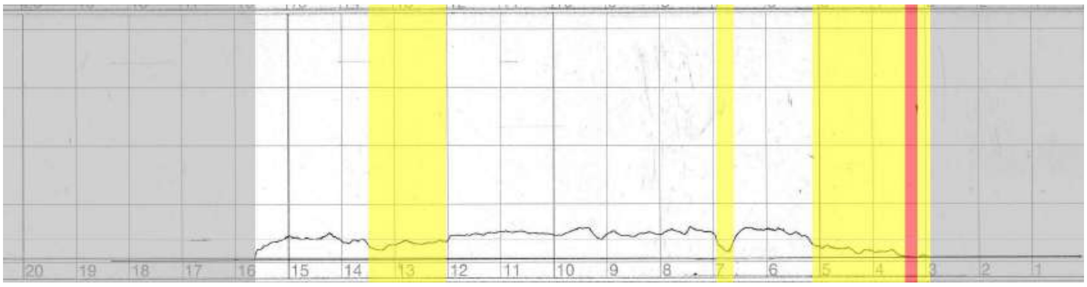


Figure 295: Micro-drill graph of point a' in the South rafter of frame 12 in the South-West range of Stirling Castle Palace identifying extensive external and internal section loss

4.8 Touch House

4.8.1 Architecture and Construction

Touch House is a country house near Stirling incorporating structures from different periods. Of the original sixteenth century building only the South-East tower and the lower portion of the North-West tower remain. The central block was replaced in 1757-62 (Gifford, 2002). The architect is not known but William Adam is often associated to this work; others hypothesize John Steinson (Gifford, 2002), not known for other works. The wright George Paterson is instead mentioned in two documents, one of 1751 (TCH letter to Mr Seton, 1751) and one of 1757 (TCH account by Paterson, 1757), where he is called 'Mr George Paterson' and buys timber for the commissioner, Hugh Seton. The fact that he is called 'Mr' suggests he had an important role in the works and that he might have been responsible even for the design of the central block. The range of offices to the North-East are instead of nineteenth-century date.

We have surveyed the roof structures of the central block (1 in Figure 296), of the North-West range (2 in Figure 296) and the roof in-between the two (3 in Figure 296). An initial assessment was carried out on 12th August 2015 and detailed investigations on 17th February 2016 in the central block and North-West range (accompanied by PhD student Clara Gonzalez Manich on both dates).

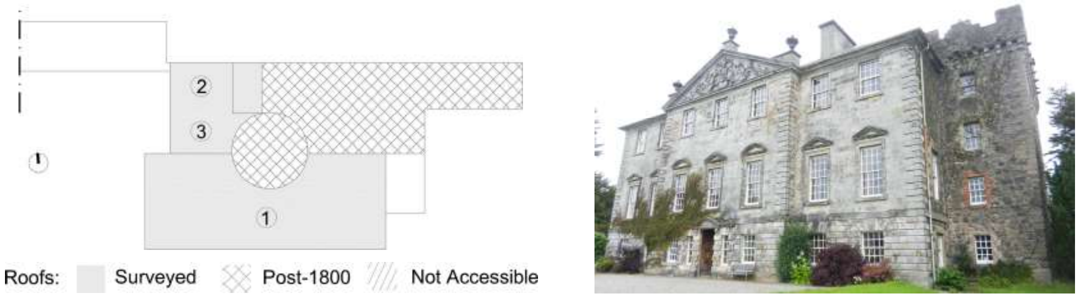


Figure 296: Touch House (sixteenth century and 1757-62): plan (left) and view from South-East (right)

The roof structure covering the central block is a composite structure supported by two transversal gable walls (Figure 297). The central part is covered with a purlin roof while complex frames are used on the sides. The purlin roof is supported by two purlins, one on each side, that span 8.1m from one gable wall to the other. The purlins are kept apart by two horizontal struts in the centre. Common rafters are tenoned into the purlins (with double tenons) and connected transversally by a lower collar that supports the roof of the attic rooms. Additional slanted struts connect the collar and the rafters. A thin ridge purlin sits between the rafters' apex and wall-plates are used at the rafter ends, protected by sprocket rafters. Sarking boards connect the common rafters and support slates, secured with metal nails. In 1930s Sir Robert Lorimer carried out some repair works (Gifford, 2002): he is probably responsible for the two steel beams that support the purlins in the central part.

On the sides of the central block the arrangement is the same but the main supporting elements are three primary rafters, two placed on the hips and one in the centre (Figure 297). Here the purlins are butt-purlins, tenoned into the primary rafters. The central primary rafter is supported by a slanted strut that springs from the gable wall. The span is 8.6m, the pitch is the same as the purlin roof (40°).

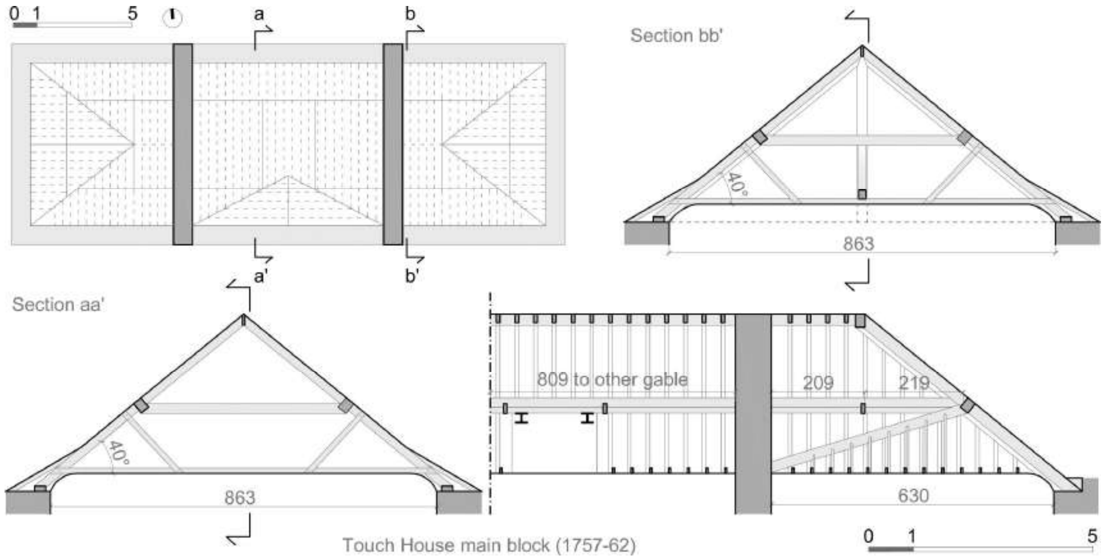


Figure 297: The roof of the central block of Touch House (1757-62)

The purlins and primary rafters are whole logs axed to a rectangular section, leaving no wanes. The purlins are 27x21cm maximum, the rafters 29x22cm. The struts and common rafters are instead half logs, axed and then sawn in two. The joints are all mortice and tenon secured with timber pegs, but the common rafters have double tenons (Figure 298 left), a feature that we have not found in other roofs. There are unusual carpentry marks on many timbers (Figure 298 right).

Figure 298: The roof of the central block of Touch House: double mortice and tenon joint securing a common rafter to a purlin (left) and unusual carprenty mark found on a common rafter (right)

The timber elements are made of *pinus sylvestris* of high quality, mostly belonging to Strength Class I or II, except for one short purlin affected by shakes. Judging from details such as dressing, scantlings, etc, the roof structure above the central block is the original eighteenth-century one, although the use of purlin roofs seems to have been limited in Scotland (section 3.3.1.4). George Paterson, the wright mentioned in Touch Hous's accounts, is known to have worked at Kinghorn Parish Church (Gifford, 1988) and Marlefield House (Cruft, 2005) as well, but unfortunately their roof structures have not been surveyed.

The archival documents held at Touch House tell us that high quality timber was brought from Norway (Copenhagen) and Russia (Riga) in the form of logs, deals, planks, of different measures (TCH account by Paterson, 1757, TCH account by Deas & Co, 1757-8), and that the logs were then cut on site for the specific uses (TCH letter to Mr Seton, 1751). The import of timber is also suggested by several unusual carpentry marks found on site. The Riga logs, known for their higher quality (Thomson, 1991), have probably been used for the primary structural elements, e.g. the purlins and principal rafters, which in fact have been found to be of very good quality.

The roof above the North-West range is a double pitch roof sandwiched between two gable walls and supported by 18 frames (Figure 299). The frames are composed of rafter couples spaced 35cm connected transversally by two collars and longitudinally by sarking boards, to which slates are secured with metal nails. The lower collars support the attic ceiling. The span is only 5m and the pitch is quite steep (49°). Some frames have vertical struts connecting the two collars, but their dressing (machine sawn) and jointing (simple lap with metal nails) suggest a recent dating. Unfortunately the connection with the lateral walls is not visible.

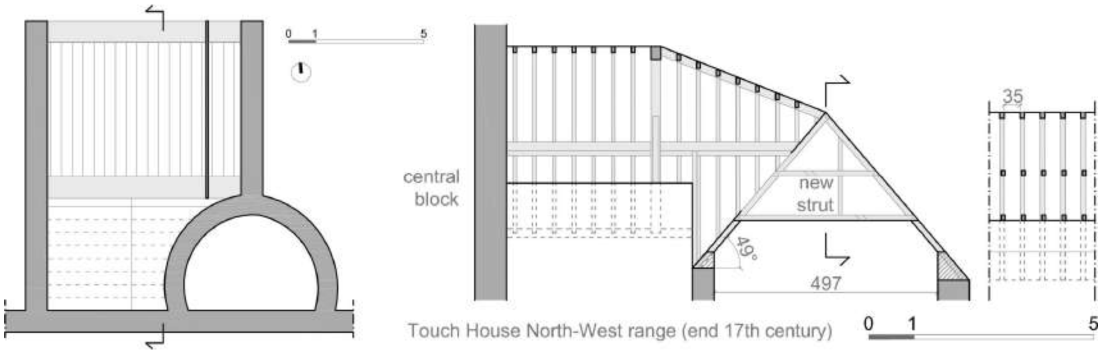


Figure 299: The roof of the North-West range of Touch House (end seventeenth century)

The timber elements are all half logs, axed and then sawn in two; however, some of them are more roughly dressed, leaving wanes and sometimes bark on the corners. The difference in dressing can be clearly seen in Figure 300. Some collars also have redundant joints, suggesting that they have been reused (Figure 302). The sections are quite variable but the height never exceeds 15cm and the base 13cm. The rafters' apex is secured by mortice and tenon joints with timber pegs, while collars are secured to the rafters with dovetail lapped joints with metal nails (Figure 300). In an area on the North side a butt-purlin, used to support the rafters in correspondance of a dormer, is reinforced by cleats (Figure 301). The timbers are numbered with big roughly sawn roman numerals, not in sequence (Figure 302); some unusual carpentry marks have been found too.

The timber elements are made of *pinus sylvestris* of variable quality, ranging from Strength Class I to lower than III. The low quality timbers have big knots or a deviated slope of grain, but none of them have defects in their critical section.

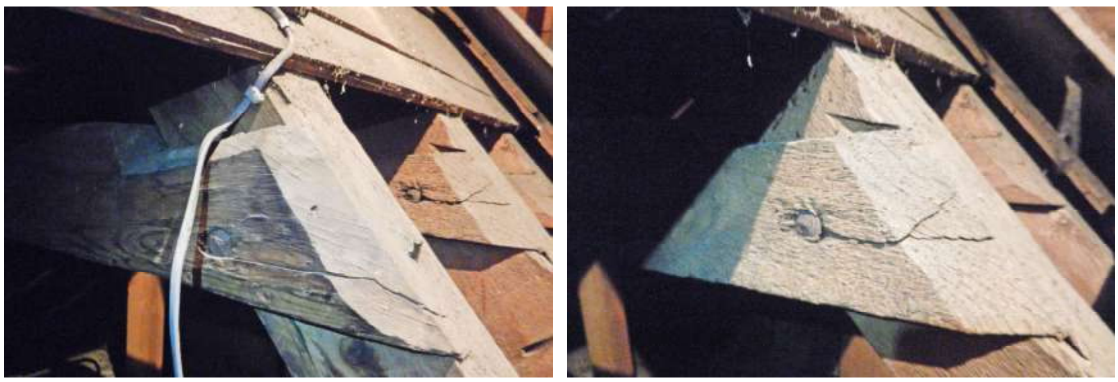


Figure 300: two collars with a different dressing in the roof of the North-West range of Touch House

Figure 301: A cleat reinforcing the joint between a rafter and a butt-purlin in the roof of the North-West range of Touch House

Figure 302: Carpentry marks and redundant joints on collars in the North-West range of Touch House; recently added struts are also visible

The North-West tower was rebuilt and extended to the East in seventeenth century (Gifford, 2002). This would be today's North-West range, whose roof structure does indeed resemble other late seventeenth-century Scottish roofs, such as Panmure House in Edinburgh (1690). This dating is also suggested by the timber dressing and the dovetail lap joints, first used in Holyrood Palace (1671).

There is an undated account of materials which could be related to these seventeenth-century works: it lists 458 yards of roofing and sarking for £117 (TCH account of materials, Undated). This does not seem sufficient to cover the whole North range but some of the timbers have redundant joints, thus they might have been reused from elsewhere or the previous roof. Other timbers have a more refined dressing that suggests an eighteenth century dating. They might have been replaced when the central block was completely replaced and linked to the North range, whose sarking is still visible on this side (Figure 303). This dating is corroborated also by a few strange marks found on the timbers on site, which might indicate their provenance from Scandinavia or Russia. Recent works have also included the replacement of the sarking on the North side, the reinforcement of some lower collars with additional timber elements and the introduction of vertical struts (Figure 304). These works might date to 1930s when the roof of the main block was strengthened by Sir Lorimer and the East side of the North range roof was replaced (RCAHMS LOR/T/1/5, 1928).

Figure 303: Remains of sarking on the North side of the roof of the North-West range of Touch House

Figure 304: Additional collars and struts reinforcing the roof of the North-West range of Touch House

4.8.2 Current Condition

Touch House is privately owned. The current owner has carried out some repair works, but the lack of funds prevents him from keeping a good inspection and maintenance regime in place. The roof of the main block is accessible through a hatch in the ceiling in the Eastern section. However, the Western section is only partly visible and not accessible. Moreover, there are some bats in the roof space. The roof of the North range can be accessed from a door in the attic rooms, but inspection is hindered by the lack of lights and walking boards.

The air temperature and relative humidity in February were around 10.5° and 68% respectively in both roof spaces. These values are not far from the optimal range identified by Ridout (2000) and correspond to an equilibrium moisture content of about 13% (Ross, 2010). The measured moisture content was a lot higher than the equilibrium one in many areas: it exceeded 18% in 32 measurement points in the North range roof and in 13 measurement points in the main block roof; it exceeded 20% in 16 measurement points in the North range roof and 7 measurement points in the main block roof. The highest moisture contents in the North range roof concentrated near the East gable, which is in fact visibly wet: the masonry is disintegrating to dust and falling on the timbers and ceiling underneath (Figure 305). There is probably a problem of water ingress; in some areas the sarking is in fact broken (Figure 306). Moreover, the ventilation is very poor.

Figure 305: The dampness disintegrating the East gable in the roof of the North range of Touch House

Figure 306: Broken sarking in the roof of the North-West range of Touch House

A few areas of the central block roof seem to be affected by biotic attack. The highest moisture contents in the main block concentrate near the gables and the roof-light, where the timbers are visibly wet, but also on the West side strut, which is affected by insect attack too (Figure 307). One purlin also shows signs of possible fungi attack near the gables (Figure 308). In fact, repair works have been carried out in in 2003 in the South-East corner where dry rot was found.

Figure 307: Insect attack on the West side strut of the roof of the central block of Touch House

Figure 308: Fungi attack on a purlin of the roof of the central block of Touch House, near a gable wall

4.9 Conclusions

The chapter describes in detail the historical and condition assessment of the eight case studies investigated, showing how different assessment methods and tools have been combined together to estimate the construction date and identify later interventions, as well as to give an initial evaluation of the structure's condition, identifying the need for urgent interventions and further monitoring. The eight case studies represent well the great variety of roof structures found amongst the 53 surveyed buildings. Despite having classified the roofs in just a few groups according to their structural typology, it is clear that each one has its own peculiar arrangement and details, and that their value also resides in their singularity. This singularity, however, complicates the assessment of these roofs. The available information for each roof is quite different, both in terms of accessibility/visibility and in terms of archival documents. Moreover, the same test can work in one roof but not in another one, which is why, although all tests have been carried out in each case study, not all test results, but only the useful ones, have been presented in this chapter.

5 The assessment of the condition of seventeenth- and eighteenth-century timber roof structures in Scotland

This chapter reviews current conservation practice of historic timber roof structures in Scotland and discusses the assessment of their present condition, with the aim to contribute in improving conservation practice. Current conservation practice is examined by looking at the approach of building owners/managers and professionals and discussing how they are affected by the lack of specific standards and training. Published and unpublished conservation projects, past interventions found during the surveys, existing available training as well as interviews to three conservation engineers, have been used to understand the approach of professionals, while questionnaires have been used to assess the approach of owners and managers. The present condition of Scottish roofs is then discussed based on the results from the preliminary surveys carried out in the 53 reference buildings and the in-depth investigations carried out in the 8 case studies. Typical pathologies and possible causes are identified for each structural typology. The assessment techniques used during the research are then evaluated and compared in terms of effectiveness, reliability, costs and training needed, in order to inform specific training for conservation professionals, which is proposed in the last section.

5.1 Current conservation practice of timber roof structures in Scotland

5.1.1 Standards, Regulations and policies

The availability of specific regulations and standards affects conservation practice because it ensures that professionals follow a standardized procedure during the assessment. Since there are no standards in UK related to the inspection and survey of in situ structures, Scottish professionals use Eurocode 5 (Eurocode 5, 2004) and British National Standards (BS ISO 13033, 2013, BS 5268-2, 2002), as suggested by the interviewed engineers (section 5.1.3). E5 and BNS provide rules on how to correctly design a new timber structure, but these are only partly applicable to in situ structures and even less to historical ones, because they do not consider the accessibility and visibility problems, the irregular geometries and arrangements, the difficulty and sometimes impossibility to determine the timber species and the mechanical properties. Some BNS give recommendations for the survey and measurement of decay and material degradation caused by fungi/insects (BS EN 1311, 1997), but the purpose is visual strength grading, not repair. There are standards for preservation treatments (BS EN 15228, 2009, BS 8417, 2014), but not for disinfestation. Even visual strength grading rules (BS 5756, 2011a, BS 5756, 2011b) do not take into consideration the difficult conditions of in situ timber, where elements are only partly accessible/visible. All test methods suggested to determine the mechanical properties are to be carried out on samples (BS ISO 13910, 2014, BS EN 408, 2012), which cannot always be taken from historic structures. In situ testing techniques are not mentioned.

Guidelines for recording Scottish historic buildings (Dallas, 2003) and designing interventions on them (Urquhart, 2007) are provided by Historic Environment Scotland (HES), the lead public body researching, taking care of and promoting Scotland's heritage. Unfortunately these guidelines do not include anything specific on timber roof structures. Only two INFORM guides, addressed to traditional building owners, are focused on rot and insect attack to timbers (Jenkins, 2008, 2016).

TRADA, the Timber Research and Development Association, provides more speficic publications on the assessment and repair of historic timbers (Slavid, 2011, TRADA, 2012, Williams, 2015), where visual inspection and non-destructive and semi-destructive testing, such as thermography and micro-drilling, are discussed. However, the topic is not extensively addressed and no standardized procedure is suggested. Moreover, only members of the association have access to these publications.

Protection policies are another important tool that greatly influences conservation practice. HES is responsible for making and maintaining lists of nationally important historic buildings and monuments. The lists include conservation areas and listed A, B or C buildings, to which different levels of protection correspond. Regrettably, most designations are based on surveys carried out decades ago that often do not include an appraisal of the interiors; roof structures, in particular, are very seldom mentioned. This clearly poses a limit to the level of control that can be enforced on interventions altering these elements.

The control over interventions is also hindered by the fact that applications for interventions are seldom approved or rejected by experts in conservation. In fact HES provides guidelines on what kind of interventions can be carried out on listed buildings (Scotland, 2010), but the task to check if these guidelines are implemented is left to local authorities, whose technical office does not always include an expert in conservation, as confirmed by NHTG (2013). HES is involved only in case of major alterations to an A listed building. The local authorities can consult voluntary associations such as the Architectural Heritage Society of Scotland (AHSS), although the members are not necessarily conservation experts and the local authority is not obliged to comply with their opinion.

The lack of specific standards and the unresolved issues in the designation process and in the process of approval/rejection of proposed interventions do not create the optimal conditions for the conservation of historic timber roof structures. As discussed in the following sections, building users and professionals are in fact lacking the necessary guidance and tools to take care of this heritage.

5.1.2 Building owners, users, managers and professionals in charge of the maintenance

An online questionnaire was sent to all building owners, managers, tenants, architects and other professionals, whom we came in contact with during our surveys, to understand what knowledge and approach they employ in taking care of their buildings. The questionnaire included questions on the ownership, available documentation, accessibility to the roof structure, current condition of the roof structure and maintenance regime (Appendix B). It was partly filled by 40 respondents, mostly owners, managers or architects in charge of the building maintenance (Figure 309).

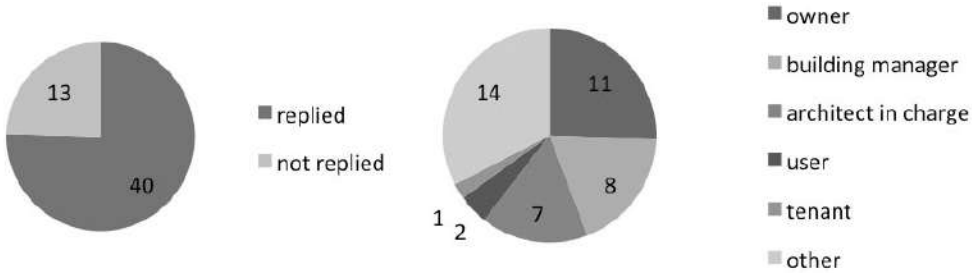


Figure 309: Respondents to the online questionnaire: number (left) and types (right)

Not all of the people responsible for the maintenance of these buildings are fully aware of the accessibility and visibility problems that their roof structures have. About half of the respondents think that the roof space of their building is easily accessible and that the timbers are clearly visible, the other half thinks that this is true only partly, but there are some dicrepancies with what we have found during our surveys (Figure 310): in one case the structure was completely inaccessible and invisible and in other cases the roof was accessible only through very small openings and with no lighting and no walking boards provided.

Inspections, especially of the roof timber structure, are not carried out regularly (Figure 311). Regular inspections are mainly implemented by HES and NTS. The other respondents specified that inspections are made only after a storm or when there seems to be a problem (Figure 311). The roof covering and flashings are inspected mainly by roofing specialists, or the respondents themselves, whilst the roof structure is mostly inspected by architects, followed again by roofing specialists and the respondents themselves; very few call an engineer (Figure 312). This is probably the reason why some of the respondents are not aware of current problems that their roofs have (Figure 313).

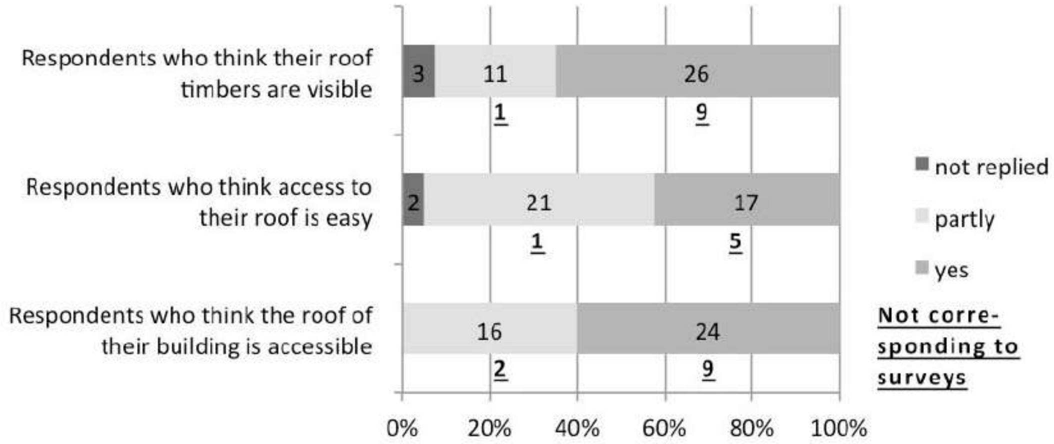


Figure 310: Accessibility and visibility of the surveyed roofs according to the respondents of the online questionnaire and compared to what we have found during our surveys

Programmed works are even less implemented than regular inspections. Only about half of the respondents have regular works programmed for the roof covering and flashings and less than 30% have programmed works for the structure (Figure 311). Programmed works are again mainly implemented by HES and NTS. The rest of the respondents specified that works are carried out ad hoc, when needed (Figure 311).

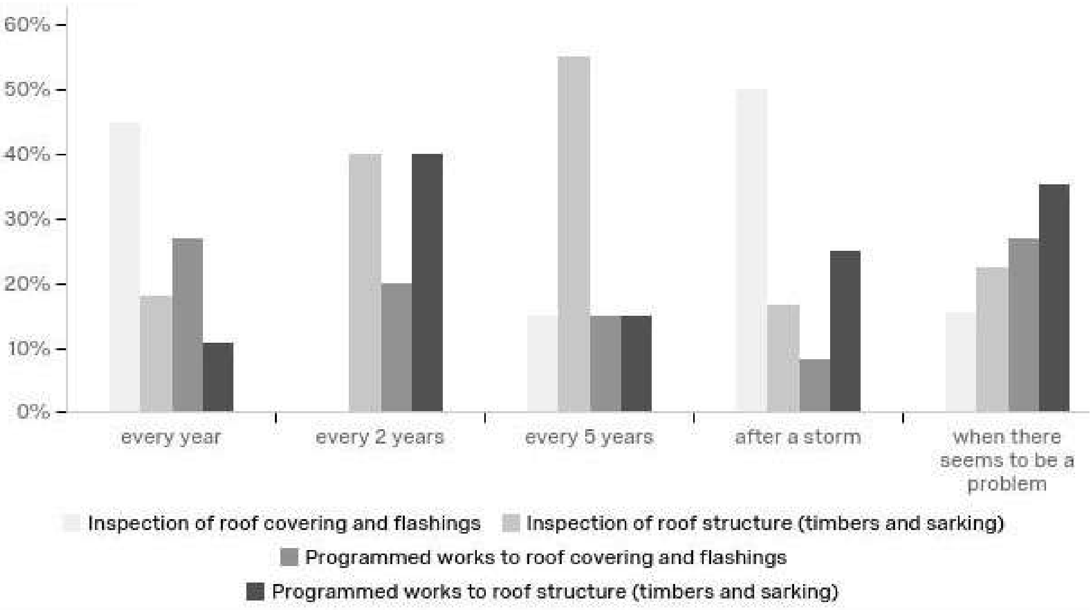


Figure 311: Frequency of inspections and programmed works to the roof structure, covering and flashings according to the respondents of the online questionnaire; 35/40 respondents replied

Moreover, most of the inspections and works are not recorded nor adequately documented. Only about half of the respondents receive a report after the inspection or works have been carried out (Figure 314). This is why they have difficulties keeping track of past repairs. 70% of the respondents claim to have some information about past interventions (Figure 314), but most of this information is not detailed (Appendix B). Furthermore, very few respondents have information on works carried out before they became responsible for the building (Figure 315).

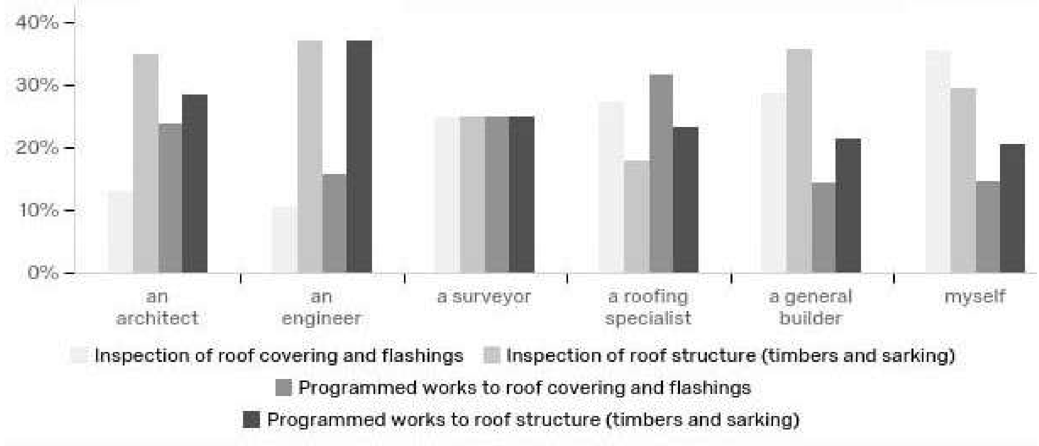


Figure 312: Professionals called to carry out inspections and programmed works to the roof structure, covering and flashings according to the respondents of the online questionnaire; 33/40 respondents replied

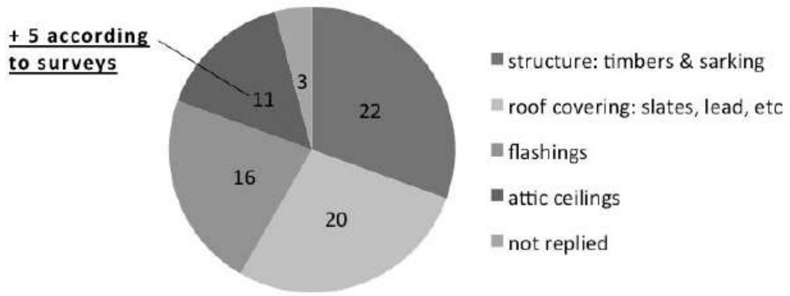


Figure 313: Current problems to the roof structure, covering, flashings and attic ceilings according to the respondents of the online questionnaire and compared to what we have found during our surveys

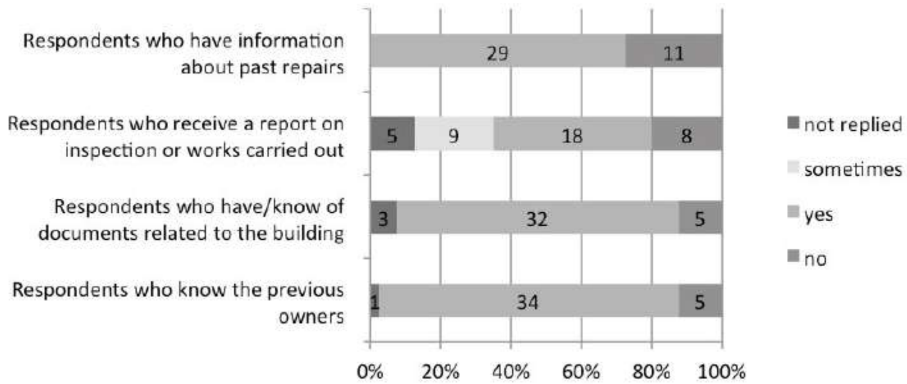


Figure 314: Building documentation according to the respondents to the online questionnaires: information on past repairs, inspection reports, historic documents, name of previous owners

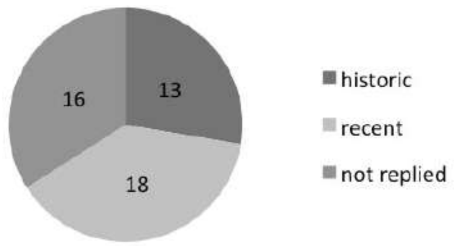


Figure 315: Types of documents related to the building that respondents to the online questionnaire know of

It must be kept in mind that the sample of respondents is not comprehensive and that 11 of them work for HES or NTS, which obviously follow certain established standards for the documentation and care of the buildings. Nevertheless, the overall picture is not reassuring as it highlights a distorted view of accessibility and visibility requirements, lack of regular inspections and programmed works and poor documentation.

5.1.3 Conservation professionals

The information gathered through the questionnaires has been integrated by interviewing three conservation engineers working in Scotland, to understand what kind of knowledge, skills and approach they have when assessing the condition of a timber roof structure and how they choose, design and carry out the necessary repair works. They have been selected amongst the engineers most frequently mentioned in association with interventions to timber roof structures. Engineer 1 works for HES, engineer 2 has his own engineering firm and engineer 3 is a director in an engineering firm. The interviews included questions regarding their education, present and past professional experience, method of assessment of historic timber roof structures, and criteria followed to design the necessary repair works (Appendix C).

Neither of the three has attended specific courses on conservation in University, because these were not offered. Engineer 2 underlines that in his experience the engineering course was all about mathematics and calculations and no aspect of design, architecture or history was considered. Engineer 3 is the only one who had specific training in conservation after University, thanks to a SPAB scholarship that allowed him to take a year off work to visit conservation sites and country houses across the country, guided by conservation practitioners. He is also the only one of the three accredited for conservation (CARE).

Carrying out a historical research prior to the inspection is not considered a priority: they rely on clients or architects to provide it. Engineer 2 is the only one stressing the importance to integrate this research by investigating the history of loads/problems/repairs, which is fundamental to understand the present condition of a historic structure.

They are never called to carry out a routine inspection, as already highlighted by the questionnaires discussed in the previous section; they are called to inspect a roof space only when the client sees an evident problem or when there is a change of use. Even HES relies on its architects to identify structural problems during their quinquennial inspection; HES engineers are not involved in the routine inspections of the buildings in their care. In fact, engineer 1 says that he never dealt with timber structures since he first started working for HES seven years ago.

During the inspections they mostly look out for water ingress and rot, because they think these are the most common problems. According to engineer 1 and 3 deflections, cracking and deformations are less common, although engineer 2 thinks otherwise. All three mention past alterations as another common issue.

Although there are various testing techniques that can help estimating the mechanical properties of timber, its resisting section and other unknowns that strongly influence the results of calculations, the interviewed engineers rely chiefly on traditional surveying techniques, visual inspection and past experience. The only tools employed are moisture meters, used by engineer 2, and coring, sometimes used by engineer 3 to test the inner condition of timber. If the timbers have big sections, or are heavily punctured, or there are signs of an active attack, they all call a timber specialist.

They sometimes carry out simple hand calculations, but not always because extensive analyses are expensive and seldom provide useful results, due to the big number of unknowns involved. Engineer 2 and 3 think it is important to identify the timber species for the calculations, so they often call a timber specialist for this purpose. Once the species is known they look up for reference properties and then adjust the calculations based on the first results they get. Engineer 1 thinks the timber species is important only if the timber element is of historical value, otherwise he makes assumptions for both the species and the properties.

Despite recognizing the importance of the minimum intervention criteria, the impossibility to reach a confident structural assessment forces engineers to 'stay on the safe side' and carry out interventions even when they are not sure it is necessary, as explained by engineer 3. When it comes to deciding what repair works are needed and how to design them, engineer 3 underlines that the availability of a skilled carpenter is not less fundamental than the philosophical criteria of minimum intervention and distinguishability. Unfortunately, it is difficult even for carpenters to acquire specific expertise in conservation, as discussed in the next section.

5.1.4 Existing training in conservation

A review of academic and training courses offered to professionals such as engineers, architects, and craftsmen to acquire specific knowledge about conservation of timber structures (Figure 316) highlights a lack of courses related to conservation engineering and timber structures in Scotland and North England, as confirmed by the interviewed engineers. Postgraduate courses in architectural conservation are offered at the moment in Scotland at the University of Edinburgh (for all professionals), the University of Strathclyde (for architects and engineers) and Heriot Watt University (for building surveyors, builders and construction managers). In North England masters in conservation are offered at the University of York (Department of Archaeology), at the University of Central Lancashire (Faculty of Science and Technology) and at the University of Sheffield (School of Architecture).

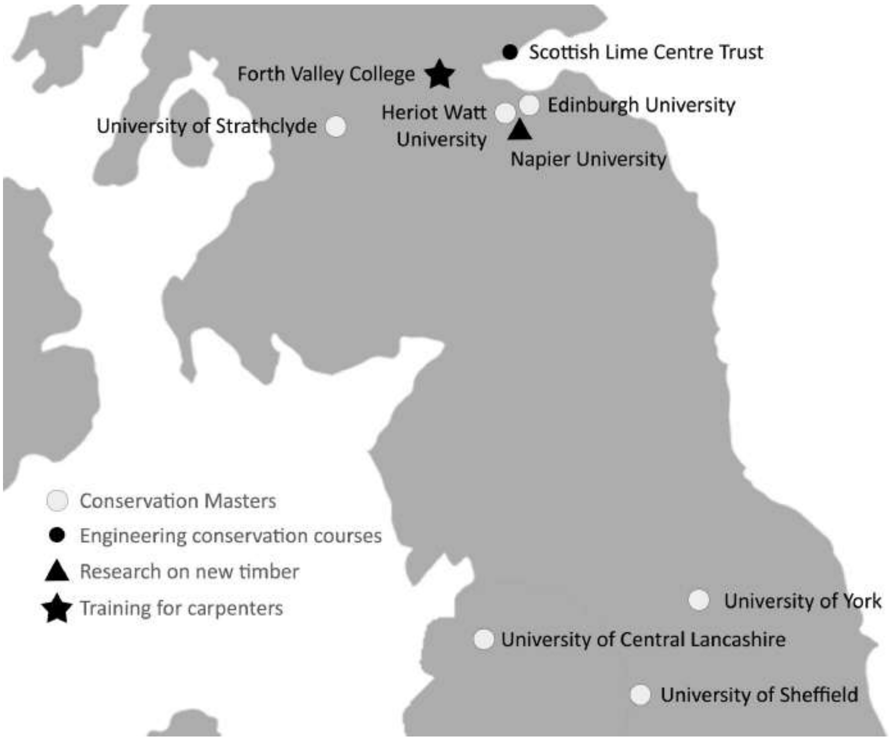


Figure 316: Available academic and training courses offered to conservation professionals dealing with historic timber structures in Scotland and North England

The only specific training in engineering conservation is a two-days seminar offered yearly by the Scottish Lime Centre Trust, entitled 'the structural repair of historic buildings' and held by Ian Hume, a conservation accredited engineer based in England. Napier University has two centres of research on timber engineering and technology, but they focus chiefly on new timber structures. This lack of training is confirmed by a research carried out by NHTG (2013) and explains why the three interviewed engineers say they have learnt most of what they know about conservation during their professional experience rather than through academic training. Experience is considered more important than training and accreditation (NHTG, 2013): in fact only one of the three interviewed engineers has attended specific training and is accredited in conservation (CARE). The register for conservation accredited engineers (CARE) includes, at the moment, 48 members of which only 4 based in Scotland.

The same is true for carpenters. Forth Valley College is the only one in Scotland offering courses on maintenance and repair of structural timbers. The only other option, even for carpenters working for HES, is to go to the Oak Frame Training Forum School near Bristol through the Carpenter’s fellowship. Therefore, just as engineers, most carpenters tend to learn 'on the job' rather than through formal training (NHTG, 2013).

5.1.5 Dissemination of conservation projects

In Scotland it is unusual to publish conservation projects, therefore it is necessary to look at unpublished professional reports to find examples of current conservation practice. This means that successful conservation projects are not available to the wider public and thus cannot inform other conservation projects and contribute in improving conservation practice.

A striking example is that of Historic Environment Scotland. HES has published many technical reports and papers, but most of them focus on upgrading and improvement of historic buildings (Fabian and Dobbie, 2014) rather than their condition assessment. Moreover, they often analyse historical and stylistic aspects (Historic Environment Scotland, 2014) or very technical ones (Baker, 2008), lacking of a more comprehensive and interdisciplinary approach. Most importantly in our case, no HES publication discusses timber structures.

If we look at unpublished work we can find an example of how HES maintains and repairs the roofs in its care. The unpublished final report on the timber roof of Newark Castle, produced by an English company to whom the assessment has been appointed by HES (Demaus Building Diagnostics Ltd, 2007), includes a thorough historical and condition assessment based on visual inspection and the use of a micro-drill and a hygrometer. The timber species is specified, although the method of identification is not stated. The document reports that decay was found at most rafter feet and other areas in contact with the damp masonry, which in turn showed some cracks and deformations linked with the roof overall movement. Based on this assessment it is suggested to reinforce the connection between the rafter feet and the wall-head with steel brackets and to connect these brackets transversally with steel wires, to counteract the roof opening (Figure 317, Figure 318). It is also recommended to dry out the masonry, improve ventilation and monitor the repairs afterwards.

The fact that this work was contracted to an English company suggests that timber specialists were not available in Scotland ten years ago. On the other hand, the report is very detailed and the proposed interventions reveal a sensible approach: they are reversible, they do not involve losing the original material and they are relatively low-cost. It is thus a pity that such a good example is not shared and published in order to inform similar projects.

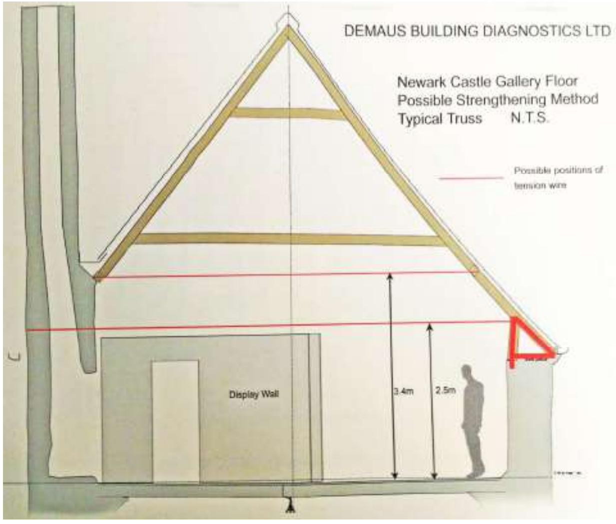


Figure 317: Proposed repairs to the roof of Newark (in red): steel brackets reinforcing the rafter feet and steel wires connecting them transversally (Demaus Building Diagnostics Ltd, 2007)

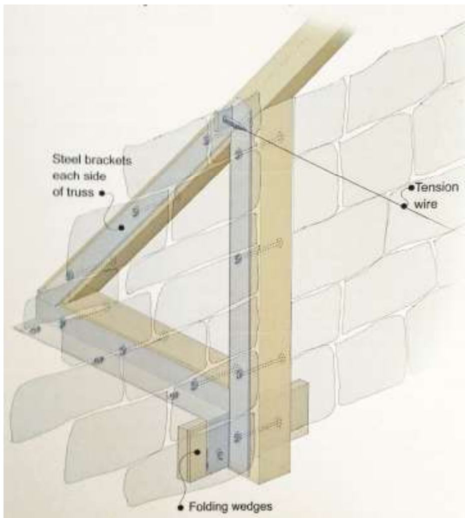


Figure 318: Detail of the steel brackets proposed as reinforcement for the rafter feet of the roof of Newark Castle (Demaus Building Diagnostics Ltd, 2007)

There are only a few contributions on the subject published by professionals: Oldriev (1916), Ruddock (1995) and Murdoch (2010) discuss the condition assessment and repair of four early Scottish timber roof structures. These studies are all quite dated since they discuss works carried out at the beginning of the twentieth century and in 1980s, but they all embrace a sensible approach to conservation, aiming at conserving the original fabric as much as possible and minimizing the impact of interventions.

Oldriev (1916) discusses the assessment and repair of the roof of Glasgow Cathedral (thirteenth century), Ruddock (1995) that of the roofs of Alloa Tower (1497 but maybe older) and a house in Kirkcaldy (1600), Murdoch (2010) explains the research and conservation works carried out at his own house, Methven Castle (1678-81). They all proceeded with a thorough historical research, aimed at assessing past problems and repairs as well, and a detailed in situ inspection. During the condition assessment they employed mainly visual techniques; in fact they had to remove parts of the roof covering and sarking boards, as well as the plaster ceiling, in order to be able to assess the condition of hidden parts of the structure. Oldriev (1916) also employed the plumb line to measure the out of plumb of the masonry walls and columns. In fact, whilst Ruddock (1995) and Murdoch (2010) found out that the main problem of their roofs was material degradation, concentrated at the rafter ends, the horizontal thrust produced by the roof of Glasgow Cathedral had created a dangerous out of plumb in the masonry walls and columns.

In Alloa and Kirckaldy it was sufficient to replace some of the rafter ends with new pieces of timber, joined to the original ones with scarf joints secured by steel bolts (Figure 319). In Methven Castle it was instead necessary to replace most of the rafters entirely and to reinforce the joints between rafters and collars with steel plates (Figure 320). The rafters were replaced with nineteenth century timbers recovered from the demolition of an industrial building nearby. Likewise, in Glasgow Cathedral most of the timbers had to be entirely replaced and other invasive interventions were needed to reduce the horizontal thrust exerted by the roof on the walls: the overall structural behaviour had to be changed by adding tie-beams and a secondary steel structure; the roof covering was also changed in order to reduce the weight on the roof structure.

The interventions described above, although partly invasive, are justified by the poor condition in which the roofs were. However, during our surveys we have seen many past repairs and interventions resulting from a less sensible approach, as discussed in the next section, suggesting that the above discussed published examples are not necessarily representative of the current approach in Scotland to the conservation of historic timber structures.

Figure 319: Repairs carried out in the roof of Alloa tower: some rafter ends, sole pieces and ashlar posts partly replaced with new timber and connected to the original timber with scarf joints and steel bolts

Figure 320: Repairs carried out in the roof of Methven Castle: many original rafters substituted with reused nineteenth century timbers, but many original collars retained and steel plates used to reinforce the lap joints between them

5.2 An overview of the typical pathologies found in the surveyed buildings

Our literature and archival research and on site surveys have highlighted a high percentage of seventeenth- and eighteenth-century Scottish buildings whose original timber roof structure has been replaced. Out of the 53 buildings we have surveyed, one had no accessibility to the roof structure and 8 had all the visible roof structures dating to post-1800 (Figure 321). In addition to these, thanks to information given by the owners/building managers/architects contacted, 6 other roofs have been identified as having the roof structure completely replaced after 1800 (Figure 321). Therefore, out of the 80 roofs whose owners/mangers/tenants/architects have replied, 14 roofs (almost 20%) have been reroofed after 1800. 20% is quite a high percentage and is probably higher since many owners/managers could not tell if the roof structure was original or not. It suggests either a conservative approach on the professionals' side, leading to the replacement of structures even when not necessary, or poor maintenance on the owners' side, leading to damage/degradation beyond repair. The results from our interviews to conservation engineers and questionnaires to building owners confirm that both things happen: engineers are often unable to reach a confident structural assessment and are thus forced to carry out unnecessary or over-dimensioned interventions to 'stay on the safe side'; on the other hand, owners and managers do not program regular inspection and maintenance works.

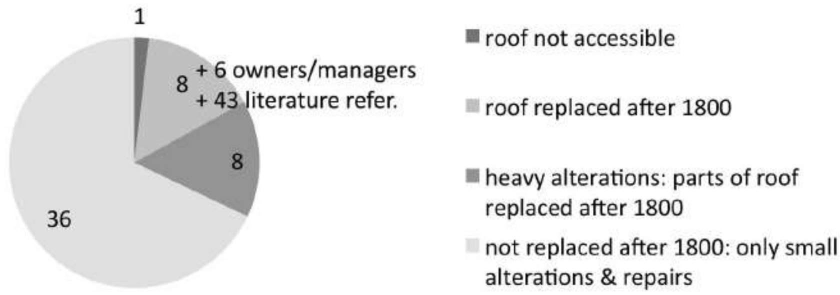


Figure 321: Replacements and alterations to surveyed roofs

It is clear that the value of these structures is not recognized and that good conservation practice is hindered by lack of information, training and method. Our surveys have allowed us to start addressing these issues, by identifying typical pathologies in each roof structure type and estimating the possible causes, summarized in Table 13 and Figure 322 and discussed in the following sections.

Table 13: Pathologies identified in the roofs surveyed, and estimated causes; the damage types are as represented in Figure 64. The roofs with no pathology have not been included. For details see Appendix E and F

Building name and roof location	Type of roof	Fungi attack	Insect attack	Mechanical damage	Estimated cause
Balcaskie House	simple frame		probably *Anobium Punctatum*		inadequate environmental conditions
Blair Castle	simple frame + complex frame	type not identified	probably *Anobium Punctatum*		inadequate environmental conditions

Cockenzie House	simple frame	Brown rot	probably *Anobium Punctatum*		poor maintenance, inadequate environmental conditions
Cowane's Hospital	simple frame		probably *Anobium Punctatum*		poor maintenance, inadequate environmental conditions
Craigston Castle	simple frame		probably *Anobium Punctatum*	stacking up of frames	poor design
Culross Palace	simple frame		probably *Anobium Punctatum*		inadequate environmental conditions
Edinburgh Panmure House	simple frame		probably *Anobium Punctatum*		inadequate environmental conditions
Edinburgh St Andrew's and St George's Church	truss			cracks	not identified
Fountainhall House	simple frame		probably *Anobium Punctatum*	stacking up of frames	poor design
Gardyne's Land	simple frame		probably *Anobium Punctatum*	permanent deformation of frames	past interventions, inadequate environmental conditions
Geilston House	simple frame		probably *Anobium Punctatum*	stacking up of frames	poor design/ maintenance
George Fort Chapel	truss		probably *Anobium Punctatum*		inadequate environmental conditions
George Fort Store	truss			disconnection of joints	poor design
Glasgow St Andrew's in The Square Church	truss	type not identified	probably *Anobium Punctatum*	cracks and disconnection of joints	inadequate environmental conditions
Glasgow Trades Hall	truss			transv. opening of roof, cracks and disconnection of joints	poor design
Glasgow Tron Church	truss			cracks and disconnection of joints	past interventions
Holyrood Palace	complex frame	type not identified	probably *Anobium Punctatum*	disconnection of joints	poor design, inadequate environmental conditions
Kelburn Castle tower	simple frame	Dry rot	probably *Anobium Punctatum*		poor maintenance, inadequate environmental conditions

Kelburn Castle W wing	simple frame	type not identified			poor maintenance
Kinross House	complex frame	type not identified	probably *Anobium Punctatum*		inadequate environmental conditions
Malleny House	simple frame		probably *Anobium Punctatum*		inadequate environmental conditions
Maybole Castle	simple frame	Dry rot	probably *Anobium Punctatum*		external action (fire), inadequate environmental conditions
Melville House	complex frame + purlin		probably *Anobium Punctatum*	permanent deformation of elements	poor design
Oakshaw Trinity Church	truss			transversal opening of roof, cracks, permanent deformation of elements, disconnection of joints	poor design, past interventions
Pilmuir House	simple frame		probably *Anobium Punctatum*		inadequate environmental conditions
Pinkie House tower	simple frame		probably *Anobium Punctatum*		inadequate environmental conditions
Pinkie House long hall	simple frame		probably *Anobium Punctatum*	transversal opening of roof, disconnection of joints	poor design
Sailor's Walk	simple frame		probably *Anobium Punctatum*	disconnection of joints	poor maintenance
Stirling Castle Palace	simple frame + complex frame + purlin	type not identified	probably *Anobium Punctatum*		inadequate environmental conditions
Stirling Castle King's Old Buildings	simple frame		probably *Xestobium Rufovillosum*		inadequate environmental conditions
Touch House main block	complex frame + purlin	type not identified		cracks	poor design, inadequate environmental conditions
Touch house in between	complex frame			permanent deformation of elements and cracks	poor design
Touch House N range	simple frame	type not identified		splitting of joints	poor maintenance, inadequate environmental conditions

Building name and roof location	Type of roof	Fungi attack	Insect attack	Mechanical damage	Estimated cause
Tweeddale House	complex frame		probably *Anobium Punctatum*		inadequate environmental conditions
Yester House central	complex frame		probably *Anobium Punctatum*	cracks and disconnection of joints	poor design, inadequate environmental conditions
Yester House sides	complex frame	type not identified	probably *Anobium Punctatum*		inadequate environmental conditions
simple frames (tot 29)		5 = **17%**	18 = **62%**	7 = **24%**	see Figure 322
complex frames (tot 18)		5 = **28%**	8 = **44%**	4 = **22%**	
purlin roofs (tot 5)		2= **40%**	1 = **20%**	2= **40%**	
trusses (tot 14)		1 = **7%**	2 = **14%**	6 = **43%**	

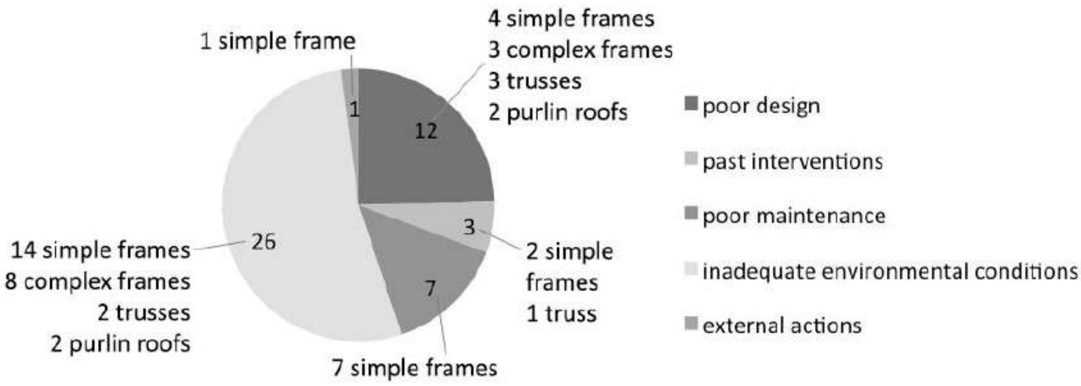


Figure 322: Estimated causes of the pathologies identified in the surveyed roofs

5.2.1 Poor initial design of the overall structural arrangements and details

Although two of the three engineers we have interviewed think that deflections, cracking and deformations are not common issues in Scottish roofs (section 2.3.4), we have found quite a few of these pathologies during our surveys and we have estimated that many of them are caused primarily by a poor initial design of the overall structural arrangement, the joints, and the timber dressing (Figure 322), as discussed below. It is not unusual for poor initial design to play a key role in causing damage in roofs (Tampone, 2007).

Simple frames sometimes show joint disconnections and splitting that can be associated with an overall transversal opening of the roof (Figure 323 left), caused mainly by the absence of tie-beams and of tension-absorbing joints. As previously discussed, tie-beams are not used in Scottish roofs before the end of seventeenth century, and even after 1700 they are not common. When there is no tie-beam the transversal opening of the roof is restricted only by collars and rafter feet. When there are two collars, as in Pinkie House (1613), the upper one is working mainly in compression and the lower one mainly in bending and tension (even because it often supports the ceiling underneath). The problem is that up to about 1670 simple lap or mortise and tenon joints are used, secured with timber pegs, for both lower and upper collars (section 3.3.2.1). These joints are capable of resisting very limited tension forces (Jasienko et al 2014): the timber pegs fail easily (also because of biotic attack) and the joints open, as in Sailor's Walk (1670s) and in Pinkie House (1613) (Figure 323 centre and right); in both cases additional collars have been recently added to counteract the roof opening.

Figure 323: Mechanical damage in common rafter roofs: schematic of the transversal opening of roofs (left), joint disconnection in a rafter foot of Sailor's Walk (1670s) (centre), an open joint between lower collar and rafter in the roof of the long gallery at Pinkie House (1613) (right)

This problem is visible even in later roofs, when the tie-beam is not used, as in Oakshaw Trinity church (1754-6) (Figure 324 left) and the Trades Hall in Glasgow (1791-4) (Figure 324 right), because Scottish wrights never develop efficient tension-absorbing joints, as discussed in section 3.3.2.1.

Figure 324: The transversal opening of eighteenth century roofs without a tie-beam: open scarf joint in a tie-beam of the roof of Oakshaw Trinity church (1754-6) (left), wooden peg inserted in an open joint between a slanted strut and a horizontal beam in the roof of Glasgow Trades Hall (1791-4) (right)

Other common rafter roofs have a problem in the longitudinal direction, with the frames stacking up and losing stability, as in Craigston Castle (1604-7), Fountainhall House (early seventeenth century) and Geilston House (1666) (Figure 325). This becomes a serious problem when the distance between the frames is more than the common 50cm, since the longitudinal rigidity is provided only by the sarking boards. It is the case of Geilston House, where the frames are spaced around 90cm and the out of plumb reaches up to 60cm at their top. In fact, additional timber frames and a steel structure have been added to support the original roof.

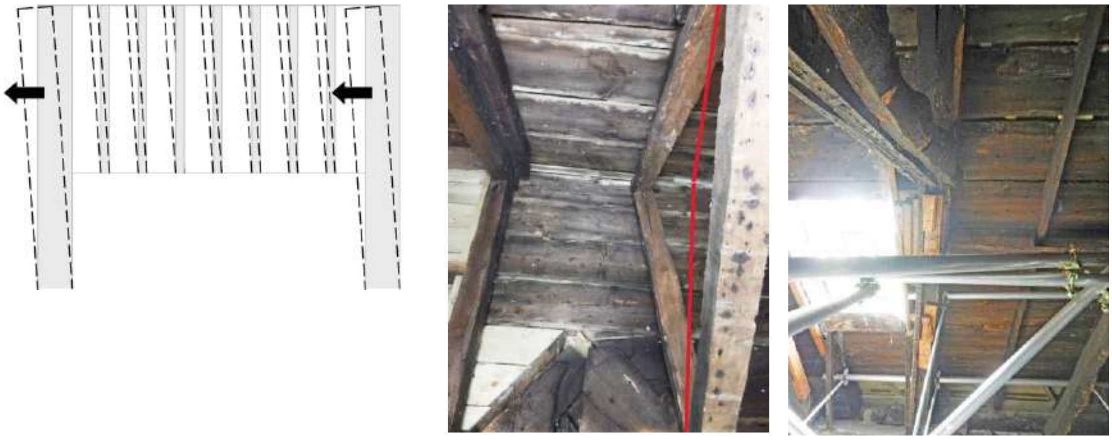


Figure 325: Mechanical damage in common rafter roofs: schematic of the stacking up of frames (left) and pictures of the roof of Geilston House (1666) (centre and right); the black line in the central picture represents the position that the frame should have if there was no out of plomb

Trusses with reduced spans are generally in good conditions, whilst those covering bigger spans sometimes have deflected elements, joint disconnections and cracks, which suggest high stresses and possibly an overall deflection and opening of the roof structure. The causes are certainly more than one and difficult to determine, but the improper design of arrangements and joints is clearly one of them. Timber elements are sometimes too slender and long and do not have sufficient propping provided, as the hip rafter in Oakshaw Trinity Church (Figure 326: the posts and struts have been added later). The same roof is also a good example of problematic asymmetrical arrangements: the fact that the struts do not encounter the posts at the same height creates unnecessary stresses in the post (Figure 326).

The Ordnance Store in Fort George is another example of insufficient propping: the long tie-beam has no supports. The lateral posts (Figure 327 right) are probably a later addition since they do not appear in a survey carried out one year after completion of the building (Figure 327 left). In any case, they do not help the tie-beam because they are jointed with mortice and tenon joints secured by timber dowels, which, as already discussed, can work mainly in compression (Figure 328 top right). In fact, additional steel reinforcements have been recently added to try to counteract the tie-beam deflection.

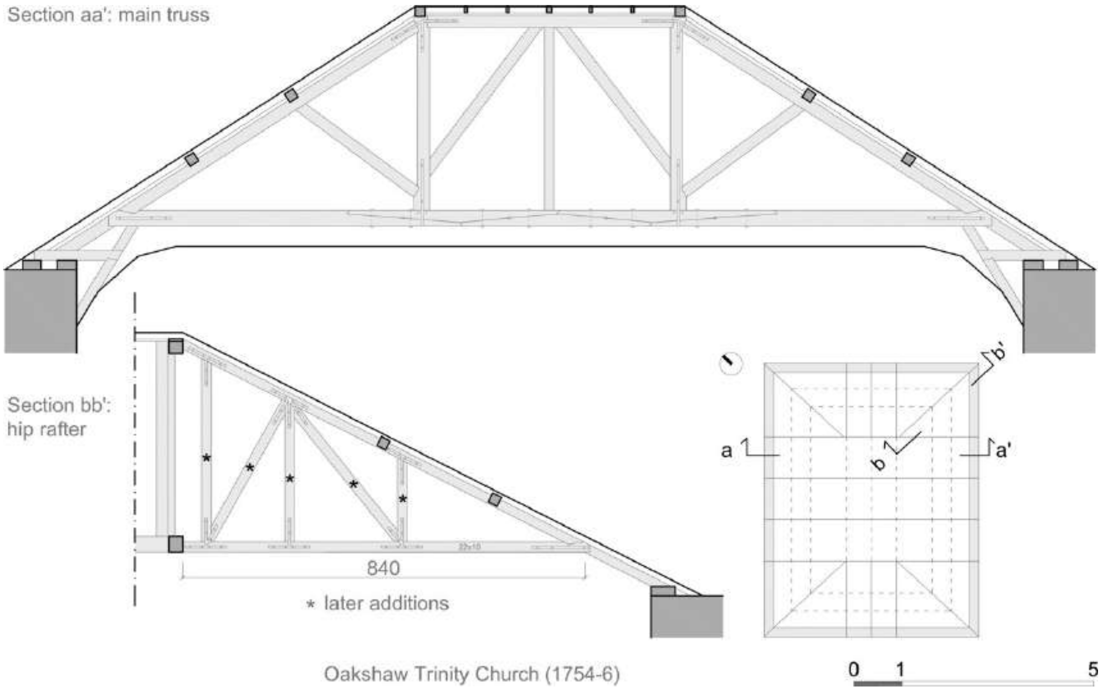


Figure 326: The roof of Oakshaw Trinity Church (1754-6)

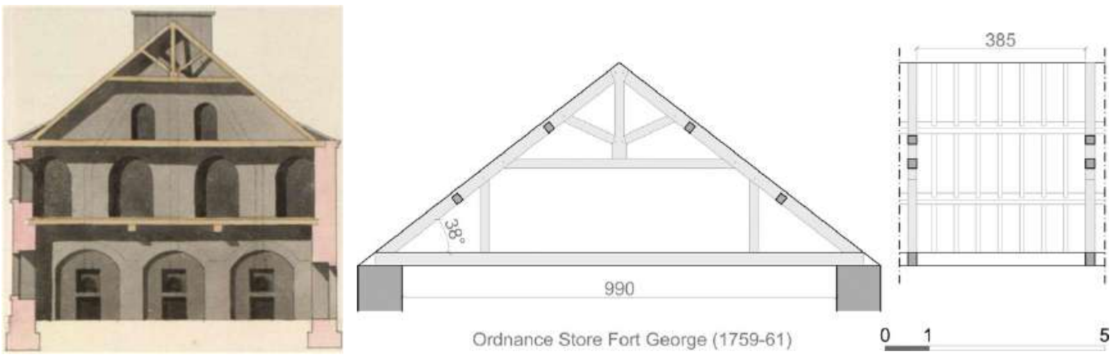


Figure 327: The roof of the Ordnance Store in Fort George (1759-61): as drawn by engineer William Skinner in 1762 after completion (NLS MS1647 Z.02/55a, 1762) (left), as surveyed by the author (right)

As previously discussed, Scottish wrights do not develop efficient tension-absorbing joints and in fact most trusses employ exclusively mortise and tenon joints secured with timber dowels or wedges. Metal straps are very seldom used and sometimes they are a later addition, as in Trades Hall in Glasgow (1791-4) where they have been added in 1856 (Figure 328 left). Scarf joints, when used, are very simple and unable to absorb tension forces, as the one in Oakshaw Trinity Church, which has opened up to 4.5cm breaking the wooden keys (Figure 328 bottom right).

Complex frames and purlins roofs also have deflected elements and cracked supports (Figure 329) caused by insufficient dimensions and insufficient number of supports, as in trussed roofs. Touch House is a good example: the original purlin roof has purlins more than 8 meters long, running from one gable to the other, with only two slender horizontal struts as intermediate supports. In 1930s two steel beams were added as additional support to avoid further deflection of the purlins (Figure 330). Another part of the roof has not been intervened on and is visibly suffering (Figure 329).

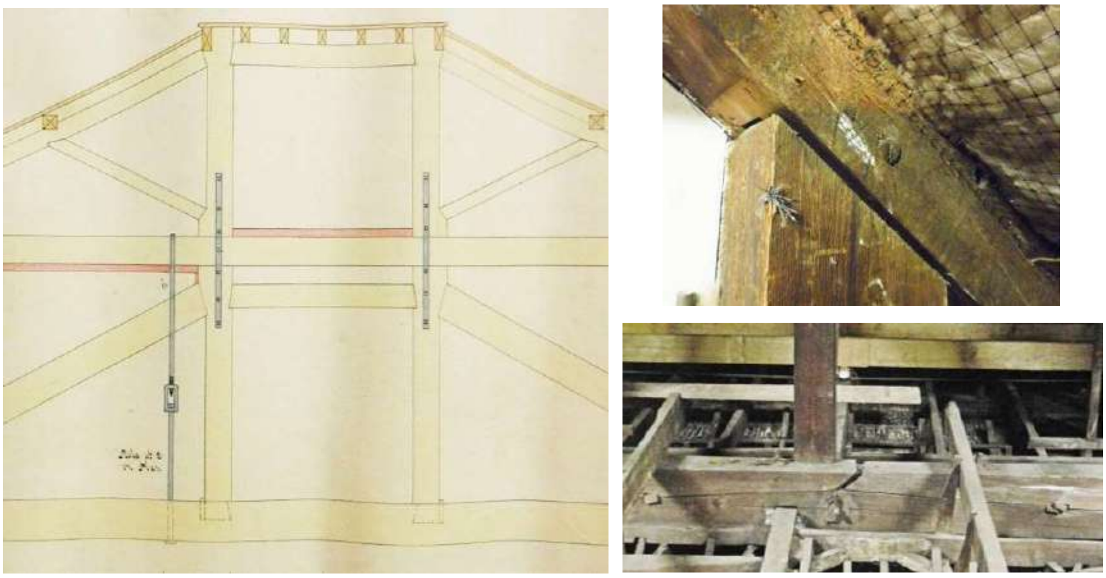


Figure 328: Mechanical damage in trussed roofs: drawing showing in red and blue the timber and steel added to the roof of the Trades Hall in Glasgow (TDH 1/899, 1856) (left), joint disconnection in the roof of Fort George Ordnance Store (1759-61) (top right) and in the roof of Oakshaw Trinity Church (1754-6) (bottom right)

Figure 329: Mechanical damage in purlin roofs and complex frames: deflected purlin in Melville House (1697-1701) (left), deflected purlin in Touch House (1757-62) (centre), crack in strut supporting the purlin in Touch House (1757-62) (right) (Serafini and Gonzalez Longo, 2016)

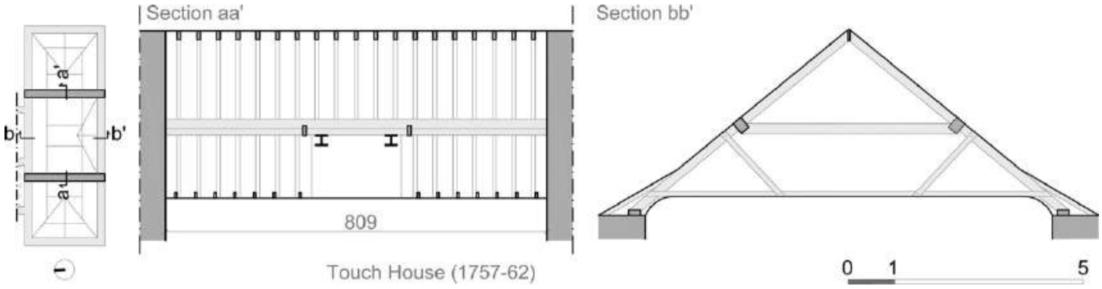


Figure 330: The central part of the roof of the main block of Touch House (1757-62)

Many common rafter roofs and almost half of the surveyed complex frames, have material degradation problems caused by biotic agents (Table 13), as stressed by the interviewed engineers as well (section 5.1.3). The optimal conditions for these agents to proliferate are generally provided by water ingress problems, as suggested by the interviewed engineers and our surveys (Table 13). However, the rough dressing of the timber elements is also a cause, since bark and sapwood are more vulnerable to insect attack (Ridout, 2000). This would explain why trussed roofs, according to our surveys, are less vulnerable to biotic attack (Table 13): the timber elements for these more complex structures were more carefully squared and finished, leaving no bark and less sapwood.

In some cases the insect attack has been treated and is not active anymore (Figure 331 left), but in other roofs new bore dust indicates active infestation (Figure 331 centre) (Figure 332). Fungi attack (Figure 331 right) is less common (Table 13) and more difficult to identify and evaluate.

Figure 331: Material degradation in common rafter roofs: old insect attack in Malleny House (1635) (left), active insect attack in Cockenzie House (1680s) (centre), fungi attack in Kelburn Castle (1581) (right)

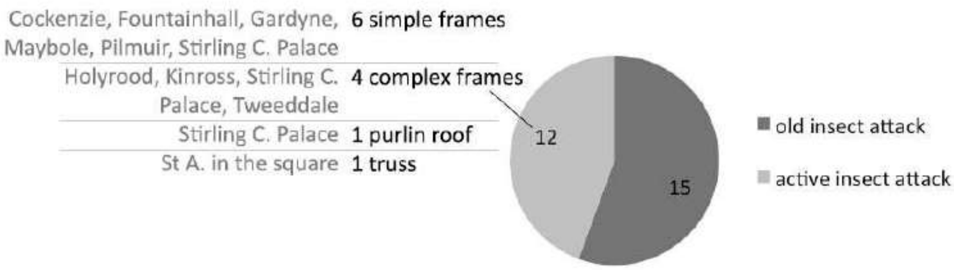


Figure 332: Estimated status of the insect attack affecting the surveyed roofs

Even when it is not active anymore, insect attack might have caused a considerable reduction of the resisting section of the elements, as highlighted by the micro-drill test. Most of the micro-drill graphs resulting from our in situ testing campaign show healthy wood or external degradation limited to the sapwood, up to 2cm deep (green circle in Figure 333, top two lines) (Figure 334). However, in a few measurement points extensive external degradation has been found, up to 4cm deep (only one deeper than 4cm) (Figure 335) and in rare occasions internal degradation, mainly in the sapwood but occasionally in the heartwood as well (Figure 336), especially in Holyrood Palace (red circle in Figure 333). Extensive degradation can cause serious mechanical damage and brittle failures.

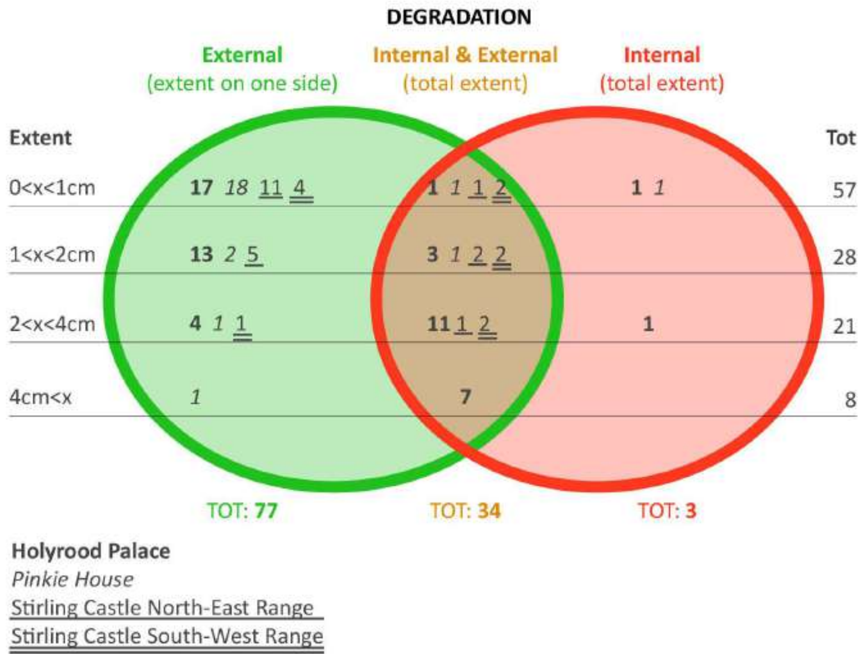


Figure 333: Number of micro-drills carried out in the roofs of Stirling Castle Palace, Holyrood Palace and Pinkie House, organized according to the position and extent of the degradation detected

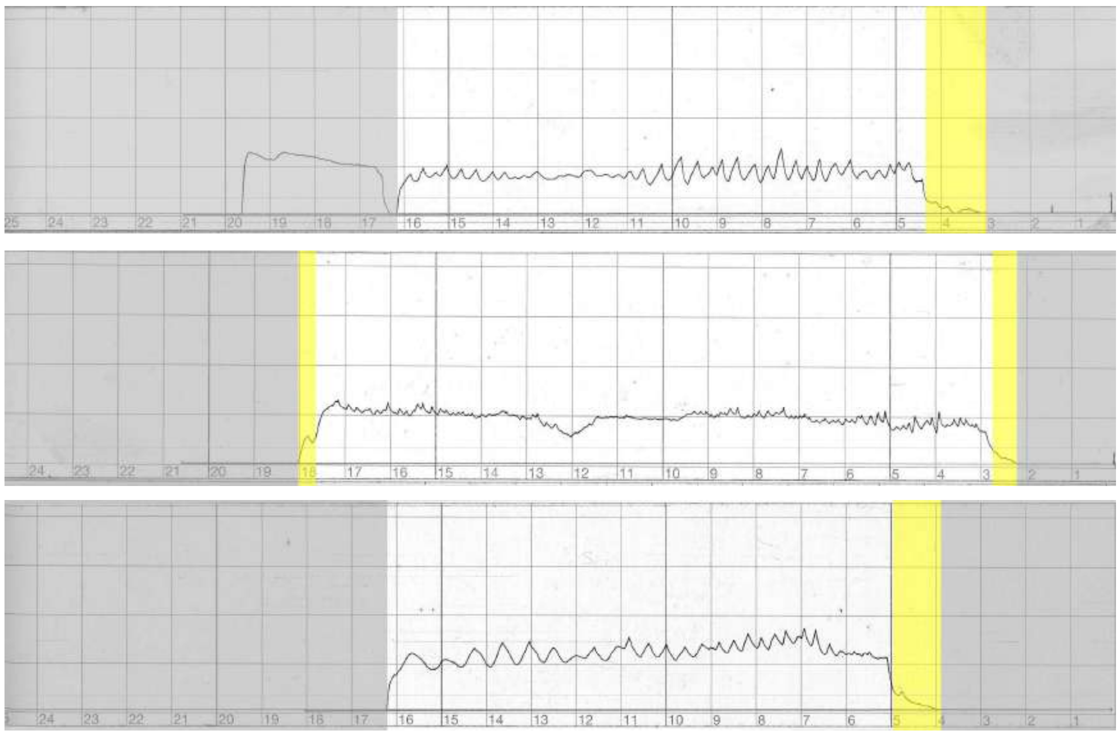


Figure 334: Examples of micro-drill graphs that show external degradation limited to the sapwood, up to 2cm deep. From the top:

- measurement point b in the Upper Beam on the North side of frame XX of Holyrood Palace

- measurement point 5 in frame I of Pinkie House

- measurement point 2 in frame 7 in the North-East range of Stirling Castle Palace

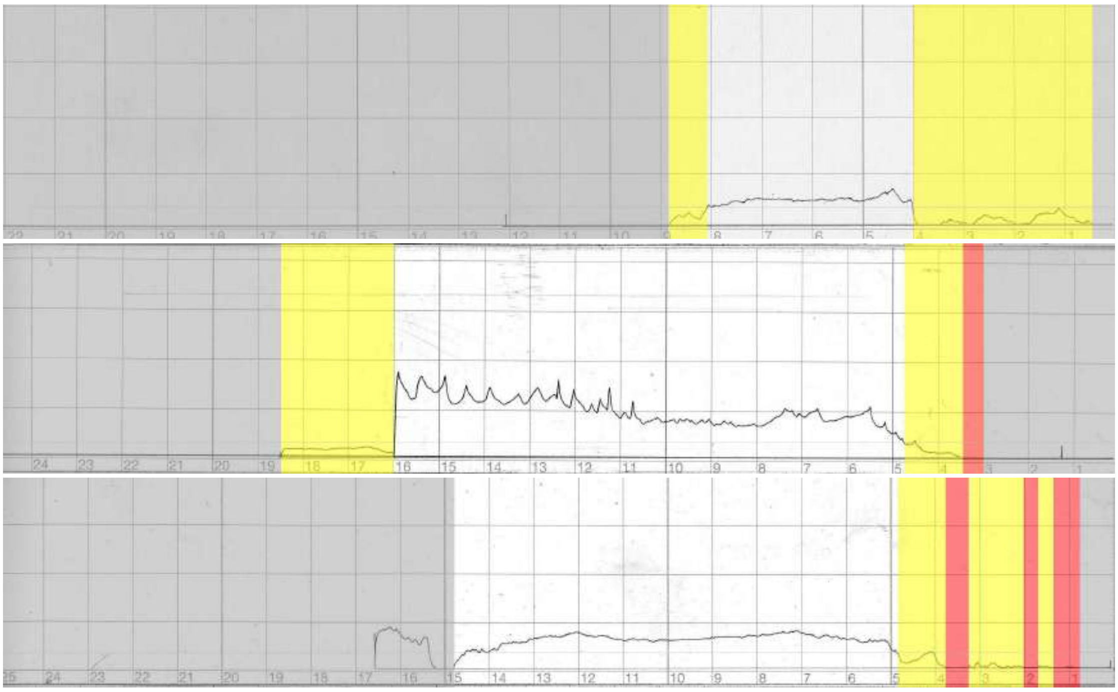


Figure 335: Examples of micro-drill graphs showing extensive external degradation (more than 2cm deep).

From the top:

- measurement point d in the Upper Beam on the Sorth side of frame X of Holyrood Palace

- measurement point b rear in frame 7 in the South-West range of Stirling Castle Palace

- measurement point 6 in frame XXVII in Pinkie House (with more than more than 4cm degradation on one side)

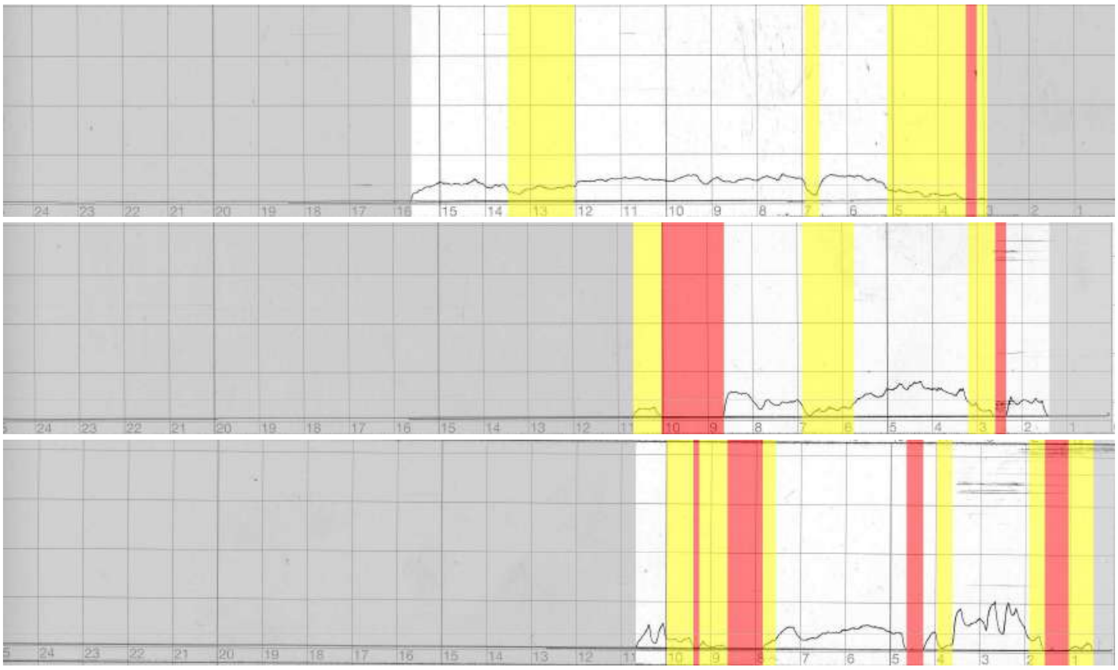


Figure 336: Examples of micro-drill graphs showing internal degradation. From the top:

- measurement point a' rear in frame 8 in the South-West range of Stirling Castle Palace

- measurement point a in the Strut on the North side of frame XLII of Holyrood Palace

- measurement point b in the Strut on the North side of frame XLIII of Holyrood Palace

5.2.2 Past repairs, alterations and interventions

Past alterations and repairs can contribute to creating or accelerating damage in some cases. Although we have estimated past interventions to be a direct cause of damage and degradation only in three of the surveyed roofs (Figure 322), the three conservation engineers we have interviewed confirm that this is a common issue in Scottish roofs (section 5.1.3). Gardyne’s Land (1675), for example, has deflected collars in the central part of the roof, because a pediment was added here in early eighteenth century; the problem has been solved with a temporary steel beam placed under the collars and pulled up by cables (Figure 337 left). Another example is Oakshaw Trinity church (1754-6), where the heavy plaster ceiling was probably added or replaced in nienteenth century, causing, together with the improper design of the structure previously discussed, deflections and joint disconnections due to the additional dead load (Figure 324 left and Figure 328 bottom right).

Figure 337: Past interventions: steel beam and ties counteracting the collars’ deflection in Gardyne’s Land (1675) (left), steel truss supporting the roof of Geilston House (1666) (centre), eighteenth century and twenty-first century timbers strengthening the original seventeenth-century timbers in Panmure House (1680s) (right)

There is often no documentation on past and recent repairs and why they have been done, as previously discussed. Temporary interventions often become permanent, and their effect on the structure is not monitored: the interventions in Gardyne's Land and Geilston House were supposed to be temporary but they've been there for about 20 years now (Figure 337 left and centre). The steel truss in Geilston House, in particular, is very bulky and hinders accessibility to the attic.

Whilst in eighteenth and nineteenth centuries timber was used to either replace the whole roof or double its structure (Figure 337 right), in twentieth and twenty-first centuries steel became more fashionable. The weight of steel can however be a problem for the masonry and the plaster ceilings. For example, timber posts and steel beams were added in Oakshaw Trinity Church to support the hip rafters that were deflecting (Figure 338 left, Figure 326); this intervention actually increased the loads on the tie-beams, incrementing their deflection and the joints’ opening (Figure 328 bottom right), and the loads on the masonry, causing cracks. Moreover, secondary elements were savagely cut to make place for the steel reinforcement, causing further problems to the plaster ceiling directly attached to these secondary beams (Figure 338 centre).

Figure 338: Past interventions: timber and steel elements counteracting the hip rafters' deflection in Oakshaw Trinity church (1754-6) (left), a secondary beamcut to make place for the steel reinforcements in Oakshaw Trinity Church (1754-6) (centre), filled checks in the roof of the Ordnance Store at Fort George (1759-61) (right)

Checks and cracks are often filled with resin (Figure 338 right). Checks are natural cracks that develop along the radius of a log, when the timber dries. They rarely are a structural problem, unless they are deep and on both sides of the timber. Filling them actually weakens the timber preventing it from swelling when the temperature and humidity change, causing further cracks to develop.

5.2.3 Inadequate environmental conditions, accessibility issues and poor maintenance

As already stated, many common rafter roofs, as well as almost half of the surveyed complex frames, have material degradation problems (Table 13). Besides the timber dressing, other factors contribute as causes. While the roof spaces of trussed roofs are bigger and more airy, common rafter roofs and complex frames generally cover dwelling houses, where the lower part of the roof spaces is plastered and occupied by attic rooms - there are only 7 exceptions where this does not happen, out of 47 roofs. This lower part of the structure, and in particular the connection with the lateral walls, is often not visible nor accessible (Figure 339), which hinders its inspection and maintenance. Moreover, the upper part can be quite small, with poor ventilation (Figure 340) and sometimes over insulation, as in Stirling Castle's King's Old Buildings (Figure 342 left).

Modern waterproofing sheets added in-between the sarking and the slates often hinders ventilation too. In Pinkie House there is nothing in-between the sarking boards and the slates, and the sarking boards are laid with 0.5-1cm space between one another allowing for air to pass through. The water can pass through as well, but air dries out the timber quickly. This 'breathable' roofing, together with the fact that the room under the roof space is heated, provides Pinkie's roof space with very good environmental conditions.

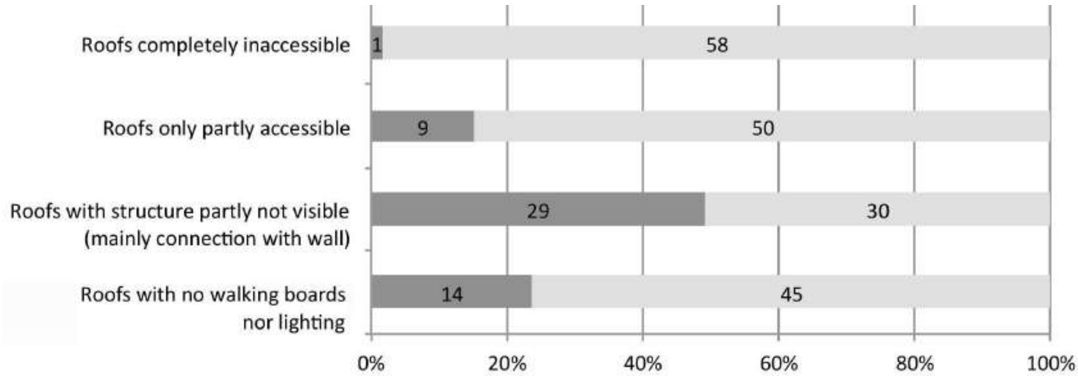


Figure 339: Accessibility and visibility issues found in the surveyed roofs

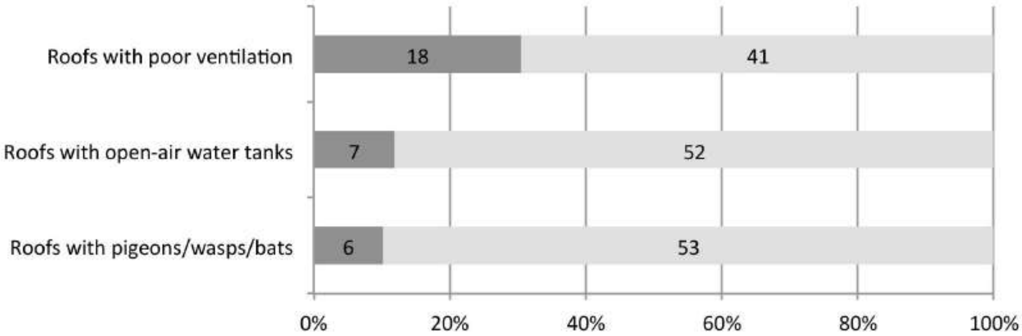


Figure 340: Surveyed roofs affected by inadequate environmental conditions

Most attic spaces are, however, not heated, especially in private houses, and this does not help in reducing humidity. In particular, the air relative humidity and the wood moisture content measured in the simple frames in Touch House and Cockenzie House have been found to have very high values, surpassing 18% in almost all of the measured points and surpassing 20% in most of them (Figure 341). High values have been measured in Cockenzie House both on rafters and collars, near or far from the gable walls, whilst in Touch House mainly in collars and rafters near the East gable wall (Appendix F). The masonry gables in both roofs are wet, disintegrating into dust and falling on the timbers and ceiling underneath. This suggests problems in the flashings, which, together with the fact that the sarking is broken in some areas, causes water ingress. This situation, together with the fact that the timbers are very slim, has forced us not to proceed with further surveys, for safety reasons. The main problem in both cases is the difficult accessibility to the roof spaces coupled with economic aspects, which makes it difficult for owners to carry out the necessary maintenance works.

Many roof spaces are also used to host uncovered water tanks (Figure 340) that increase humidity and thus foster biotic attack, as in Kelburn Castle (Figure 342 centre). Moreover, the presence of pigeons, wasps, and bats hinders accessibility and maintenance (Figure 340): access to many properties has been denied because of the presence of bats or wasps, and a few of the surveyed roofs proved to be problematic because of pigeons' droppings (Figure 342 right).

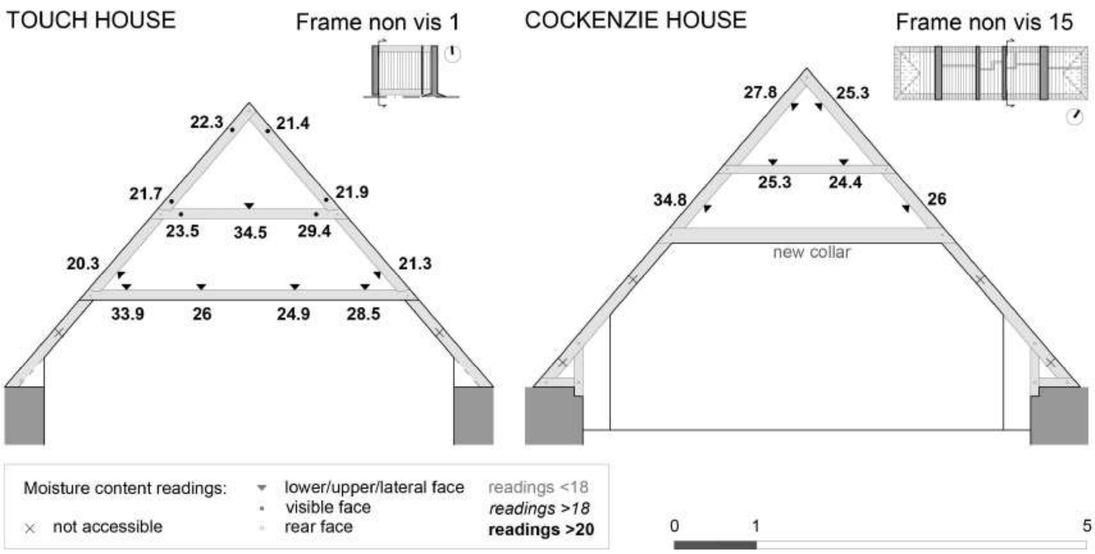


Figure 341: Moisture content readings in one frame in the roof of the North range of Touch House (left) and in one frame in the roof of Cockenzie House (right)

Figure 342: Unfavourable conditions in simple frames: over-insulation in the roof of King's Old Buildings in Stirling Castle (1557) (left), uncovered water tank in Kelburn Castle (1581) (centre), pigeons' droppings in George Heriot School (1630s) (right)

Finally, owners, tenants, estate managers and professionals in charge of the building's maintenance do not always know how to access roof spaces and do not always have the necessary equipment to do it (ladders, torches, etc). As discussed in section 5.1.2, most of them do not feel that accessibility is a problem, also because they do not carry out regular inspections and maintenance works. The extreme example is that of Prestonfield House were the roof structure is completely invisible (Figure 339), hidden behind plaster, as no hatch has been provided for the inspection of the roof space.

5.3 Evaluation of the assessment techniques used

The previous section discusses the condition of the surveyed roofs based on the results of the assessment methods used. The results of visual inspection, VSG and various tests have been combined to give the best evaluation possible of the safety of the roof structures. However, it is interesting to consider the performance of the techniques used, in order to provide a detailed evaluation of each of them, so to inform future training for conservation professionals. This section will discuss the adopted techniques in terms of: 1) effectiveness and reliability; 2) knowledge and skills required; 3) costs. This discussion will clarify which of the assessment techniques have actually provided valuable information, which of them have been practical to implement, what expertise and skills is required to use each particular technique and what are the costs involved.

5.3.1 Effectiveness and reliability of the assessment techinques used

The foremost requirement for an assessment technique is to provide useful results, in other words to be effective. In addition, the results have to be reliable, to allow for a confident evaluation of the structure's condition. It is therefore important to classifiy the techniques in terms of effectiveness and reliability, according to the survey conditions. To do so we identified the specific requirements that have to be in place for each technique to be effective and reliable, as summarized in Table 14.

Visual assessment techniques, such as visual identification of pathologies and VSG, are highly effective if the roof structure is accessible and visible. It must be kept in mind, however, that the reliability of their results is limited to the surface: internal degradation, damage and natural defects cannot be assessed visually. Moreover, in case of fungi attack we have found that it is often difficult to identify the type of fungi and evaluate its status (active or not) based only on other examples and guidelines provided by the literature. With regard to VSG, it is necessary to observe all the faces of the timber elements in order to classify them in specific a stregnth class. The results of VSG are consistent with those obtained from the visual identificaiton of pathologies. However, it would be interesting for future research to validate VSG results against laboratory measurements of mechanical properties for the timber structures examined here.

When the roof structure was accessible only through small apertures, we used a snake camera to perform endoscopic imaging and observe the timbers. However, the effectiveness of our snake camera was limited by the short length of the probe, its low resolution and by the fact that insulation sheets between the timber elements often hindered the probe movements.

The identification of the timber species can be done macroscopically in situ or microscopically in the lab after collecting a sample. The macroscopic identification of the timber species requires the transversal section of wood to be visible (e.g. the end of a beam), otherwise a sample must be collected and cut transversally. The macroscopic identification is challenging even for experts, as it is often not possible to distinguish between the different softwoods. Conversely, the microscopic identification of the timber species is much more reliable. In fact, in one occasion we were able to distinguish pine from spruce only after analysing the sample with the optical microscope.

The measurement of the environmental conditions using an air thermometer and a hygrometer does not pose any specific issues in terms of effectiveness and reliability. Measuring the air temperature/humidity with an air thermometer clearly requires access to the roof space but it does not necessarily require visibility of the roof structure. Measuring the wood moisture content with a hygrometer does not require full visibility of the roof structure either, but it does require access to the wood surface. Both techniques are considered reliable and robust as they promptly provide a quantitative measurement of punctual properties of the wood structure, such as local temperature or water content.

Table 14: Summary of the effectiveness and reliability of the assessment techniques used during the surveys. The effectiveness column details on the requirements needed to obtain useful results, such as accessibility, visibility, sampling, environmental conditions, instrumental resolution, and timber thickness. The reliability column specifies wether the results obtained from each technique can be considered reliable and to what extent.

Assessment technique		Effectiveness	Reliability
Visual identification of historically relevant features and pathologies		requires accessibility and visibility of the roof structure	reliable, but limited to surface and difficult to identify type and status of fungi
Visual Strength Grading (VSG)		requires accessibility and visibility of all faces of the timber elements	results consistent with visual identification of pathologies
Timber species identification	Macroscopic	requires visibility of the roof structure and in particular of the transversal section of wood *or* wood sampling	reliable but it is difficult to distinguish among softwoods
	Microscopic	requires visibility of the roof structure *and* wood sampling	reliable
Measurement of environmental conditions	Thermometer	requires access to roof structure	reliable
	Hygrometer	requires access to wood surface	reliable
Other non-destructive and semi-destructive testing	Rubber hammer	requires access to wood surface	no useful information obtained
	Ultrasonic test	requires access to wood surface and timbers with limited thickness	inconsistent with micro-drill results
	Micro-drill	requires access to wood surface	reliable
	Snake Camera	requires accessibility through slits/holes and good resolution camera	no useful information obtained
	Thermal Camera	requires heated environment	reliable

The same consideration does not hold for timber sounding with a rubber hammer, as it was arduous to perceive differences in sounding. This method, therefore, appears prone to subjective biasing depending on the surveyor's experience. On the other hand, literature reports that sounding is effective only for extensive degradation/damage (Ross et al., 1999). As the published studies do not report quantitatively on the degree of damage that can be assessed with rubber hammer testing, we cannot exclude that we never encountered such extensive damage. The effectiveness and reliability of the thermal camera, the ultrasonic device and the micro-drill are discussed separately in the following sub-sections.

5.3.1.1 The effectiveness and reliability of the thermal camera

We have used the thermal camera both in roof spaces and attic spaces underneath, to identify damp areas and water ingress problems, as well as thermal bridges, and to investigate the connection between the roof structure and the lateral walls hidden behind timber or plaster panelling. Unfortunately, we have obtained interesting results only in some heated attic spaces.

As detailed in chapter 2 (section 2.1.3.1), thermal imaging, or infrared thermography (IRT), allows visualizing and quantifying temperature variations across surfaces by detecting infrared radiation emitted by objects: the warmer the object, the more infrared radiation it emits (Riggio et al., 2015b, Young, 2014). This means that for useful thermal images to be recorded there needs to be a temperature contrast: without heat to drive evaporation, a damp patch on a wall will have the same temperature as an adjacent dry surface.

Unfortunately all of the roof spaces where we carried out thermal imaging were not heated and owners never allowed heating because of fire safety reasons. Outdoor temperatures never allowed a natural heating of the roof spaces either (as, for example, in Colla and Gabrielli, 2015): our in situ campaign was carried out between January and June 2016, when temperatures in Scotland seldom surpassed 15°. Therefore, none of the thermograms we have taken in roof spaces show any relevant feature, even after increasing the thermal contrast by reducing the visualised temperature range in the post-processing. Some examples are visible in Table 15 (B, C, E, I, O, T): the temperature differences are easily identified as air coming through ridges and eaves, gaps in the insulation sheets, or other features not useful to assess the geometry or condition of the roof structure.

On the contrary, most attic spaces where we carried out thermal imaging were heated and thermography provided valuable results. The only exceptions are: the attic of Newhailes House (Table 15 L), where no temperature difference was identified despite the attic being heated; the attic of Touch House (Table 15 S), where the attic spaces where not heated and no temperature difference was identified; the attic of St Andrew's in the Square church (Table 15 D), where the thermograms only revealed gaps in the insulation sheets above the ceiling.

In Abbeystand Buildings (Table 15 A), Holyrood Palace (Table 15 H), Pinkie House (Table 15 M) and Stirling Castle Palace (Table 15 P) thermal images allowed assessing the position and geometry of the structure hidden behind the plaster/timber panelling. In fact, in all four roofs the position and dimension of the rafters, and sometimes collars, hidden behind the panelling is visible in the thermographic images taken in the attic spaces.

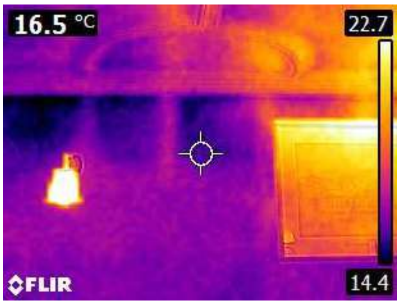
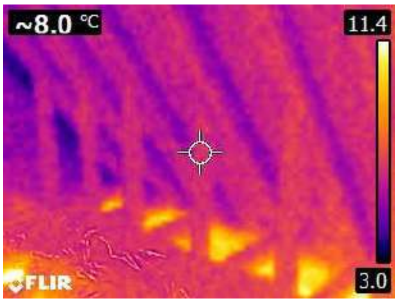
In Pinkie's roof (Table 15 M), in particular, it has been useful to assess the geometry of the connection with the wall: the fact that no timbers are visible in the lower part of the thermographic image, below the timber ceiling, suggests that no ashlar posts are present and that the lower part of the rafters is embedded in rubble masonry. This hypothesis is confirmed by the comparison with the thermographic images taken in the attic of Abbeystrand Buildings, where the ashlar posts are instead clearly visible (Table 15 A) .

In other heated attics thermography has allowed identifying damp areas where water ingress might be causing damage, as in Cockenzie House (Table 15 F, G), Pinkie House (Table 15 N), Stirling Castle Palace (Table 15 Q) and the King's Old Buildings in Stirling Castle (Table 15 R). Cockenzie House's attics are not heated but since the rooms are quite small it has been possible to heat them with a small electric heater. After one or two hours, depending on the room's dimensions, the thermographic images showed good results. In Cockenzie House and Stirling Castle Palace the damp areas revealed by thermography confirmed what was found in the roof spaces: very damp gable walls disintegrating into dust and falling on the timbers and ceiling. In the King's Old Buildings it was not possible to assess the condition of the timbers and gable wall because the roof could only be accessed from a small hatch on the North side and no walking boards were provided. In Pinkie House's case it was also impossible to assess the masonry's condition because the connection between the roof structure and the lateral wall was not accessible nor visible from the roof space.

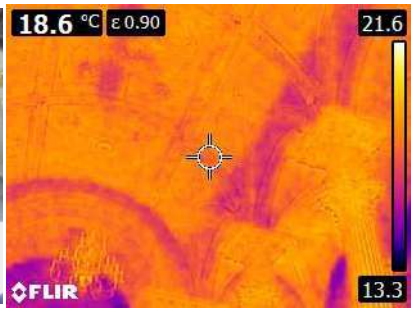
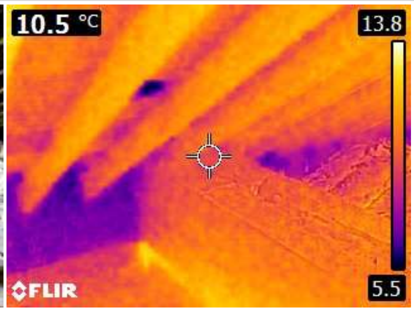
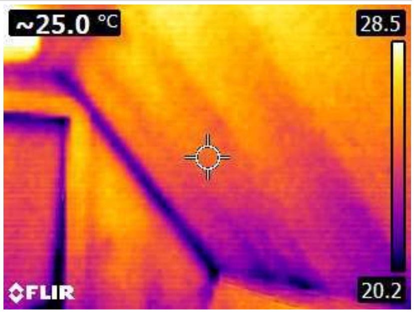
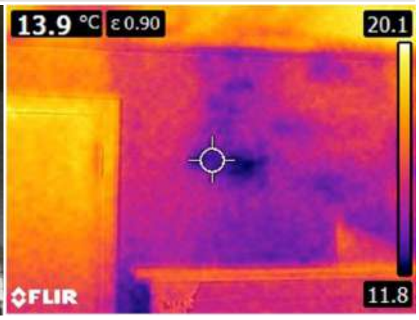
Therefore it can be concluded that, in environmental conditions such as the ones found in Scotland, thermal imaging is effective only in heated spaces. With regard to the reliability of thermal images, it only depends on the ability of who takes the images and interprets them, as discussed in section 5.3.2.

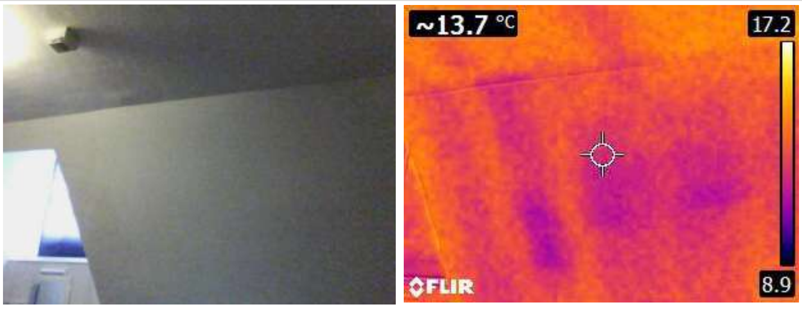
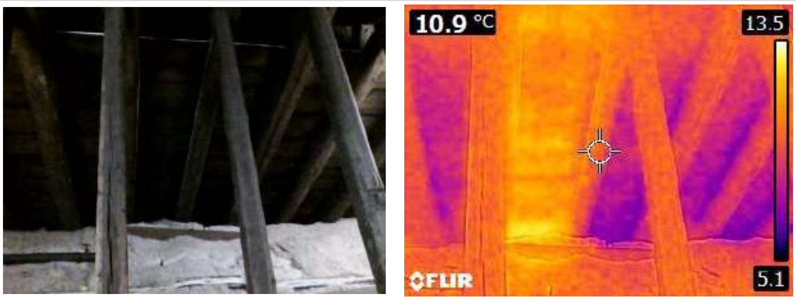
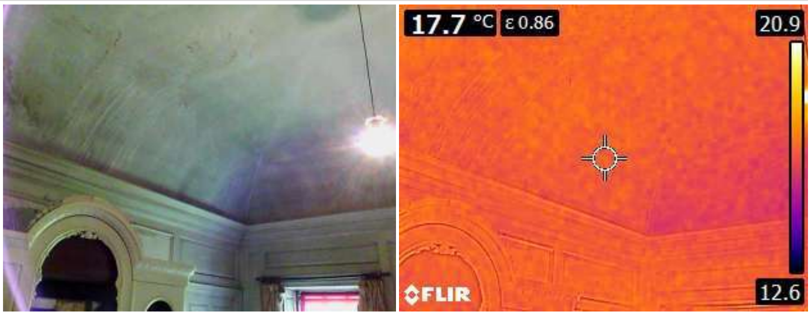
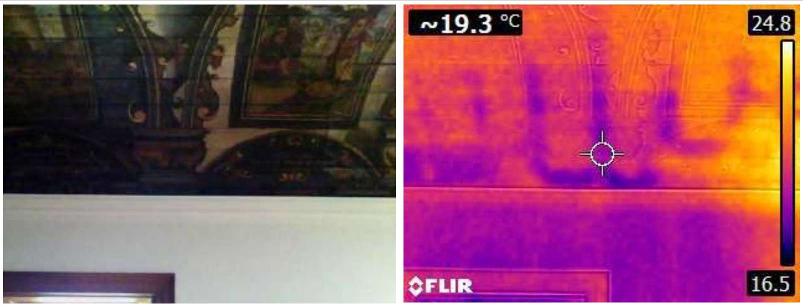
Table 15: The most significant thermograms taken in the attic and roof spaces of the case studies, with at least one example (when available) for both the roof space and the attic space of each case study. The measured air temperature/humidity and wood moisture content are also reported to show the environmental conditions in which the thermograms have been taken

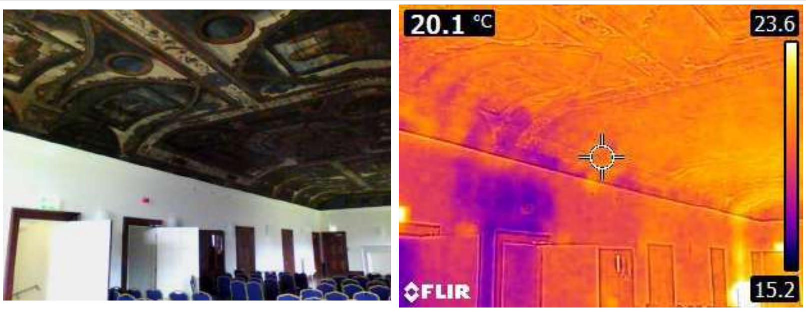
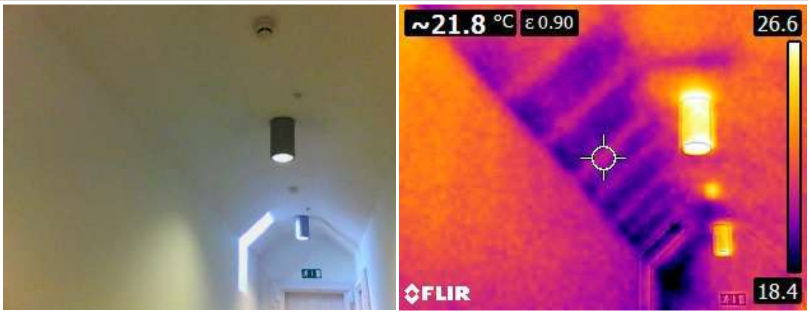
<table>
<tr><th colspan="2">Building</th><th>Air temp. hum.</th><th>Photographic image</th><th>Thermogram</th></tr>
<tr><td rowspan="4">Abbey strand

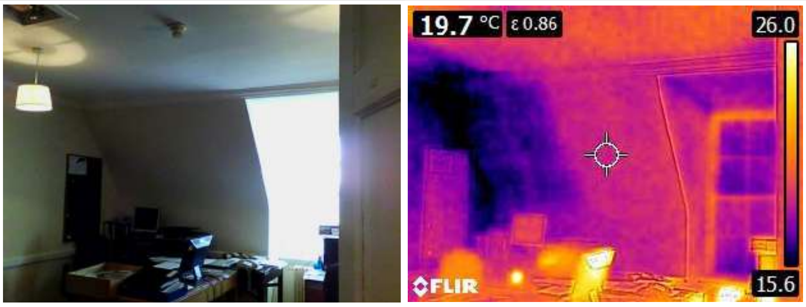
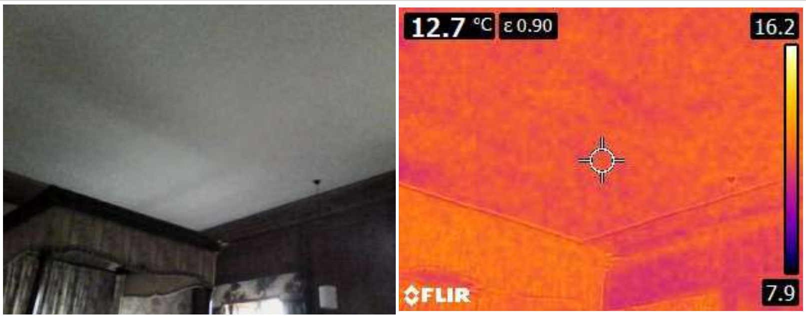
12/02/2016</td><td rowspan="2">attic</td><td rowspan="2">17°
51%</td><td></td><td>
</td></tr>
<tr><td colspan="2">A) higher temperatures identify the position of the timber roof structure hidden behind the wall and the ceiling: the presence of an ashlar post, typical of the Scottish rafter foot, is highlighted</td></tr>
<tr><td rowspan="2">roof</td><td rowspan="2">10°
65%</td><td></td><td>
</td></tr>
<tr><td colspan="2">B) higher temperatures identify the heat coming from the attic space underneath (wood MC not recorded)</td></tr>
<tr><td rowspan="3">St Andrew's and St George's church

03/02/2016</td><td>attic</td><td colspan="3">not accessible at time of test</td></tr>
<tr><td rowspan="2">roof</td><td rowspan="2">13.2°
54.4%</td><td></td><td>
</td></tr>
<tr><td colspan="2">C) lower temperatures at the eaves identify deficiencies in the flashings allowing air to come in from outside (wood MC=14.1%)</td></tr>
</table>

St Andrew's in the Square church 16/02/2016	attic	18.4° 35.2%	  ***D)** lower temperatures at the top of the columns and in the central part of the vaults identify missing insulation sheets above the plaster ceiling; the masonry parts in the bottom left corner are also identified by lower temperatures*
	roof	13.3° 56.2%	  ***E)** lower temperatures identify the masonry and a gap in the sarking boards between the rafters allowing air to come in from outside (wood MC=16%)*
Cockenzie House 22/01/2016	attic	9.7° (14° after heating) 77.3%	  ***F)** lower temperatures at the junction between the roof structure and the gable wall identify deficiencies in the flashings*   ***G)** lower temperatures on an intermediate gable wall identify damp masonry*

	roof		*not accessible at time of test*
Holyrood Palace	attic 02/06/2016	19.6° 52%	 ***H)*** *higher temperatures identify the position of the timber roof structure hidden behind the plaster panelling*
	roof 12/02/2016	11° 55%	 ***I)*** *higher temperatures between two rafters identify a gap in the insulation sheets allowing heat to come up from the attics (wood MC=16.5%)*
Newhailes House 03/06/2016	attic	17.7° 56.5%	 ***L)*** *no differencies in temperature highlighted*
	roof		*not accessible at time of test*
Pinkie House 09/03/2016	attic	18.7° 38%	 ***M)*** *lower temperatures identify the position of the timber roof structure hidden behind the painted timber ceiling*

			 ***N)** lower temperatures on a lateral wall identify damp masonry*
	roof	14.8° 48.7%	 ***O)** lower temperatures identify gaps between the sarking boards and the rafters allowing air to come in from outside, while higher temperatures identify gaps in the insulation sheets allowing heat to come up from the attic space (wood MC=15.6%)*
Stirling Castle Palace 10/02/2016	attic	17.1° 52%	 ***P)** higher temperatures identify the position of the timber roof structure hidden behind the plaster panelling*
			 ***Q)** lower temperatures identify damp masonry and plaster*
	roof		*not accessible at time of test*

Stirling Castle King's Old Buildings 10/02/2016	attic	17° 45%	 ***R)** lower temperatures on an intermediate gable wall and external wall identify damp masonry*
	roof		*not accessible at time of test*
Touch House 17/02/2016	attic	13.8° 55.2%	 ***S)** no differencies in temperature highlighted*
	roof	10.3° 69%	 ***T)** lower temperatures on an intermediate gable wall identify a gap in the masonry allowing air to pass (wood MC=18.3%)*

5.3.1.2 The effectiveness and reliability of the ultrasonic waves test and the micro-drill test

The ultrasonic waves test and the micro-drill test have been used to investigate the internal condition of the timber elements. As detailed in chapter 2 (section 2.1.3.4), the ultrasonic waves test emits sound waves with high frequencies into the material and measures how much time is needed for the waves to pass through the object; once the distance between the two sensors on the opposite sides of the objects is known, the velocity can be calculated and compared with reference velocities for sound materials, in order to assess the presence or not of internal flaws. As detailed in chapter 2 (section 2.1.3.1), the micro-drill test measures the resistance of wood to the penetration of a drill at a constant rotational speed and penetration rate. A graph representing this resistance is traced by the device during the test and provides a density profile of the section of the timber element.

The two tests are quite different: the micro-drill is semidestructive while the ultrasonic waves test is non-destructive, therefore preferable; the ultrasonic waves test has a numerical output while the micro-drill has a graphical one, easier to interpret. Most of all, the ultrasonic waves test has been designed to be used on concrete structures and its application to timber structures is quite recent. On the contrary, the micro-drill test has been designed specifically for timber and has been used for a longer time; the available literature is vaster and the implementation of the test has been studied in more detail. Therefore, the results of the micro-drill test can be considered reliable (from a qualitative point of view, as detailed in section 2.1.3.5) and can be used to "verify" the reliability of the the ultrasonic test results. In order to do so, the ultrasonic test and the micro-drill test have been performed in the same measurement points.

The results of the micro-drill test have already been presented in section 5.2.1 (Figure 333, Figure 334, Figure 335, Figure 336). The results of the ultrasonic test are summarized in Figure 343. Most of the measured velocities do not show a decrease higher than 10% compared to the reference velocity 1470 m/s. This, according to Dackermann et al. (2014), should correspond to healthy wood (green circle in Figure 343). Some of the measurements in Holyrood Palace have been taken with a higher Voltage and Gain (light blue circle in Figure 343), because the signal was not strong enough. The increase of these parameters is not recommended as it increases the noise in the signal. These measurements have all recorded good velocities. In other measurement points in Holyrood Palace, even after having increased the Voltage and Gain to the maximum levels, the signal was still unstable and it was therefore impossible to record a measurement (Purple circle in Figure 343). Only 12 measurements recorded a decrease in velocity higher than 10% compared to the reference velocity 1470 m/s (intersection between red and green circles in Figure 343), and 3 of them recorded a decrease in velocity higher than 10% compared to the reference velocity 1200 m/s (red circle in Figure 343), which should correspond to unhealthy wood (Rodríguez Liñán et al., 2015).

The results of both the ultrasonic waves test and the micro-drilling test depend on the original quality of the timber and on its present condition (e.g. the extent of material degradation and damage). In the case of the ultrasonic waves test it is not possible to determine the contribution of these two factors in the final result. The micro-drill, on the contrary, produces a graphic result based on which we can qualitatively estimate the original quality of the timber and the amount of degradation/damage affecting it.

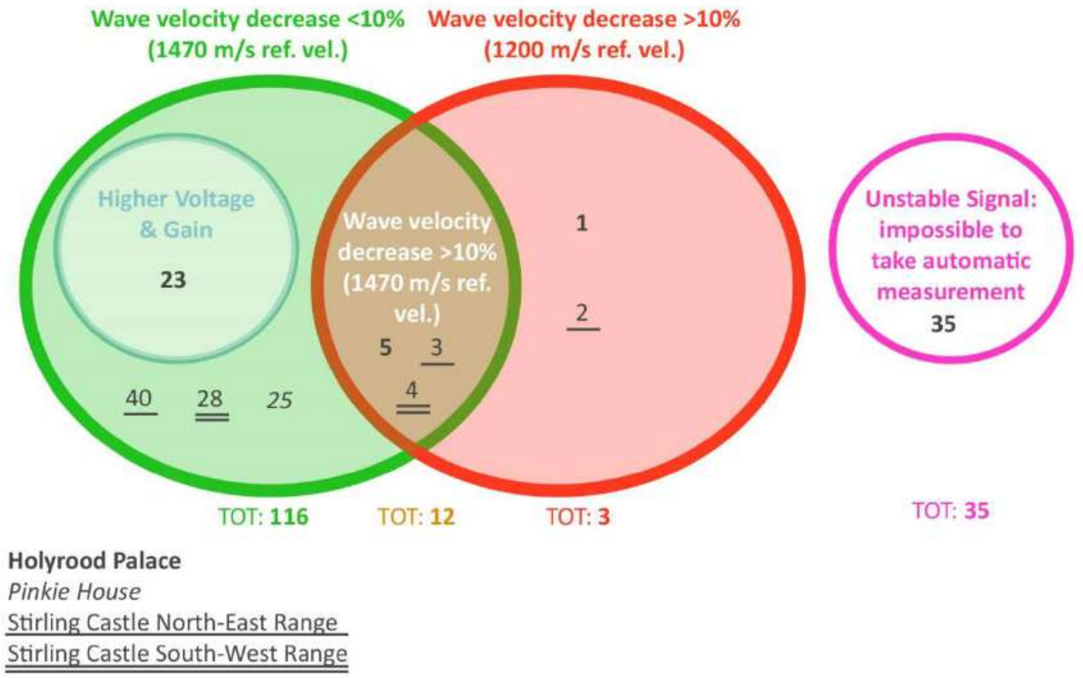


Figure 343: Results of the ultrasonic measurements taken in the roofs of Stirling Castle Palace, Holyrood Palace and Pinkie House

The original quality of the timber can be estimated by looking at the white part of the micro-drill graph, corresponding to non-degraded timber (example in Table 16). The graph shows the energy consumed by the drill to penetrate the timber at a constant rotational speed and penetration rate. It can be assumed that timber with a higher resistance to penetration has a better quality (Nowak et al., 2016). Thus an average height (representing the energy consumed by the drill = the resistance to penetration) has been calculated for each graph and three categories (high quality, medium quality, low quality) have been estimated based on the highest height divided by 3.

The extent of material degradation has been quantified according to the following procedure:

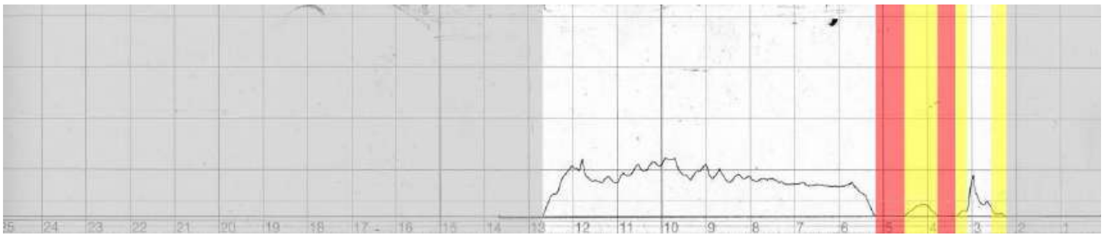
- An ideal graph has been calculated considering only the non-degraded wood: the area under the curve in the white part of the graph (85282 pixels in the example in Table 16) has been divided by the corresponding depth (8,09 cm in the example in Table 16) and then multiplied by the total depth (10.47cm in the example in Table 16);
- The real area has been measured (87418 pixels in the example in Table 16);
- The extent of material degradation/damage has been calculated in percentage:

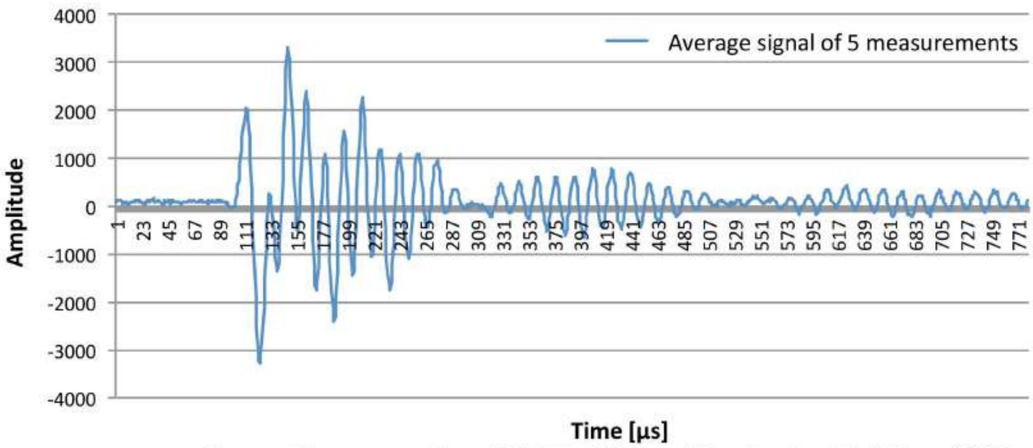
$$\mathrm{Md} = \frac{\mathrm{A_{id}} - \mathrm{A_r}}{\mathrm{A_{id}}}\, 100\ [\%]$$

(Md = material degradation extent; Aid = ideal area; Ar = real area)

Table 16: Example of measurement taken in the roof of Holyrood Palace: comparison between density loss calculated based on the ultrasonic results and extent of material degradation identified by the micro-drills. The density loss has been calculated based on the measured time of flight of ultrasonic waves, from which their velocity has been calculated, corrected based on grain orientation and moisture content and compared to reference velocities, as detailed in chapter 2 (section 2.4.3.4)

Location	Visible Decay	Moisture Content [%]	Velocity [m/s]	Relative Velocity Decrease [%]		**Density Loss Ultrasonic [%]**	**Material degr/damage Resistograph [%]**
				Reference 1470 m/s	Reference 1200 m/s		
Holyrood Palace Frame XVIIII North Strut Point a	no	15.7	1340	8.9	-11.5	**0.3**	**20.8**





The resulting average time of flight is 101,6µs with a standard deviation of 0,89µs

The micro-drills have then been grouped in six categories, based on the combination of original quality and extent of material degradation:

- High quality and low degradation/damage: 8 micro-drills;
- High quality and high degradation/damage: 0 micro-drills;
- Medium quality and low degradation/damage: 36 micro-drills;
- Medium quality and high degradation/damage: 4: micro-drills;
- Low quality and low degradation/damage: 5 micro-drills;
- Low quality and high degradation/damage: 3 micro-drills.

The extent of material degradation/damage has been considered to be low if less than 10% (Tannert et al., 2014). The micro-drill has been used in the same measurement points where the ultrasonic device has been used, thus the micro-drilling graph shows density variation along the path we assume the ultrasonic wave took. Figure 344 shows the ultrasonic wave velocities grouped according to the category to which the corresponding micro-drill belongs. Only the ultrasonic wave velocities measured without increasing the default values of voltage and gain have been considered.

High and low wave velocities are evenly distributed in all 5 categories. A different arrangement would have been expected: timber with high quality and low degradation/damage should have higher wave velocities than timber with low quality and high degradation/damage.

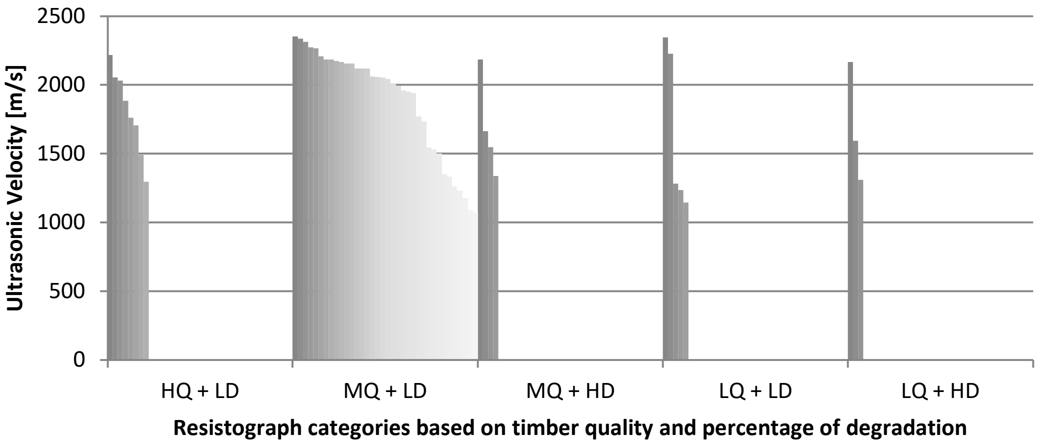


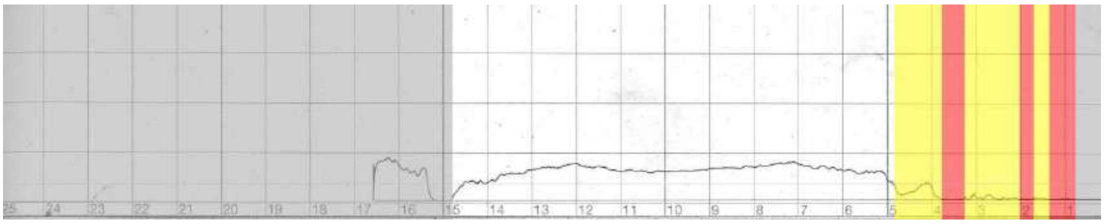
Figure 344: Ultrasonic wavs velocities grouped according to the categories of the corresponding micro-drills: HQ = High Quality, MQ = Medium Quality, LQ = Low Quality, LD = Low Degradation, HD = High Degradation

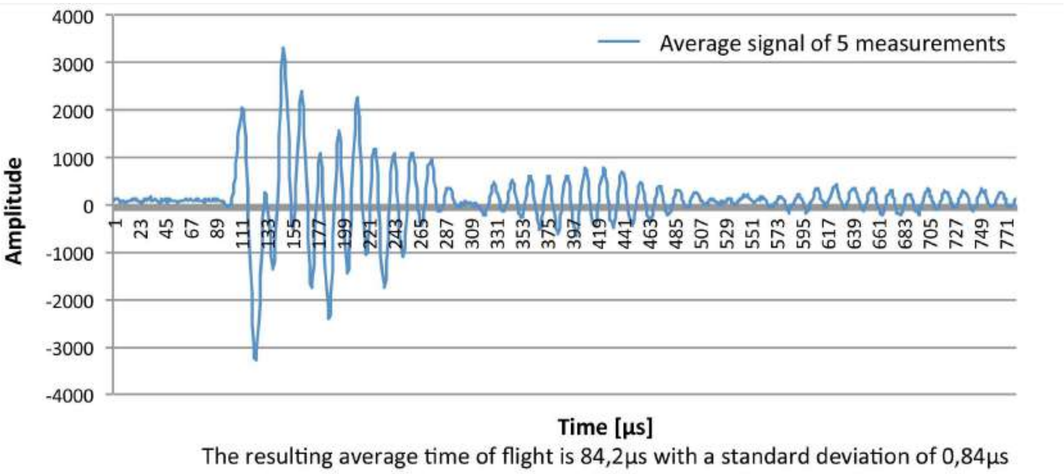
This means that in some cases the ultrasonic device measured a high velocity (supposedly corresponding to good quality/healthy wood), whilst the micro-drilling test highlighted a low quality timber with extended degradation (example in Table 17). In other cases the ultrasonic device measured a low velocity (supposedly corresponding to low quality/unhealthy wood), whilst the micro-drilling test showed a high quality timber with very limited degradation (example in Table 18).

In those measurement points where the ultrasonic device was not able to record a measurement automatically due to the unstable signal (Purple circle in Figure 343), at first it was thought that there might be extensive degradation/damage that caused the instability of the signal. However, the hypothesis was incorrect, as the micro-drilling device often reported the wood to be healthy in the same measurement points (Figure 345).

Table 17: Example of measurement taken in the roof of Pinkie House, where the ultrasonic test results do not correspond to the results of the micro-drill test: the ultrasonic test measured a high velocity, while the micro-drilling test highlighted internal decay

Location	Visible Decay	Moisture Content [%]	**Velocity [m/s]**	Relative Velocity Decrease [%]		Density Loss Ultrasonic [%]	**Material degradation Resistograph [%]**
				Reference 1470 m/s	Reference 1200 m/s		
Pinkie House Frame XVII Point 1	no	18.1	**2165**	-47.3	-80.5	-32.5	**26.3**

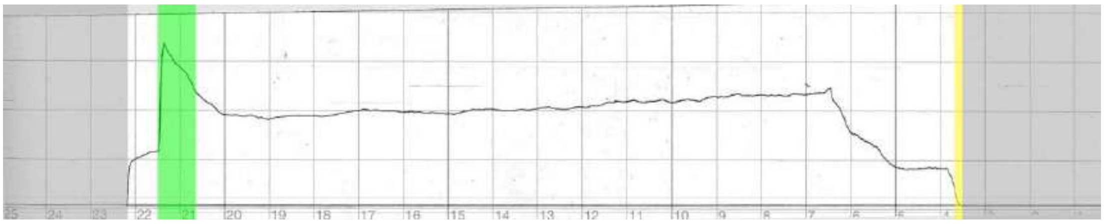


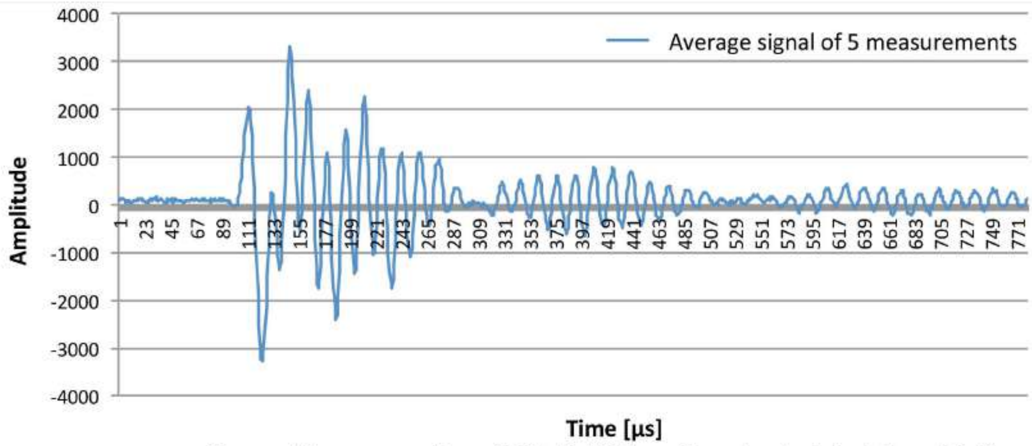


The discrepancies between the uiltrasonic results and the micro-drill results could be linked to problems with the setup of the ultrasonic test. In fact, due to the rough dressing of the timbers, the coupling of the transducers was problematic since the very beginning of the survey campaign and it hindered an effective transmission of the wave energy into the wood. However, once silicone polymer putty was used as coupling agent, it was possible to record automatic measurements in most measurement points, with the only exception of most points in Holyrood Palace (Figure 343). Holyrood Palace's roof is the only one where it has been necessary to increase the Voltage and Gain in all measurement points except for 6. In 23 measurements points it was possible to record automatic measurements after icnreasing the Voltage and Gain, while in 35 measurement points it was not sufficient, as the signal remained unstable.

Table 18: Example of measurement taken in the roof of Stirling Castle Palace, where the ultrasonic test results do not correspond to the results of the micro-drill test: the ultrasonic test measured a low velocity, while the micro-drilling test highlighted healthy wood

Location	Visible Decay	Moisture Content [%]	**Velocity [m/s]**	Relative Velocity Decrease [%]		Density Loss Ultrasonic [%]	**Material degradation Resistograph [%]**
				Reference 1470 m/s	Reference 1200 m/s		
Stirling Castle Palace North-East range, Frame 1, Point 16	no	17.1	**1295**	11.8	-8	1.9	**1**





The resulting average time of flight is 78,8µs with a standard deviation of 0,45µs

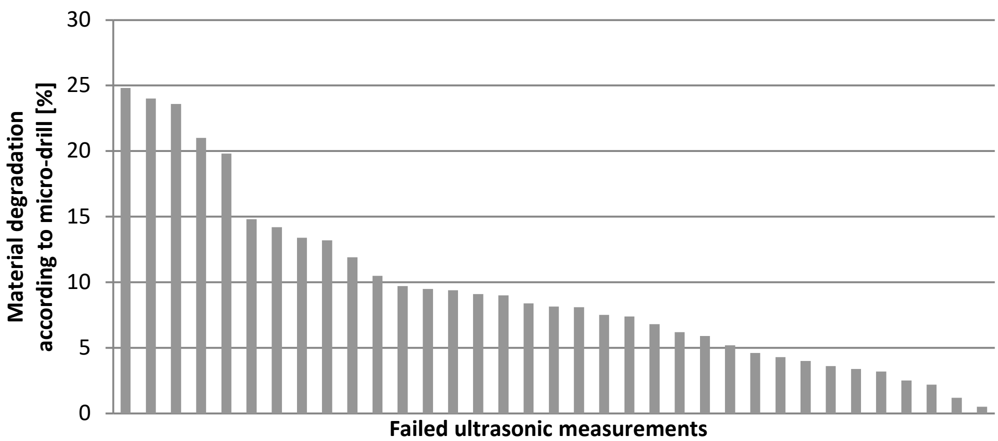


Figure 345: Extent of material degradation estimated for the micro-drill graphs in the measurement points where the unstable signal has not allowed recording the ultrasonic wave velocity

There is one important characteristic that differentiates Holyrood Palace's roof from those of the other case studies: its timbers have bigger sections. Stirling Castle's timbers range from sections of 6.5cm to 10.7cm, Pinkie House's timbers from 11.5cm to 15cm, but Holyrood Palace's timbers have sections up to 23cm. As detailed in chapter 2 (section 2.1.3.4), the attentuation of sound waves increases with the distance they travel, especially in case of high frequencies. This is because higher frequency waves have shorter wavelengths that are able to detect more subtle interior defects, but attenuate more quickly. The graph in Figure 346 highlights that it was impossible to take measurements due to the unstable signal only in sections equal to or bigger than 10cm. Moreover, the graph in Figure 347 highlights that the ultrasonic results that agree with micro-drill results have been obtained mainly for small timber sections, while the results that do not agree have been obtained bigger sections.

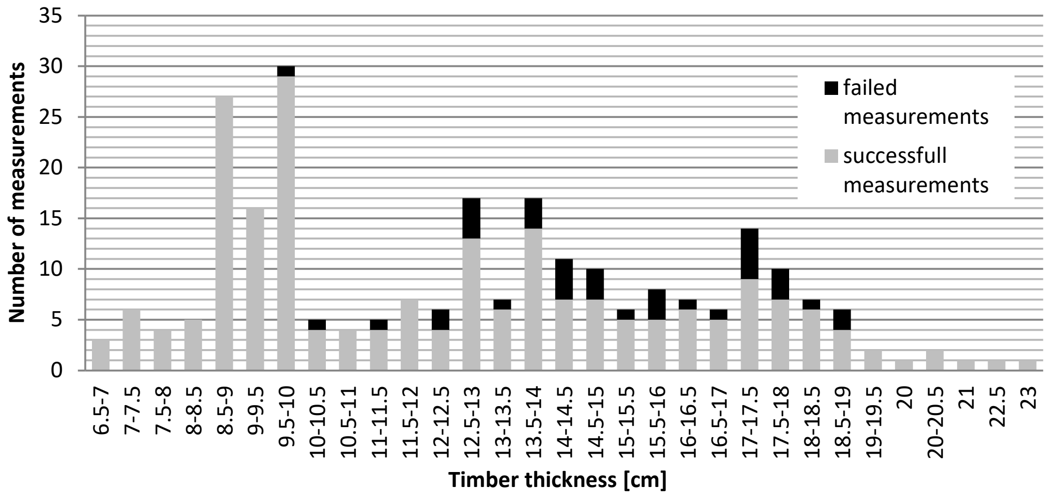


Figure 346: Graph showing the failed ultrasonic measurements, that could not be recorded due to the unstable signal (highlighted in black) distributed according to the thickness of the timber elements tested

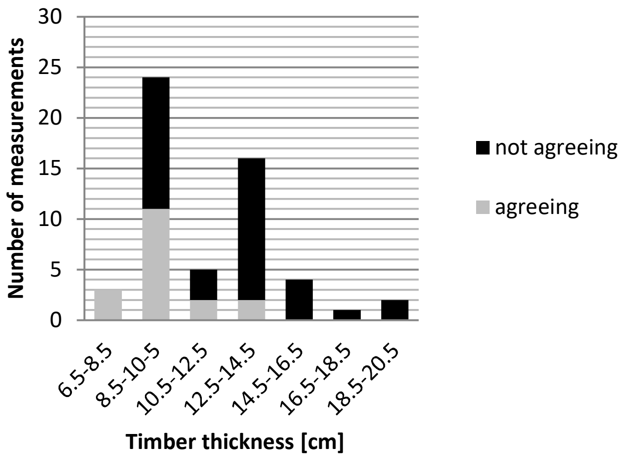


Figure 347: Graph showing the correspondance between the ultrasonic results and the micro-drill results distributed according to the thickness of the timber elements tested

The number of measurements taken is not sufficient to draw ultimate conclusions, but it does highlight that the ultrasonic waves test is not effective for timbers with big sections, in spite of recent research stating otherwise (Cescatti et al., 2014, Morales Conde et al., 2015, Rodríguez Liñán et al., 2015). On the contrary, it is not possible to make considerations on the reliability of the ultrasonic waves test, because the number of micro-drill measurements taken on small sections of timber is too low (Figure 347).

5.3.2 Knowledge and skills needed to implement the assessment techniques used

Expertise is a key parameter that can affect the effectiveness and reliability of any assessment techinque, as stressed by many publications (Dackermann et al., 2014, Hasníková and Kuklík, 2014, Feio and Machado, 2015). **Error! Reference source not found.** summarizes the specific knowledge and skills needed to correctly implement the different assessment techniques used, according to our experience during the surveys campaign.

The visual identification of historically relevant features requires knowledge related to types of historic structural typologies and construction techniques and details such as joints, timber dressing, fasteners, etc. Likewise, the visual identification of pathologies requires knowledge related to the different types of degradation and damage that might affect timber and the possible causes. Literature is full of classifications and examples, but it is not rare to find new features or variations of a type of joint or structure that are present only in a certain geographical area. These variations often produce types of damage different to that of other already known structures. It is therefore important to have a deep understanding of the structural behaviour of timber in order to be able to understand how a structure, even of a new type, is working, and what might be the cause of its pathologies. To do so it is also fundamental to know which features, details and parameters need to be measured and how.

Visual Strength Grading requires knowledge related to wood anatomy and timber natural defects, as well as knowledge of the VSG standards that can be applied depending on the timber species, age and survey condition. Each VSG standard, in fact, requires certain parameters to be measured in a specific way, and its guidelines must be closely followed during the survey in order to have reliable results.

According to our experience, the knowledge and skills needed to carry out visual assessment techniques are not hard to acquire. Conversely, while it is relatively easy to acquire through literature the necessary knowledge needed to carry out different in situ tests, operating the corresponding equipment involves practical procedures that we have sometimes found hard to learn and implement.

The timber species identification, both macroscopic and microscopic, requires a deep knowledge of the wood anatomy of different timber species. It is in fact necessary to know which features must be looked for and where, as well as being able to identify them. While the macroscopic identification only involves using hand lenses, the microscopic identification requires being able to take samples, cut slices for the microscope and operate the microscope, all quite difficult operations.

The measurement of the environmental conditions involves using an air thermometer and a hygrometer. The use of a thermometer is not at all difficult, but the use of a hygrometer with pins, as the one we used, can be quite arduous: it is fundamental to acquire knowledge about wood anatomy, to understand in which point and direction the measurements must be taken, and the pins must be hammered inside the wood with precision and care, otherwise they bend and break. Some practice is needed to become confident in the procedure. Knowledge related to the optimal environmental conditions for wood is then needed to interpret the results.

Timber sounding with a rubber hammer, although operatively simple, is very difficult to interpret: it is in fact impossible to learn simply through literature which sounds are associated with which features (defects, damage, degradation). Unfortunately, we have not obtained any meaningful results from this test, perhaps because we did not have the chance to learn from an expert how to interpret the different sounds.

The ultrasonic test and micro-drill test require knowledge related to wood anatomy, timber defects/damage/degradation and the working principles of acoustic waves, to understand in which point and direction the measurements must be taken and be able to interpret the results correctly. All of these can be acquired through literature. Operating the ultrasonic device is however not straightforward; in our case, if it hadn't been for an expert's suggestion to use silicon polimer putty instead of the gel mentioned in literature and provided by the device's manufacturer, we would have obtained no results at all. It is also difficult to postprocess the results and interpret them. The post-processing, in particular, is not fully exaplained in literature, especially the phase related to the calculation of the time-of-flight: as explained in chapter 2 (section 2.1.3.4), the time-of-flight automatically provided by the device is not accurate.

Endoscopy with a snake camera, on the contrary, does not pose any specific issues in terms of knowldge and skills needed, except that the interpretation of the acquired images might be difficult because of their scarce resolution, as in our case. Thermography requires instead knowledge related to timber defects/damage/degradation, to interpret the results, and the working principles of electromagnetic waves, to operate the thermal camera correctly. The post-processing of the thermal images with the software provided bny the camera's manufacturer is instead quite easy.

Table 19: Knowledge and skills needed to implement the assessment techniques used

Assessment technique		Knowledge	Skills
Visual identification of historically relevant features and pathologies		historic structural typologies and construction techniques and details; types of timber damage/degradation and causes; timber structural behaviour	identifying and measuring overall geometry, construction details, damage and degradation
Visual Strength Grading (VSG)		timber defects, wood anatomy, VSG standards	identifying and measuring timber defects
Timber species identification	Macroscopic	wood anatomy of different timber species	using hand lenses
	Microscopic	wood anatomy of different timber species	taking samples, cutting timber slices, using a microscope
Measurement of environmental conditions	Thermometer	optimal environmental conditions for timber	using a thermometer
	Hygrometer	optimal environmental conditions for timber, wood anatomy	using a hygrometer
Other non-destructive and semi-destructive testing	Rubber hammer	wood anatomy, timber damage/degradation/defects, sounds associated with different featrures	operating the equipment
	Ultrasonic test	acoustic waves working principles, wood anatomy, timber damage/degradation/defects	using an ultrasonic device, post-processing the results and interpreting them
	Micro-drill	wood anatomy, timber damage/degradation/defects	operating the equipment and interpreting the results
	Snake Camera	timber damage/degradation/defects	operating the equipment and interpreting the results
	Thermal Camera	electromagnetic waves working priciples, timber damage/degradation/defects	operating the equipment, post-processing the results and interpreting them

The above-mentioned knowledge and skills have been acquired by the author through a critical literature review, but mostly by interacting with experts, researchers and professionals in the field. Some previous experience in the visual identification of historically relevant features and damage/degradation and in the use of in situ testing techniques was acquired during the MSc studies at the ITAM Institute in Prague (Serafini, 2013). The MSc dissertation consisted in the historical and structural assessment of a seventeenth-century timber roof in Prague Old Town, surveyed through visual inspection and the use of NDTs and SDTs: humidity recordings, stress waves test, resistance microdrilling, pin pushing and loading jack. The presence of two experts during two out of five days of the surveying campaign was crucial to the learning process of the author.

Further expertise was gained during the PhD thanks to the participation in COST Action FP1101 and to short visits to Napier University (Edinburgh), HES Conservation Science Team and Padova University (Italy). Specific knowledge on timber damage/decay/defects, guidelines and different testing techniques was acquired during a training school in Portugal and a Short Term Scientific Mission in Italy, organized and funded by COST FP1101. During the 4 days training school the author had the chance to learn more about natural defects of timber, VSG and related regulations, carpentry joints as well as some in situ and laboratory testing techniques, whose use was demonstrated on several full-scale timber joints and a complete truss, tested to failure in the laboratory. The two weeks STSM at IVALSA Institute in San Michele All'Adige (Italy), supervised by Dr. Mariapaola Riggio, was instead focused on learning about different typologies of historic timber roof structures and different types of degradation/damage affecting them.

The contact with Dr. Daniel Ridley Ellis, associate professor and head of the Centre for Wood Science and Technology at Napier University, allowed gaining knowledge about wood anatomy and Visual Strength Grading of new timber as well as practical skills on the use and interpretation of results of the ultrasonic test and tomography. The University was visited on two occasions, during which Dr. Ellis demonstrated the use of the above-mentioned testing devices, while Dr. Ellis joined on one occasion the preliminary survey in St Andrew's and St George's church.

Dr. Maureen Young, conservation scientist at HES, gave useful advice on the use of thermography, both in person and by e-mail. A two days visit at the Forestry Faculty of the University of Padova allowed instead learning about wood anatomy and timber species identification techniques. Researcher Alan Crivellaro provided the knowldge, supervision, sample and laboratory instruments necessary to learn how to identify different timber species, macroscopically and microscopically.

The close contact with these experts was fundamental. The most useful learning sessions were the practical ones, especially in situ, because the author could directly benefit from the experts' past experience. These sessions made it clear that expertise cannot be gained through literature only, it must be passed on through mentoring.

5.3.3 Costs involved and overall evaluation of the assessment techniques used

The use of testing devices involves additional costs associated with their purchase and maintenance. In addition, the tests can be semi-destructive, which clearly limits their use. Other parameters such as physical effort demanded, time needed, possibility to implement the test alone, as well as the fact that the test is only specific for wood or can be used in other parts of the building, need to be considered. In order to fully evaluate the assessment techniques used, all of the parameters discussed above have been grouped in 3 topics (costs, on-site procedure, results) and graded on a one-to-four scale, where 1 is the best (Table 20). The effectiveness and realiability requirements and the knowledge and skills needed have been considered in the evaluation but are not detailed in the table since they have already been discussed in sections 5.3.1 and 5.3.2.

The on-site operation has been evaluated considering accessibility and visibility requirements (section 5.3.1), also related to the equipment dimensions, knowledge and skills needed to implement the technique and operate the equipment correctly (sections 5.3.2), the possibility of carrying out the technique/test alone, the physical effort demanded and the time needed. The results have been evaluated considering the knowledge and skills needed to interpret them, the amount of processing required and the reliability of the final results, discussed in the previous section.

Visual surveying techniques (visual inspection and VSG) do not have the drawbacks associated with the use of instruments: they allow gathering a wide range of information without disruption to the structure nor any additional cost, they can be carried out by one person alone with no particular phisical effort, and the time needed depends only on the dimensions of the roof structure and on the level of detail in which the investigation needs to be carried out. Visual strength grading is however specific for wood only.

The same is true for timber sounding with a rubber hammer: it is very cheap, non-destructive, easy to use on site. However, as detailed in the previous section, an experienced ear is needed (and is not easy to acquire), otherwise the results will not be valuable, and it is specific for wood only.

The timber species identification is a semi-destructive assessment technique (unless a macroscopic evaluation can be carried out on the end face of the timber element where the transversal section is visible, but this rarely happens). It can be carried out by one person alone but the preparation of the timber slices for the microscope slides is manually demanding; however, many slides can be made from one single sample. The use of a microtome is not necessary but obviously simplifies the procedure. Portable light transmission microscopes are now on the market for very low prices, allowing for the identification to be done directly on site. Moreover, light transmission microscopes can also be used to analyse samples from other construction materials.

Thermography is a non-destructive test; it can be carried out by one person alone and the processing and interpretation of results is not difficult, but the purchase cost is medium-high. On the other hand, the thermal camera can be useful in the assessment of other parts of the building, since it is not a test specific for wood.

The snake camera is a cheap and straightforward test that can be carried out by one person alone. The cost is however proportional to the results: images from a low-cost camera will have a lower resolution and will thus be more difficult to interpret. The test can be non-destructive or minor-destructive, depending on the need to make small holes to introduce the probe. Unfortunately insulation sheets in-between the timbers often hinder accessibility and visibility, making the test unsuccessful. On the other hand, just like the thermal camera, the snake camera can be used to assess other parts of the building.

Table 20: Evaluation of the testing equipment used during the surveys based on the costs involved, the test implementation and the results; the effectiveness and realiability requirements and the knowledge and skills needed have been considered in the evaluation but are not detailed in the table since they have already been discussed in sections 5.3.1 and 5.3.2. The grades' scale is 1=best, 4=worst.

Equipment	Costs	On site procedure	Results
Visual Inspection	**1** £0 (0€)	**2**	**2**
Visual Strength Grading	**1** £0 (0€)	**2** specific for wood	**2**
Rubber Hammer	**1** ~ £4 (5€)	**2** specific for wood	**3**
Microscope	**2** ~ £60 (70€)	**2** semi-destructive; preparation of the timber slices for the microscope slides is manually demanding	**2**
Thermal Camera	**3** ~ £660 (750€)	**2**	**1**
Snake Camera	**2** ~ £40 (50€)	**2** insulation sheets often hinder accessibility and visibility	**2**
Thermometer	**1** ~ £15 (20€)	**1**	**1**
Hygrometer	**3** ~ £800 (900€)	**3** requires physical effort; is time-consuming; difficult to hammer without deflecting pins; semi-destructive	**1**
Micro-drill	**4** ~ £8000 (9000€)	**3** heavy and bulky; drill sometimes deviates; specific for wood; semi-destructive	**2**
Ultrasonic	**4** ~ £7800 (8800€)	**4** difficult to have good coupling and good signal; difficult for one person to operate alone; not effective for timbers with big sections	**4** long and difficult data-processing

Air thermometers are very cheap, easy to use and with straightforward results. Hygrometers can instead be of different types (Riggio et al., 2014), with variable purchase costs. The cost is medium/high in the case of resistance type hygrometers adequate for different materials, able to measure the moisture content inside the timber rather than on its surface only, and incorporating automatic corrections for the air temperature and the timber species, such as the one we used. The GANN Hydromette RTU 600 is not easy to operate. It incorporates a hammer used to insert and extract the pins from the wood. A bit of training is necessary to understand how to hammer correctly without deflecting the pins, which need to be replaced whenever this happens. The cost for the replacement pins is also to be considered. The physical effort is quite high and the test is time-consuming. The results are however straightforward. Both thermometers and hygrometers can be operated by one person alone.

The micro-drill device is quite heavy and bulky, thus it is sometimes difficult to bring it in the roof space and carry out the test. The test can, however, be carried out by one person alone. The drill sometimes deviates but the results can be interpreted straight away and if there are doubts the test can be repeated as it is quite quick. The purchase cost is nevertheless high and the test is semi-destructive.

The ultrasonic device is also expensive but it is non-destructive. It is difficult to operate because the coupling between the transducers and the surface of the wood is often not optimal, and this can create unstable signals. Moreover the test requires two people, one keeping the transducers and one operating the touch screen. The test is effective only for timbers with small sections and the data processing is quite long.The grades given to each assessment technique are summarized in Figure 348. This evaluation is not comprehensive as there are many other non-destructive and semi-destructive tests that can be used in situ to assess historic timber structures, as detailed in chapter 2 (section 2.1). Moreover, the tests compared are not interchangeable, but complementary, as they give information on different aspects of the timber structure. However, as detailed in chapter 2, these devices have been selected based on availability and cost, thus they are representative of what is available to Scottish professionals.

Looking at Figure 348 it can be noted that: besides visual techniques which are obviously costless, the thermometer and hammer are the cheapest (1), followed by the snake camera/microscope (2), the thermal camera/hygrometer (3), and finally the micro-drill and ultrasonic device which are the most expensive (4). The thermometer is also the test that requires less training and effort on site (1), followed by most of the other techniques (2), the microscope/micro-drill (3), and the ultrasonic test that is the most difficult (4). This work highlights that further research is needed in order to overcome the problems in the setup and results processing of the ultrasonic test and make it appealing to professionals working with historic timber structures. On the contrary, the micro-drill test is minor-destructive, expensive and needs training, but it is reliable and it gives information on the internal condition of timber elements, which no other considered technique does.

This research also highlights that not every test is suitable for all survey conditions and every type of roof structure: the thermal camera, for example, requires a heated environment; the use of the snake camera is hindered by the presence of insulation sheets; the micro-drill is quite bulky and thus requires a comfortable hatch to access the roof space; and finally, the ultrasonic device is not suitable for structures made of timbers with big sections. It is therefore important to design each assessment according to the techniques that can be effective for the particular roof space and structure that needs to be investigated.

Costs involved	4			**Microdrill**	**Ultrasonic**
	3		**Hygrometer** **Thermal Camera**		
	2		**Snake Camera** **Microscope**		
	1	**Thermometer**	**Visual Inspection** **VSG**	**Hammer**	
	0	1	2	3	4
	On-site procedure and interpretation of results				

Figure 348: Comparison between assessment techniques used during the surveys; the best grade is 1; x=non destructive test, x=minor destructive test

5.4 Proposal of specialising course for conservation professionals

This research has highlighted that Scottish building owners, users, managers and professionals would benefit from targeted training providing them with the necessary skills and knowledge to value, conserve and maintain historic timber roof structures. Regular maintenance rather than extraordinary repairs should be implemented and, when repairs are necessary, trained professionals should be available and able to implement the state-of-the-art tools and methods. Owners often adduce lack of funding as the main reason preventing them from carrying out the necessary inspections and repair works. However, it is clear that if trained professionals inspected roof spaces regularly, damage could be detected in its early stages, when it could be solved in an easier, quicker and cheaper way.

Based on our findings and on examples of training schools organized by COST Action FP1101 on similar topics (D'Ayala et al., 2015), we outline the aims, learning outcomes, structure and contents of a course on the assessment of historic timber roof structures which could be proposed to start addressing the lack of training of professinals in this specific field. Separate training courses should be designed for buildings owners/users/managers and for craftsmen. Since the author is an architect and has focused the research on the assessment of roof structures that architects and engineers carry out, the designed course is addressed to participants with this profile only.

The aim of the course would be to raise awareness amongst engineers and architects about the importance of conserving historic timber roof structures and to equip them with the knowledge and skills necessary to address the issues and challenges involved in the first phase of any conservation project: the assessment. Professionals would learn how to read and analyse a timber roof structure, gaining a thorough understanding of which aspects need to be investigated and how they can be investigated, in order to reach a critical evaluation of the structure both from a historical and a structural point of view.

The assessment of historic timber structures involves different disciplines (construction history, structural engineering, material science, etc) therefore the course would be necessarily multidisciplinary. Ideally, a team of experts, professionals and researchers with different backgrounds and expertise should be invited to give the lectures; this would allow attendees to understand the main focus of each discipline and would underline the need for close collaboration and interaction between different professionals such as engineers, architects, historians and wood technologists.

The contents would review a wide range of topics, based on the present research:

- The historic development of Scottish timber roof structures, with a glimpse to the wider European context, looking at different typologies, structural arrangements and details such as types of joints, timber dressing, tool marks, carpentry marks. The analysis of these aspects can help in estimating the structure's date and value, but also in understanding its structural behaviour.
- Basics of wood anatomy and techniques to identify timber species: macroscopic analysis with hand lenses and microscopic analysis using a light transmission microscope. Particular attention will be paid to Scots pine and oak, the two main species used in Scottish timber roof structures. Basic knowledge on wood anatomy is necessary to understand the structural behaviour of timber and to be able to identify the timber species, which is one of the most important parameters when carrying out structural tests and calculations.
- Visual assessment techniques: detailed visual inspection, to assess the geometry and condition of the structure, with particular attention to the different types of degradation and damage that can affect timber, and Visual Strength Grading (VSG), to assess the natural defects of the structure and estimate the elements' strength and stiffness. Typical damage and decay of Scottish timber roofs will be reviewed as well, pointing out weak points to which special attention should be paid during the inspection.

- In situ and laboratory testing techniques for structural timber to further investigate the structure condition and mechanical properties. Specific testing techniques to estimate the mechanical properties would be included, although they have not been discussed in the present study.

Although this topic has not been covered by the present research, the course should also review different methods of structural analysis of historic timber roof structures, both as assessment and verification tool: traditional hand calculations, numerical modelling, physical modelling. This would be restricted to attendees with an engineering background and would allow them to understand how the data gathered during the survey can be used to verify the structure's safety.

Following the example of COST Action FP1101 training schools (D'Ayala et al., 2015), of which the author has had first hand experience during the training school in Minho in May 2015, the course could be organized in 5 one-day modules, with each module corresponding to a topic: the mornings used for ex-cathedra lectures and discussion and the afternoons for site visits and practical sessions directly related to the mornings' topics. Edinburgh would be the best location since many examples of roof structures from different periods would be available in a restricted geographical area.

The learning outcomes would include the ability to:

- estimate the structure date and value based on the analysis of its typology and construction details;
- identify different timber species;
- carry out an effective visual inspection, knowing where to look for faults, and being able to identify the type and extent of damage/decay and estimate its causes;
- grade timbers visually, according to current standards;
- use testing techniques to further assess and estimate the condition and mechanical properties of the structure;
- use the gathered data to evaluate the structure safety.

In order to make the course appealing to professionals, accreditation could be sought from professional bodies such as the Institute of Historic Building Conservation (IHBC). The course could then be completed by another training on the design and implementation of repair interventions, which are beyond the scope of this study.

5.5 Conclusions

The review of current conservation practice in this chapter highlights the lack of specific standards, regulations, training and published projects. This lack is reflected in the approach of building owners, managers and conservation professionals. There are no standards in UK related to the inspection and survey of in situ timber structures and neither HES nor TRADA address the subject extensively. Listings by HES mention roof structures very rarely and applications for interventions are seldom judged by experts in conservation. Owners and building managers seldom program regular inspections and maintenance works and often they do not provide basic accessibility and visibility conditions. There is also a lack of academic and training courses in conservation engineering in Scotland and North England and most professionals do not publish and share their conservation projects. The result is that professionals still rely mainly on traditional methods and past experience, which entails making several assumptions, and sometimes replacing the whole structure or implementing unnecessary or over-dimensioned interventions, as confirmed by our surveys.

In order to contribute in improving current conservation practice we have investigated the condition of seventeenth- and eighteenth-century timber roof structures in Scotland and evaluated the assessment tools and methods employed. We have identified typical pathologies and possible causes for each type of structure. We found that about one fourth of the surveyed roofs show pathologies caused by flaws in their initial design, while in a few cases past alterations and repairs contributed to creating or accelerating damage because of inadequate materials used, loads increased or the overall structural behaviour modified. We also noticed that poor environmental conditions and poor accessibility are a major issue, mainly causing biotic attack in common rafter roofs incorporating attic rooms, but also hindering the inspection and maintenance of many roofs.

The pathologies and causes have been assessed with state-of-the-art techniques that we have evaluated in terms of effectiveness, reliability, skills and knowldge needed to implement them and costs involved. Not all assessment techniques employed have given results, and in some cases it has not been possible to assess their reliability, but the particular environmental and testing conditions in which each test can be useful have been identified. This has highlighted that it is fundamental to design each assessment according to the techniques that can be effective for the particular roof space and structure that needs to be investigated. Moreover, expertise has been identified as a key parameter, to be acquired through mentoring, not literature only. This is why, based on our findings, we have also outlined the aims, learning outcomes, structure and contents of a course on the assessment of historic timber roof structures which could be proposed to start addressing the lack of training of professinals in this specific field.

6 Conclusions

This thesis researches the conservation of seventeenth- and eighteenth-century timber roof structures in Scotland, largely forgotten up to now. Previous studies fail in characterizing the extent, nature and condition of these structures, especially post-1650, mainly because of the shortage of measured surveys. This missing body of knowledge, together with the absence of specific standards and training, hinders good conservation practice. The result is that many roofs are heavily altered or replaced, and thus lost, depriving future generations of a substantial part of this important heritage.

In order to address these issues, a database with a related mapping of 1500 Scottish buildings of the period has been created and a representative sample of roofs has been studied through in situ surveys and archival research. Preliminary surveys have been carried out in 53 buildings and thorough, in-depth investigations have been performed in eight case studies, using state-of-the-art tools, methods and standards. This has allowed gathering data on 59 original timber roof structures.

Thanks to this data, we have characterized the surviving family of seventeenth- and eighteenth-century Scottish timber roof structures and traced their historic development, demonstrating that they form a heritage of great extent and quality. The collected data has also been used to identify typical pathologies and possible causes for each roof structural typology. Moreover, the assessment techniques used have been evaluated in terms of effectiveness, reliability, costs involved and training needed, in order to understand when they can be useful during the assessment. Based on the findings, a specialisation course for conservation professionals has been proposed.

6.1 Research outcomes

Our research has allowed tracing the historic development of seventeenth- and eighteenth-century Scottish timber roof structures. For the first time, structural arrangements, construction methods and details, materials, know-how and foreign influences have been comprehensively described and classified. From this evidence, a distinctive Scottish school of roof carpentry has emerged, little influenced by Europe up to mid eighteenth century and retaining characteristic features even after.

We can confirm Hanke's (2006) statement that up to late seventeenth century the majority of Scottish roofs is of a simple common rafter form, hidden behind decorated ceilings, with no subdivision between load-bearing and non load-bearing rafters, no longitudinal members other than the sarking boards, no tie-beams nor wall-plates. This is remarkable considering the wider European context, where these features are introduced much earlier. Thus, Scottish common rafter roofs might give an indication as to how very early North-West European roofs looked like. While previous research has relied mainly on archive material, we have surveyed 29 roofs with such characteristics while also finding more than 50 drawings of them in archival documents and unpublished work.

Previous research had highlighted that the extensive use of simple common rafter roofs is due to the limited spans and thick walls that characterized Scottish architecture of the time, and to the timber trade with North Europe, which provided short small beams and deals in great quantity (Hanke, 2006, Newland, 2011). Our research demonstrates that Scotthish roofs evolve when these conditions change at the end of seventeenth century, with the introduction of classical and baroque architecture in Scotland. Scottish wrights are forced to develop roof structures able to span increasingly wider spans with shallow pitches and hipped arrangements, whilst supporting heavy plaster ceilings. Our work has allowed highlighting and understanding this important development that had been disregarded by previous literature, mainly due to the lack of measured surveys.

The analysis of our surveys and archive material also highlighted that the imported timber products and the know-how of wrights gradually change to meet the structural requirements of the new architecture, where gable walls disappear, walls become thinner and spans wider. We observed that: (i) the traditional rafter feet are substituted by tie-beams, wall-plates and butt-purlins, to reinforce the longitudinal and transversal connection and stability of the roof; (ii) tension-absorbing elements and joints are introduced to counteract the elements' deflection and the roof opening; (iii) the subdivision between load-bearing and non load-bearing rafters is introduced to better distribute the loads; (iv) timber scantlings become more rectangular and are differentiated based on the elements' structural role, confirming Thomson's (1999) statement that sawmilling in Scottish ports develops to process imported timber. These characteristics have emerged in 18 roofs we have surveyed.

However, our investigations also demonstrate that these innovations are not sufficient to attain undisturbed wide spans and that it is eventually necessary to import from elsewhere a completely different structural type: the Italian trussed roof, that we have found starting from 1740s in 14 public buildings and country houses, used even for reduced spans. In fact, only with the use of trussed roofs Scottish wrights are able to get rid of the intermediate supporting walls used up to then. We have also surveyed 5 purlin roofs, showing that wrights experimented using different solutions.

Interestingly, we found that despite the introduction of ~~a~~ new type of roof structure (the trussed roof) some distinctive Scottish features are maintained: the sarking, the raised tie-beams, the idea of bringing the load down on the masonry, the predominant use of Scots Pine, slates as roofing material and roman numerals as assembly marks. At the same time, we recorded details that suggest instead foreign influences: joggles, a distinctive English feature (Yeomans, 1992), cleats and notches, typical Italian features (Munafò, 2002, Serlio, 1545), bulb-shaped joggles and unusual carpentry marks, whose origins remain uncertain. Moreover, our archival research has highlighted that the English influence, probably prompted by the Union in 1707, is traceable in the language too: the English word 'carpenter' partly substitutes the Scottish word 'wright' during the eighteenth century.

Our research also sheds new light on the role that wrights, architects and patrons played in importing technological knowledge from various sources and in adapting it to the local tradition. According to previous research, wrights become increasingly important during seventeenth century, some even aspiring to the role of architect (Dunbar, 1976, Newland, 2012b). However, our studies on the seventeenth-century roofs of George Heriot's Hospital (NRS GD421/5/2, 1633-42) and Brechin Castle (NRS GD45/18/1616/25, 1694 in Newland 2010) suggest that the reliance on imported short timbers, and the consequent extensive use of simple roofs, partially obliterated the wrights' role in the roof design in this period. We also found evidence that a mason is called to judge the quality of the wright's work in Brechin's Castle and to repair it. This suggests that wrights did not always have a prerogative on timber-work at the end of seventeenth century.

Our investigations on St Andrew's in the Square church (1751-3) suggests instead that when wrights start working as professional architects, as pointed out by Lewis (2006, 2015) and highlighted by our research (we have found many teams of wrights and masons that design churches in the eighteenth century), they hand over the timber-work to another wright. The wright Allan Dreghorn works at St Andrew's as architect, but the client asks the wright John Robertson to make three plans and estimates of the roof (Renwick, 1911). This entails that it was the wright's responsibility to design the roof structure, even if the architect was a wright.

The request to see three plans of the roof of St Andrew's in the Square also shows that the client wanted to have a say not only on the budget but also on the design of the roof structure. Other patrons, from both centuries, give specific instructions for the design of their roof: James Baine says that the Earl of Panmure binds him at Brechin Castle to make the roof in a certain way rather than how he would have done it (NRS GD45/18/1616/21, 1694 in Newland 2010); the Marquis of Tweeddale asks the architect William Adam to change the present roof of his house at Yester, which is an M-roof, into a platform roof (NLS MS14551/109, 1742-49).

Our research on the work of the Adams shows that architects were also influentieal in the design of roof structures: they play an important role in the introduction of the trussed roof in Scotland. William is the first to draw a trussed roof for a Scottish building in 1720, as suggested by Hanke (2006), but, according to our surveys, only one of his buildings of the period has a trussed roof:

Hopetoun House (1721-48). This makes us think that, although William aspired to build trusses, Scottish wrights were unable or unwilling to construct them, at least at the beginning, probably because they had limited knowledge on the structural behaviour of timber and on the strength and durability of different timber species. In fact, our surveys highlight that Scottish wrights: (i) introduced tension-absorbing joints and elements very late compared to the rest of Europe; (ii) often used them incorrectly and did not develop them fully; (iii) used the same species for all of the elements of the structure; (iv) often did not distribute elements of different quality according to the stresses they had to endure. Our conclusion is that the Adams were forced to bring wrights from abroad in order to implement their designs; this external influence is also suggested by the heterogeneity of solutions and details used in Scottish roofs and highlighted by our surveys.

Since our work is based on a limited sample of surveyed roofs and consulted archive material, many questions remain unanswered. Nevertheless, the work succeeds in demonstrating that seventeenth- and eighteenth-century Scottish roofs form a heritage of considerable extent and interest, worth studying in more detail and worth conserving as adequately as possible, in order to secure the knowledge of future generations and to ensure long life to the buildings they are part of. Unfortunately, this is not always the case. In fact, we have found that these structures are not always adequately conserved, not only because their value is not recognized, but also because there is a lack of specific standards and training for the assessment of historic timber structures, as emerged from a critical literature review, questionnaires to building users and interviews to conservation engineers. Indeed, the assessment of historic timber structures is challenging, as timber is an organic material with variable properties. Recent research has started addressing this issue (Dackermann et al., 2014, Kloiber et al., 2015b, Riggio et al., 2014, Tannert et al., 2014), but the lack of specific standards and training forces Scottish professionals to rely mainly on traditional methods and past experience, that are often inadequate as they entail making several assumptions.

UK has no standards for the survey of in situ timber structures and Eurocode 5 and BNS are only partly applicable. HES guidelines do not include anything specific on the subject and TRADA's publications partially address the topic, but do not suggest a standardized procedure. Protection policies also have flaws: listings by HES mention roof structures very rarely and applications for interventions are seldom judged by experts in conservation. This situation is worsened by the fact that owners and building managers seldom program regular inspections or maintenance works and often do not ensure basic accessibility and visibility conditions. On top of that, there is also a lack of academic and training courses in conservation engineering in Scotland and North England and most professionals do not publish or share their conservation projects.

The result is that professionals are not provided with the specific knowledge, guidance and tools to take care of historic timber roof structures. Thus, they sometimes replace the whole structure or implement unnecessary or over-dimensioned interventions, because they are unable to reach a confident structural assessment. In fact, we have found a high percentage of seventeenth- and eighteenth-century Scottish buildings whose original timber roof structure has been replaced.

In order to address these issues and to contribute in improving conservation practice, we have investigated the condition of seventeenth- and eighteenth-century timber roof structures in Scotland, identifying typical pathologies and possible causes for each type of roof structure. We found that about a fourth of the surveyed roofs show damage and material degradation caused by poor initial design of the structural arrangements and details. Common rafter roofs and trusses have problems of transversal opening due to the absence of tie-beams and to the use of joints unable to resist tension forces. Common rafter roofs also have problems of longitudinal instability, due to the absence of longitudinal bracing; trusses and purlin roofs show instead deflections and cracks due to the use of slender timbers, insufficient propping and problematic asymmetrical arrangements.

Our surveys highlighted that in a few cases past alterations and repairs have contributed to creating or accelerating damage because of inadequate materials used, loads increased or the structural behaviour modified. Moreover, we noticed that most past interventions are poorly documented and some that were meant to be temporary have become permanent, without being monitored.

We observed that common rafter roofs are the most affected by biotic attack. The causes are the rough dressing of the timbers, poor maintenance and poor environmental conditions. Since most of these roofs are plastered and used as attic rooms, the lower part is often not visible nor accessible, hindering inspection and maintenance. At the same time, the roof's upper part is generally small and poorly ventilated, due to modern waterproofing sheets added in-between the sarking and the slates and excessive insulation. Finally, many roofs host uncovered water tanks that increase humidity.

The lack of inspections and maintenance certainly increases all of these problems and is mainly due to accessibility problems that characterize many of the roofs we have surveyed: the presence of bats or wasps, pigeons' droppings, lack or hatches or hatches with very limited dimensions, absence of walking boards. We found some roofs or substantial parts of roofs completely inaccessible. Moreover, our questionnaires to owners, users and managers highlighted that they do not always know how to access their roof spaces and do not always have the necessary equipment to do it.

The pathologies and causes summarised above have been identified using state-of-the-art assessment techniques that are available to Scottish professionals, such as: visual inspection to identify historically relevant features and pathologies; VSG to assess the quality of timbers; a thermometer to measure the air temperature/humidity; a hygrometer to measure the wood moisture content; a light transmission microscope to identify the timber species; a snake camera and a thermal camera to investigate hidden parts of the structure and identify damp areas; a rubber hammer, an ultrasonic device and a micro-drill device to assess the internal condition of timbers.

These methods have been evaluated in terms of effectiveness and reliability. Our research highlights that not every test is suitable for all survey conditions or all types of roof structures. It is therefore important to design each assessment according to the techniques that can be effective for the particular roof space and structure that need to be investigated. We found that the snake camera is ineffective if it has low resolution and in presence of accessibility issues, such as insulation sheets between timbers. At the same time, the thermal camera does not provide valuable results unless the space is properly heated. We did not obtain useful results from the rubber hammer either, because of the lack of an experienced ear. Finally, thanks to the comparison with the results of the micro-drill, we proved the ultrasonic device to be ineffective for timbers with big sections, in spite of recent publications stating otherwise (Dackermann et al., 2014, Llana et al., 2016, Machado et al., 2009).

We have also ranked the assessment techniques used according to the costs involved, the physical effort demanded, the time needed, the possibility to implement the test alone, the fact that the test is non-destructive or semi-destructive and if it is specific for wood or can be used in other parts of the building. The thermometer has been graded best, followed by (in order of cost) visual techniques, the snake camera and microscope, the hygrometer and thermal camera: these are either semi-destructive, not easy to use, not always effective or require more training. The hammer is as cheap as the thermometer and visual techniques but the expertise required for it to be effective is hard to acquire. Next comes the micro-drill: it is very expensive; it requires training and specific knowledge and it is not easy to use on site because of its dimensions and weight. It is however extremely effective and reliable and it gives information on the internal condition of timber, which no other considered technique does. Lastly, the ultrasonic device: it is as expensive as the micro-drill but it is more difficult to operate and interpret and it is not effective for timbers with big sections.

This evaluation highlights the importance of combining different testing techniques to enhance the assessment of timber structural elements and to evaluate the reliabilty of the tests' results. Our geometric survey has benefitted not only from visual techniques but also from the use of the thermal camera to see hidden parts of the structure. We have assessed the timber quality both through VSG, which consider the visible natural features, and by analysing the micro-drill graphs, that show density variations. We have identified water ingress problems with a thermometer, a hygrometer and a thermal camera, each providing information on the non-optimal environmental conditions, high wood moisture contents and damp areas. The combined use of the rubber hammer, the micro-drill and the ultrasonic device to assess the internal condition of timber has allowed to understand which of these tests is more effective and reliable and in which survey conditions.

6.2 Our work also confirms that expertise is a key parameter and that it must be acquired through mentoring. In fact, the knowledge and skills necessary to implement the assessment techniques used have been acquired by the author mostly by interacting with experts, researchers and professionals in the field. This is why, based on our findings, we have also outlined the aims, learning outcomes, structure and contents of a course on the assessment of historic timber roof structures which could be proposed to start addressing the lack of training of professinals in this specific field.Final remarks

In heritage conservation, values are critical to decide what to conserve and how to do it. Values give some things significance over others and thereby transform some objects and places into "heritage". The ultimate aim of conservation is not to conserve material for its own sake but, rather, the values embodied by heritage: "The value of architectural heritage is not only in its appearance, but also in the integrity of all its components as a unique product of the specific building technology of its time" (ISCARSAH, 2003). A monument is authentic because it provides identity to cultures, regions and towns, because it's a document on ancient knowledge, culture, technology, and a witness of cultural and technical achievements from whose study and use we can still learn and improve today.

Historic timber roof structures must be conserved because they are precious witnesses of the efforts and inventiveness of mankind in search of new shapes and steadier configurations, using available materials. These structures have cultural significance: they help understanding the past, enrich the present and will be of value to future generations (ICOMOS, 1999a). Timber elements carry traces of the tools used to work them, of marks made to transport/assemble them, of past problems and interventions. All these traces help us understanding the past and conserving crafts knowledge that is linked to the values, history and identity of the communities in which it is practiced. Crafts involve a particular kind of learning process that needs to be rediscovered and documented to be able to reuse it. The perpetuation of this knowledge allows conserving the traditional building characteristics of the area and using the most appropriate materials and techniques in conservation (Donkin, 2004).

This thesis represents a fundamental first step in recording the important heritage of seventeenth- and eighteenth-century Scottish timber roof structures. Prior to this work very few measured surveys and documents were available. Now various surveys and transcribed archival documents can be analysed, interpreted and built upon by future researchers and conservation and government bodies to build the skills and knowldege needed to conserve the Scottish timber built heritage.

In order for future generations to be able to keep learning from the past, the government must take immediate action to conserve this heritage. Grant funding should be made available even for privately owned buildings, given that certain conditions are met: regular inspections carried out at least on a bi-annual basis - following the example of Monument Watch (Vandesande and Van Balen, 2016)-, interventions approved by a committee of conservation experts and buildings accessible to the wider public on certain dates, in order to allow everyone to benefit from the knowledge of the past. This would hopefully solve some of the problems we have met during our surveys: poor accessibility and visibility conditions, no regular inspections or maintenance in place, and sometimes even no interest in the history of the building itself, since access was denied for no particular reason.

We have focused on timber roof structures but certainly the same conservation policies are applicable to all other structural components of a building, equally important. The methodology we have employed can and should be applied to assess roofs of other periods, in other regions, or to assess other parts of the building. The relational database we have created is already being used by other members of ADCRU and the digital form developed with COST Action FP1101 is being used by other members of WG1 for this purpose.

The coordination between the archival research, historical documentation, in situ inspections, measurements and experimental phases has proven to be fundamental not only to constitute this data bank useful for future research and conservation policies, but also to evaluate the structures' safety. As proven by our surveys, historical and archival research allow finding out about problems that the structure had in the past, interventions or repairs that were carried out; sometimes even the timber species is reported, a key parameter to carry out a structural analysis and evaluate the structure safety. The assessment of the history of loads and problems is fundamental to understand the present condition of a historic structure and to evaluate the adequacy of past interventions.

Once professionals have made a diagnosis of problems and causes based on all the available information, they should design interventions with the primary aim to maintain as much as possible the original fabric in place, improving the legibility of its historical integrity (ICOMOS, 1965). The interventions should preferably use compatible techniques and materials, be reversible, not impede future conservation work nor access to evidence incorporated in the structure (ICOMOS, 1999b).

According to our surveys the interventions that have shown to be more in line with this approach are, for example, those that add timber elements next to the damaged ones: the biotic attack is stopped by improving the environmental conditions but the damaged elements are left in place, simply adding a new element next to it (as in Panmure House). This approach ensures the safety of the structure, by placing a new healthy member able to take the loads, and conserves the original fabric, allowing to read the original structure, its past problems and repairs. However, in some cases it might be preferable to replace parts of the structure with prosthesis (as in Brodie Castle Stables), in order not to crowd up the structure, or to make other punctual interventions such as improving connections with steel elements (as in St Andrew and St George's Church). What should not be done in any case is to damage the original timbers as in Oakshaw Trinity Church or to leave temporary interventions un-monitored for years, as in Geilston House. Moreover, contrary to what we have found during our research, interventions should be fully documented, in order for future generations to know what has been done and why. When successfull, interventions should also be published and shared, in order to inform similar projects.

Specific training must be provided to professionals in order for them to acquire the necessary skills and knowledge to apply this approach. It is also necessary to train experts that can form a committee suitable for the evaluation and approval of interventions. The specialisation course we have proposed should be organized in collaboration with all the active conservation researchers and bodies (HES, NTS, NHTG). Funds could be raised by these bodies and a contribution could be asked to participants in exchange of accreditation and inclusion in a list of timber experts. The translation of this work into actual training would ensure that the created data bank is not only a repository but an innovative way of building skills for the conservation of Scottish timber built heritage.

6.3 Recommendations for future research

Although our research represents an important first step in the study of historic timber roof structures in Scotland, it is based on a limited sample of surveyed roofs and consulted archival documents compared to the number of identified buildings. Future research should therefore focus on widening this sample. This will help finding out more about the design and construction processes and the role of architects, wrights and patrons. Archive material could also be useful in interpreting the unusual carpentry marks we have found. If correctly interpreted, these marks could complement dendrochronology in providing information on the timber date and provenance. Since some of the marking found clearly represents trading companies, the cooperation with experts from Belgium, Netherlands, Germany, Baltic regions and Scandinavian countries would be extremely helpful.

Moreover, it must be kept in mind that the construction date of most of the surveyed roofs has been estimated. In order to progress with more precise construction history analyses it would be necessary to proceed with the dendrochronological dating of more roofs of the period.

Our research findings could also be used to trace guidelines for the assessment of each type of roof structure and to derive vulnerability factors to predict failure mechanisms and identify urgent interventions. With this aim, future research should also focus on the assessment and estimation of mechanical properties and on the use of structural analysis, two topics not addressed by this thesis.

References

ADAM, W. 1812. *Vitruvius Scoticus: plans, elevations, and sections of public buildings, noblemen's and gentlemen's houses in Scotland,* Mineola, N.Y., Dover Publications.

ADDYMAN, T. 2000. Brodie Castle, Old Stables, Moray (Dyke & Moy parish), 18th-century stables. *Discovery Excavations Scotland,* 1**,** 59-60.

ADDYMAN, T. 2011. Panmure House, Canongate, Edinburgh - Analytical and historical appraisal of the house and its urban context.

ADDYMAN, T., MACFADYEN, K. & BOISSERIE, F. 2006. Sailors' Walk, 445-453 High Street, Kirkcaldy, Fife (Kirkcaldy and Dysart parish), building record and analysis. *Discovery Excavations Scotland,* 7**,** 81-82.

ALCOCK, N. W. 1981. Cruck construction: an introduction and catalogue. *CBA Research Report, volume 42.* London: Council for British archaeology.

APTED, M. R. 1966. *The painted ceilings of Scotland, 1550-1650,* Edinburgh, H.M.S.O.

ARCE, D., RETAMONZO, S., AGUILAR, R. & CASTANEDA, B. A mixed methodology for detailed modelling of architectural heritage. *In:* VAN BALEN & VERSTRYNGE, eds. Structural Analysis of Historical Constructions – Anamnesis, diagnosis, therapy, controls, 2016 Leuven. Taylor & Francis, 104-111.

ARIAS, P., CARLOS CAAMANO, J., LORENZO, H. & ARMESTO, J. 2007. 3D modeling and section properties of ancient irregular timber structures by means of digital photogrammetry. *Computer-Aided Civil and Infrastructure Engineering,* 22**,** 597-611.

AUGELLI, F. 2014. Wooden Cultural Heritage. Guidelines, Standards and Methods of Representation. *Scientific papers of National university of architecture and construction of Armenia,* II**,** 21-33.

BAGGIO, C., BERNARDINI, A., COLOZZA, R., CORAZZA, L., DELLA BELLA, M., DI PASQUALE, G., DOLCE, M., GORETTI, A., MARTINELLI, A. & ORSINI, G. 2007. Field manual for post-earthquake damage and safety assessment and short term countermeasures (AeDES). *European Commission—Joint Research Centre—Institute for the Protection and Security of the Citizen, EUR,* 22868.

BAJNO, D., BEDNARZ, L. J. & NOWAK, T. 2015. Preservation of the roof truss in the city hall of Opole (Poland): an analysis. *In:* JASIEŃKO, J. & NOWAK, T. (eds.) *Structural Health Assessment of Timber Structures.* Wrocław, Poland.

BAKER, P. 2008. In-Situ U-Value Measurements in Traditional Buildings - Preliminary Results. *Historic Environment Scotland Technical Papers.* Centre for Research on Indoor Climate & Health, Glasgow Caledonian University.

BALDI, B. 1621. *In mechanica Aristotelis problemata exercitationes: adiecta succinta narratione de autoris vita et scriptis,* Mainz, Johan Albin Witwe.

BARBARO, D. 1552. *I Dieci Libri dell'Architettura di M. Vitruvio,* Venice.

BARBER, D. & MILLS, J. 2011. *3D Laser Scanning for Heritage. Advice and guidance to users on laser scanning in archaeology and architecture*, English Heritage.

BAROZZI DA VIGNOLA, G. 1562. *Regola delli cinque ordini d'architettura*.

BELL, D. 2004. A lost aesthetic: traditional architectural form in wood and its neglect. *Architectural Heritage,* 15**,** 1-19.

BENEDETTI, D. & PETRINI, V. 1984. Sulla vulnerabilità sismica degli edifici in muratura: un metodo di valutazione. *L'industria delle costruzioni*.

BERTOLINI, C., BIGLIONE, G., CESTARI, L., CORRADINO, G., CRIVELLARO, A., DE LUCA, D., MARZI, T., PANOSCH, P. & PASQUINO, R. 2010. Restoration of historic timber structures: the great roof structures of the cathedral of Vercelli. *WCTE World Conference on Timber Engineering.*

BERTOLINI CESTARI, C., CHIABRANDO, F., INVERNIZZI, S., MARZI, T. & SPANÒ, A. 2013. Terrestrial laser scanning and settled techniques: a support to detect pathologies and safety conditions of timber structures. *Advanced Materials Research,* 778**,** 350-357.

BERTOLINI CESTARI, C., INVERNIZZI, S., MARZI, T. & SPANO, A. 2015. Numerical survey, analysis and assessment of past interventions on historical timber structures: the roof of Valentino Castle. *In:* JASIEŃKO, J. & NOWAK, T. (eds.) *Structural Health Assessment of Timber Structures.* Wrocław, Poland.

BERTOLINI CESTARI, C., TOULIATOS, P., MILTIADOU, A., DELINIKOLAS, N., MENICHELLI, C., CRIVELLARO, A., MARZI, T., TSAKANIKA, E., PIGNATELLI, O. & BIGLIONE, G. 2007. The timber of Hagia Paraskevi Basilica in Chalkida, Greece: multi-disciplinary methodological approaches for the understanding of the structural behaviour. Analysis and diagnosis. *ICOMOS IWC - XVI International Symposium.* Florence, Venice and Vicenza.

BINDING, G. 1991. *Das Dachwerk auf Kirchen im deutschen Sprachraum vom Mittelalter bis zum 18 Jh.,* Munich.

BLÁHA, J. 2006. The evolution of Roof Timber Frames in the Southern Part of Bohemian-Moravian Uplands from the 14th Century to the 19th Century. *In:* DRDÁCKÝ, M. (ed.) *European Research on Cultural Heritage: State of the Art studies.* Prague: ARCCHIP ITAM.

BLÁHA, J. 2013. Historic traceology as a complex tool for rediscovery of lost construction skills and techniques. *WIT Transaction on The Built Environment,* 131**,** 3-13.

BRANCO, J., PIAZZA, M. & CRUZ, P. 2010. Structural analysis of two king-post trusses: non-destructive evaluation and load-carrying tests. *Construction and Building Materials,* 24**,** 371-383.

BRANDON, R. & BRANDON, J. A. 1849. *Open timber roofs of the middle ages,* London, D. Bogue.

BROWN, J. 1795. Estimate for the incorporation of weavers for a house proposed to be built in Weaverstreet. Mitchell Library City Archives in Glasgow.

BROZOVSKY, J. & ZACH, J. 2008. An Assessment of the condition of timber structures. *9th International Conference on NDT of Art.* Jerusalem.

BRÜHWILER, E., VOGEL, T., LANG, T. & LÜCHINGER, P. 2012. Swiss standards for existing structures. *Structural Engineering International,* 22**,** 275-280.

BS 5268-2 2002. Structural use of timber. Code of practice for permissible stress design, materials and workmanship.: British Standards Institution.

BS 5756 2011a. Visual strength grading of hardwood. Specification.: British Standards Institution.

BS 5756 2011b. Visual strength grading of softwood. Specification.: British Standards Institution.

BS 6100 1992. Glossary of Building and civil engineering terms. Part 4: Forest products - Section 4.4 Carpentry and joinery. British Standards Institution.

BS 8417 2014. Preservation of wood. Code of practice.: British Standards Institution.

BS EN 408 2012. Timber structures. Structural timber and glued laminated timber. Determination of some physical and mechanical properties.: British Standards Institution.

BS EN 1311 1997. Round and sawn timber. Method of measurement of biological degrade.: British Standards Institution.

BS EN 15228 2009. Structural timber. Structural timber preservative treated against biological attack.: British Standards Institution.

BS ISO 13033 2013. Bases for design of structures. Loads, forces and other actions. Seismic actions on nonstructural components for building applications.: British Standards Institution.

BS ISO 13910 2014. Timber structures. Strength graded timber. Test methods for structural properties. . British Standards Institution.

BUILDINGS AT RISK REGISTER WEBSITE - BUILDINGS. 2016. *Buildings at Risk* [Online]. Available: http://www.buildingsatrisk.org.uk/search/category/101 [Accessed 9/11/2016.

CACCIOTTI, R., BLASKO, M. & VALACH, J. 2015. A diagnostic ontological model for damages to historical constructions. *Journal of Cultural Heritage*, 40-8.

CAMPBELL, J. W. P. 2002. Wren and the development of structural carpentry 1660–1710. *Architectural Research Quarterly,* 6, 49-66.

CANMORE WEBSITE - SITES. 2016. *Sites* [Online]. Available: https://canmore.org.uk/site/search [Accessed 9/11/2016.

CANTINI, L., TEDESCHI, C., TIRABOSCHI, C. & BINDA, L. 2013. Use of Thermovision for the Survey of a Timber Vault in Torino. *Nondestructive Testing of Materials and Structures.* Springer.

CARPENTIER, O., CHARTIER, T., ANTCZAK, E., DESCAMPS, T. & PARYS, L. V. 2015. Active and quantitative thermography using frequential analysis applied to the monitoring of historic timber structures. *In:* JASIEŃKO, J. & NOWAK, T. (eds.) *Structural Health Assessment of Timber Structures.* Wrocław, Poland.

CASTON, P. Historic Roof Trusses between 1500 and 1700 in German-speaking Central Europe: Documentation, Analysis and Development. 2nd International Congress in Construction History, 2006 Cambridge. 579-597.

CESCATTI, E., BETTIOL, G., GONZALEZ MANICH, C. & MODENA, C. 2014. Analysis of an Historical Wooden Roof, the Case of San Fermo. *In:* PENA, F. & CHAVEZ, M. (eds.) *9th International Conference on Structural Analysis of Historical Constructions.* Mexico City.

CHING, F. D. K. 2011. *A Visual Dictionary of Architecture*, John Wiley & Sons.

COLLA, C. 2015. Verification of sonic tomography outcome through local testing of mechanical properties in historic timber beam. *In:* JASIEŃKO, J. & NOWAK, T. (eds.) *Structural Health Assessment of Timber Structures.* Wrocław, Poland.

COLLA, C. & GABRIELLI, E. 2015. On-site Integrated Non-Destructive Diagnosis of Historic Timber Elements: the case of the Roof of Palazzo D'accursio, Bologna. *In:* JASIEŃKO, J. & NOWAK, T. (eds.) *Structural Health Assessment of Timber Structures.* Wrocław, Poland.

COLLINS DICTIONARY. 2016. *Truss* [Online]. Available: http://www.collinsdictionary.com/dictionary/english/truss [Accessed 22/11/2016.

CORKHILL, T. 1948. A glossary of wood.

CORVOL-DESSERT, A., HOFFSUMMER, P., HOUBRECHTS, D., LAMBERT, G. N., LAVIER, C., LOCATELLI, C., MAYER, J., PARISET, J. D., PRÉVET, A., TAUPIN, J. L. & TRENARD, Y. 2009. *Roof Frames from the 11th to the 19th Century. Typology and Development in Northern France and in Belgium,* Paris, BREPOLS.

COURTENAY, L. T. 1985. Where Roof Meets Wall: Structural Innovations and Hammer-Beam Antecedents, 1150–1250. *Annals of the New York Academy of Sciences,* 441**,** 89-124.

CRAE, J. Undated. Palace of Holyroodhouse roofs. *HES report.* Unpublished.

CRAWFORD, G. 1858. A sketch of the rise and progress of the Trades' House of Glasgow, its constitution, funds and bye-laws. *A sketch of the rise and progress of the Trades' House of Glasgow, its constitution, funds and bye-laws.* Glasgow: Bell and Bain.

CRESPO DE ANTONIO, M., LUENGAS CARRENO, D. & SANCHEZ BEITA, S. Applications of the hole-drilling technique in timber structures. Case studies. *In:* VAN BALEN & VERSTRYNGE, eds. Structural Analysis of Historical Constructions – Anamnesis, diagnosis, therapy, controls, 2016 Leuven. Taylor & Francis, 776-781.

CRIVELLARO, A., RUFFINATTO, F. & WIEDENHOEFT, A. C. 2016. Caratteri macroscopici per l'identificazione dei legni. *Sherwood Foreste e Alberi Oggi,* 216**,** 16-17.

CRONE, A. 2001. Gardyne's Land, Dundee: dendrochronological analysis of the structural timbers. unpublished.

CRONE, A. 2008a. The Native Oak & Pine Project; dendrochronological analysis of Duff House, Banff. unpublished.

CRONE, A. 2008b. Newark Castle. unpublished: Historic Scotland.

CRONE, A. 2011. Drum Castle, Aberdeenshire; dendrochronological analysis of the Cross Chamber roof timbers and the Castle steps. unpublished: Historic Scotland.

CRONE, A. & FAWCETT, R. 1998. Dendrochronology, Documents and the Timber Trade: New Evidence for the Building History of Stirling Castle, Scotland.

CRONE, A. & GALLAGHER, D. 2008. The Late-medieval Roof over the Great Hall in Edinburgh Castle. *Medieval Archaeology,* 52**,** 231-260.

CRONE, A., GRIEVE, N., MOORE, K. & PERRY, D. R. 2004. Investigations into an early timber-frame roof in Brechin, Angus. *Tayside Fife Archaeol. J.***,** 152-65.

CRONE, A. & MILLS, C. 2008. Dendrochronological studies at Fort George, Ardersier, by Inverness. Unpublished.

CRONE, A. & MILLS, C. 2011. The Native Oak and Pine Dendrochronology Project and some observations on Timber and Woodworking In Scottish Buildings C.1450–1800. *Vernacular Building***,** 19-42.

CRONE, A. & MILLS, C. M. 2007. The construction of a native oak chronology for north-east scotland; recent work at Drum and Crathes, Aberdeenshire unpublished.

CRONE, A. & MILLS, C. M. 2012. Timber in Scottish buildings, AD 1450 – AD 1800; A dendrochronological perspective. *Proceedings of the Society of Antiquaries of Scotland,* 142**,** 329-369.

CRONE, A. & SPROAT, D. 2011. Revealing the History Behind the Facade: A Timber-framed Building at No. 302 Lawnmarket, Edinburgh. *Architectural Heritage,* 22**,** 19-36.

CRUFT, K. 2005. *Borders*, New Haven, CT ; London : Yale University Press.

CRUZ, H., YEOMANS, D., TSAKANIKA, E., MACCHIONI, N., JORISSEN, A., TOUZA, M., MANNUCCI, M. & LOURENÇO, P. B. 2015. Guidelines for the on-site assessment of historic timber structures. *International Journal of Architectural Heritage,* 9**,** 277-289.

CURL, J. S. & WILSON, S. 2015. *Oxford Dictionary of Architecture*, Oxford University Press.

D'AYALA, D., TSAKANIKA, E., DESCAMPS, T., LANATA, F., KURZ, J., HARTE, A., BRANCO, J. & QUINN, N. 2015. Interdisciplinary knowledge transfer and technological applications for assessment, strengthening and monitoring of timber structures in Europe. *In:* JASIENKO, J. & NOWAK, T. (eds.) *Structural Health Assessment of Timber Structures.* Wroclaw.

DACKERMANN, U., CREWS, K., KASAL, B., LI, J., RIGGIO, M., RINN, F. & TANNERT, T. 2014. In situ assessment of structural timber using stress-wave measurements. *Materials and Structures,* 47**,** 787-803.

DALLAS, R. 2003. Guide for practitioners: measured survey and building recording for historic buildings and structures. Edinburgh: Historic Environment Scotland.

DAVIES, N. & JOKINIEMI, E. 2008. Ashlar-post. *Dictionary of Architecture and Building Construction.* Routledge.

DAVIES, N. & JOKINIEMI, E. 2012. *Architect's Illustrated Pocket Dictionary*, Routledge.

DE BRAY, S. 1631. *Architectura Moderna,* Amsterdam.

DE L'ORME, P. 1578. *Nouvelles inventions pour bien bastir et à petit frais,* Paris.

DEMAUS BUILDING DIAGNOSTICS LTD 2007. Gallery Roof Timber Assessment, Newark Castle, Port Glasgow, Final report. Unpublished.

DICTIONARYOFCONSTRUCTION.COM. 2017. *Purlin roof* [Online]. WebFinance Inc. Available: http://www.dictionaryofconstruction.com/definition/purlin-roof.html [Accessed May 06 2017].

DIGGES, L. 1592. *Tectonicon, Or the Art of Measuring*, Miller.

DONKIN, L. 2004. *Crafts and conservation: Synthesis report for ICCROM*, ICCROM.

DRDÁCKÝ, M., MLÁZOVSKÝ, V. & RŮŽIČKA, P. 2006. Lessons from Historic Carpentry *In:* DRDÁCKÝ, M. (ed.) *European Research on Cultural Heritage: State of the Art studies.* Prague: ARCCHIP ITAM.

DU CERCEAU, J. A. 1576-9. *Premier [et Second] volume des plus excellents bastiments de France,* Paris.

DUNBAR, J. G. 1956-7. Some cruck-framed buildings in the Aberfeldy district of Perthshire. *Proceedings of the Society of Antiquaries of Scotland***,** 81-92.

DUNBAR, J. G. 1972. The building of Yester House, 1670-1878. *Transac E Lothian Antiq Fld Natur Soc*, 20-24.

DUNBAR, J. G. 1976. The organization of the building industry in Scotland during the 17th century. *In:* SCOTTISH VERNACULAR BUILDINGS WORKING GROUP (ed.) *Building construction in scotland: some historical and regional aspects.* Edinburgh: Scottish Vernacular Buildings Working Group.

DUNBAR, J. G. 1978. *The architecture of Scotland,* London, Batsford.

DUNLOP, T. 1750-1756. Account of wright work for repairs to Tweeddale House in Edinburgh. National Library of Scotland archives.

ECA SL34/4/2 1706-1774. St Mary's Chapel Incorporation apprentices book. Edinburgh City Archives.

ECA SL 34/1/7 1740-55. St Mary's Chapel Incorporation record 1740-1755. Edinburgh City Archives.

ECA SL 34/4/1 1706-74. St Mary's Chapel Incorporation apprentices book 1706-1774. Edinburgh City Archives.

EISSING, T. 2009. *Kirchendacher in Thuringen und dem sudlichen Sachsen-Anhalt: Dendochronologie, Flösserei, Konstruktion,* Erfurt, Thüringisches Landesamt für Denkmalpflege und Archäologie.

EN 335 2013. Durability of wood and wood-based products. Use classes: definitions, application to solid wood and wood-based products. Brussels: CEN.

EN 335-2 2006. Durability of wood and wood-based products - Definition of use classes - Part 2: Application to solid wood. Brussels: CEN.

EN 1912 2007. Structural timber - Strength classes - Assignment of visual grades and species Brussels: CEN.

EN 16069 2012. Conservation of cultural property - Condition survey and report of built cultural heritage. Brussels: CEN.

EUL LAII87/1A 1684-7. Holyroodhouse, Stirling Castle, Dumbarton Castle, Edinburgh Castle Vouchers of expenditures on works (1684-87). Edinburgh University Library.

EUL LAII87/6 1684-6. Wright work at Holyroodhouse and Stirling Castle (4 vouchers, 1684-6). Edinburgh University Library.

EUL LAII87/7 1686. Timber for Holyroodhouse and fees of carvers (4 vouchers, 1686). Edinburgh University Library.

EUL LAII88/3 1721-1805. Note of money paid for repairs on Holyroodhouse since the union (1721-1806). Edinburgh University Library.

EUROCODE 5 2004. Design of timber structures. European Committee for Standardization.

FABIAN, C. & DOBBIE, L. 2014. Case Study 13: Kirkcudbright - Conservation works to an 18th century townhouse. *Historic Environment Scotland Refurbishment.*

FAWCETT, R. 2002. *Scottish medieval churches. Architecture and furnishings,* Stroud, Tempus.

FEIO, A. & MACHADO, J. S. 2015. In-situ assessment of timber structural members: Combining information from visual strength grading and NDT/SDT methods – A review. *Construction and Building Materials,* 101, Part 2**,** 1157-1165.

FENTON, A. & WALKER, B. 1981. *The rural architecture of Scotland,* Edinburgh.

FLETCHER, J. M. & HASLOP, F. W. O. 1969. The West range at Ely and its Romanesque roof. 126**,** 171-176.

FLETCHER, J. M. & SPOKES, P. S. 1964. The origin and development of crown-post roofs. *Medieval Archaeology,* 8**,** 152-183.

FORNEAU, N. 1767. *L'art du trait de charpenterie,* Rouen, Dumésnil.

FRESE, M. & BLAS, H. J. 2011. Statistics of damages to timber structures in Germany. *Engineering Structures,* 33**,** 2969-2977.

FRONTINI, F., SIEM, J. & NILSEN, D. 2015. Assessment of an historic timber structure using NDT: "Bryggenhusene" in Trondheim (Norway). *In:* JASIEŃKO, J. & NOWAK, T. (eds.) *Structural Health Assessment of Timber Structures.* Wrocław, Poland.

GH REPORTS 1997. Reports on repair works carried out on the roofs of George Heriot Hospital. Private archive at George Heriot School.

GIBBS, J. 1728. A book of architecture, containing designs of buildings and ornaments. London.

GIFFORD, J. 1984a. *Edinburgh,* Harmondsworth, Penguin Books.

GIFFORD, J. 1984b. *Edinburgh*, Harmondsworth : Penguin.

GIFFORD, J. 1988. *Fife,* Harmondsworth, Penguin Books.

GIFFORD, J. 1992. *Highland and islands,* London, Penguin Books.

GIFFORD, J. 1996. *Dumfries and Galloway,* London, Penguin Books.

GIFFORD, J. 2002. *Stirling and Central Scotland,* New Haven, London, Yale University Press.

GIFFORD, J. 2007. *Perth and Kinross,* New Haven, London, Yale University Press.

GIFFORD, J. 2012. *Dundee and Angus,* New Haven, London, Yale University Press.

GLENDINNING, M. & MACKECHNIE, A. 2004. *Scottish architecture,* London, Thames & Hudson.

GOCAL, J., KRUSINSKY, P. & CAPKOVA, E. 2015. Static Analysis of Historical Trusses. *In:* JASIENKO, J. & NOWAK, T. (eds.) *Structural Health Assessment of Timber Structures.* Wroclaw.

GOGOLIN, M. R. 2008. *Więźby dachowe kościołów Pomorza Zachodniego od końca XIII w. do połowy XIX wieku*, Bydgoszcz.

GÓMEZ SÁNCHEZ, I. 2006. Las estructuras de madera en los Tratados de Arquitectura (1500-1810). Madrid.

GOMME, A. 2002. Scottish hammerbeam roofs, and one that isn't. *Architectural Heritage,* 13**,** 20-35.

GONZALEZ MANICH, C., GONZALEZ LONGO, C. & MONARI, F. 2017. La fabrica de piedra durante los siglos XVII y XVIII en Escocia: estudio preliminar. *X Congreso Nacional y II Congreso Internacional Hispanoamericano de Historia de la Construcción.* Donostia.

GONZALEZ-LONGO, C. 2008. Conserving, Reinstating and Converting Queensberry House. *8th InternationalSeminar on Structural Masonry, Istanbul***,** 5-7.

GONZÁLEZ-LONGO, C. 2012. James Smith and Rome. *Architectural Heritage,* 23**,** 75-96.

GONZALEZ-LONGO, C. & THEODOSSOPOULOS, D. From Master Mason to Architect: James Smith's Construction Techniques at the End of 17th Century in Scotland. *In:* CARVAIS, R., GUILLERME, A., NEGRE, V. & SAKAROVITCH, J., eds. 4th International Congress in Construction History, 2012 Paris.

GORSE, C., JOHNSTON, D. & PRITCHARD, M. 2013. *A Dictionary of Construction, Surveying and Civil Engineering*, Oxford University Press.

GOW, I. 1995. *Scottish country houses: 1600-1914,* Edinburgh, Edinburgh University Press.

HANG-JUN, W., GUANG-QUN, Z. & HENG-NIAN, Q. 2013. Wood Recognition Using Image Texture Features. *PLoS ONE,* 8.

HANKE, T. 2004. The stable of Halkerston Lodge and Moray House: roof architecture of the 1630s in the region around Edinburgh. *Edinburgh Architect. Res.,* 29**,** 33-37.

HANKE, T. 2006. *The Development of Roof Carpentry in South East Scotland Until 1647.* University of Edinburgh. Unpublished.

HANKE, T. 2008. Stirling Castle Palace. Archaeological and Historical Research 2004 - 2008. Aspects of timber in post-Renaisance Scotland: the case of Stirling Palace. Kirckdale Archaeology, Historic Scotland

HANKE, T. 2012. Newark Castle, Port Glasgow: a proto-modern roof of the late 16th century. *Post-Medieval Archaeology,* 46**,** 1-35.

HANKE, T. 2014. Structural Carpentry at Abbeystrand, Edinburgh. Unpublished.

HANSSON, E. F. 2011. Analysis of structural failures in timber structures: Typical causes for failure and failure modes. *Engineering Structures,* 33**,** 2978-2982.

HARDING, P. 2012. John Mylne IV (1611-1667):'Great Artisan, Grave Senator'. *Architectural Heritage,* 23.

HARRIS, C. M. 1977. *Illustrated Dictionary of Historic Architecture*, Courier Corporation.

HARRIS, C. M. 2006. *Dictionary of Architecture and Construction*, McGraw-Hill.

HASNÍKOVÁ, H. & KUKLÍK, P. 2014. VARIOUS NON-DESTRUCTIVE METHODS FOR INVESTIGATION OF TIMBER MEMBERS FROM A HISTORICAL STRUCTURE. *WOOD RESEARCH,* 59**,** 411-420.

HAY, G. D. 1976. Some aspects of timber construction in Scotland. *In:* SOCIETY OF ANTIQUARIES OF SCOTLAND (ed.) *Building construction in scotland: some historical and regional aspects.* Edinburgh: Scottish Vernacular Buildings Working Group.

HES REPORT BY ADAMS 1954. HES uncatalogued technical report by Adams W R. Histioric Environment Scotland.

HEWETT, C. A. 1980. *English historic carpentry*, Phillimore.

HISTORIC ENVIRONMENT SCOTLAND 2011. *Dictionary of Scottish building*.

HISTORIC ENVIRONMENT SCOTLAND 2014. Scottish Courts. *Research Reports.*

HISTORIC ENVIRONMENT SCOTLAND WEBSITE - DESIGNATIONS. 2016. *Designations* [Online]. Available: http://portal.historicenvironment.scot/designations [Accessed 09/11/2016.

HISTORIC ENVIRONMENT SCOTLAND WEBSITE - HOLYROOD PALACE. 2016. *Holyrood Palace designation* [Online]. Available: http://data.historic-scotland.gov.uk/pls/htmldb/f?p=2200:15:0::::BUILDING,HL:28022,holyroodhouse [Accessed 16/10/2016.

HOFFSUMMER, P. 2007. The evolution of roofing in Northern France and Belgium from the 11th to the 18th century as revealed by dendrochronology. *TRACE—Tree Rings in Archaeology, Climatology and Ecology,* 5**,** 21-27.

HOFFSUMMER, P. 2011. *Les charpentes du XIe au XIXe siècle. Grand Ouest de la France*, Brepols.

HOLZER, S. M. Analysis of historical timber structures. *In:* VAN BALEN & VERSTRYNGE, eds. Structural Analysis of Historical Constructions – Anamnesis, diagnosis, therapy, controls, 2016 Leuven. Taylor & Francis, 1203-1210.

HOLZER, S. M. & KOCK, B. 2008. *Meisterwerke Barocker Bautechnik*, Schnell & Steiner.

HOURIHANE, C. P. 2012. *The Grove Encyclopedia of Medieval Art and Architecture* Oxford University Press.

HOWARD, D. 1995. *Scottish Architecture: Reformation to Restoration, 1560-1660*, Edinburgh University Press.

HOWARD, D. 2001. Reflexions of Venice in Scottish Architecture. *Architectural History,* 44**,** 123-135.

ICOMOS 1965. INTERNATIONAL CHARTER FOR THE CONSERVATION AND RESTORATION OF MONUMENTS AND SITES (THE VENICE CHARTER 1964) Venice: ICOMOS.

ICOMOS 1999a. The Burra Charter: The Australia ICOMOS Charter for Places of Cultural Significance. Australia.

ICOMOS 1999b. Principles for the preservation of historic timber structures. Mexico: ICOMOS.

IMPOSA, S., MELE, G., CORRAO, M., COCO, G. & BATTAGLIA, G. 2014. Characterization of Decay in the Wooden Roof of the S. Agata Church of Ragusa Ibla (Southeastern Sicily) by Means of Sonic Tomography and Resistograph Penetration Tests. *International Journal of Architectural Heritage,* 8**,** 213-223.

ÍÑIGUEZ-GONZÁLEZ, G., MONTON, J., ARRIAGA, F. & SEGUES, E. 2015. In-situ assessment of structural timber density using non-destructive and semi-destructive testing. *Bioresources,* 10**,** 2256-2265.

INNOCENT, C. F. 1971. *The development of english building construction*, David and charles.

ISCARSAH 2003. ICOMOS Charter – Principles for the analysis, conservation and structural restoration of architectural heritage. Victoria Falls.

ISO 13822 2001. Bases for design of structures - Assessment of existing structures. Geneva.

JAMIESON, J. 1808. Etimological Dictionary of the Scottish language. Edinburgh.

JANSE, H. 1989. *Houten kappen in Nederland 1000-1940,* Amsterdam, Delftse Universitaire Pers, Rijksdiuenst voor de Monumentenzorg.

JASIEŃKO, J., NOWAK, T. & HAMROL, K. 2013. Selected methods of diagnosis of historic timber structures–principles and possibilities of assessment. *Advanced Materials Research,* 778**,** 225-232.

JASIENKO, J., NOWAK, T. & KAROLAK, A. 2014. Historical Carpentry Joints. *Wiadomosci Konserwatorskie***,** 58-82.

JENKINS, M. 2008. Rot in timber. *In:* SCOTLAND, H. E. (ed.) INFORM ed. Edinburgh: HES Technical Conservation Group.

JENKINS, M. Three Key Aspects of the History of Brick Construction in Scotland. *In:* CARVAIS, R., GUILLERME, A., NEGRE, V. & SAKAROVITCH, J., eds. 4th International Congress in Construction History, 2012 Paris.

JENKINS, M. 2016. Insect attack to timber. *In:* SCOTLAND, H. E. (ed.) INFORM ed. Edinburgh: HES Technical Conservation Group.

JONES, D. 1991. Box beds in Eastern Scotland. *Regional Furniture* V**,** 79-85.

KASAL, B. 2010. Core drilling. *In:* KASAL, B. & TANNERT, T. (eds.) *In-situ assessment of structural timber, RILEM State of the art reports.* Springer.

KASAL, B. & LEAR, G. 2010. Moisture measurement. *In:* KASAL, B. & TANNERT, T. (eds.) *In-situ assessment of structural timber, RILEM State of the art reports.* Springer.

KASAL, B., LEAR, G. & ANTHONY, R. 2010. Radiography. *In:* KASAL, B. & TANNERT, T. (eds.) *In-situ assessment of structural timber, RILEM State of the art reports.* Springer.

KLOIBER, M., BLAHA, J., VACLAVIK, F., RUZICKA, P. & KUNECKY, J. 2015a. Modern diagnostic methods and traditional carpentry techniques used for the renovation of the white tower belfry in Hradec Kralove. *In:* JASIEŃKO, J. & NOWAK, T. (eds.) *Structural Health Assessment of Timber Structures.* Wrocław, Poland.

KLOIBER, M., DRDÁCKÝ, M., MACHADO, J. S., PIAZZA, M. & YAMAGUCHI, N. 2015b. Prediction of mechanical properties by means of semi-destructive methods: A review. *Construction and Building Materials,* 101**,** 1215-1234.

KLOIBER, M., DRDÁCKÝ, M., TIPPNER, J. & HRIVNÁK, J. 2015c. Conventional compressive strength parallel to the grain and mechanical resistance of wood against pin penetration and microdrilling established by in-situ semidestructive devices. *Materials and Structures,* 48**,** 3217-3229.

KLOIBER, M., FRANKL, J., DRDÁCKÝ, M., BRYSCEJN, J., TIPPNER, J. & KUCEROVA, I. 2010. Change of mechanical properties of norway spruce wood due to degradation caused by fire retardants. *Wood Research,* 4**,** 23-38.

KLOIBER, M., KUNECKÝ, J., TIPPNER, J. & SEBERA, V. A new Diagnostic Device for In-Situ Determination of Strength and Modulus of Deformability in Compression of Wood Parallel to Fiber. SAHC2014 9th International Conference on Structural Analysis of Historical Constructions, 2014a Mexico City.

KLOIBER, M., TIPPNER, J. & HRIVNÁK, J. 2014b. Mechanical properties of wood examined by semi-destructive devices. *Materials and Structures,* 47**,** 199-212.

KOHLER, J. & STEIGER, R. 2011. The reassessment of existing load bearing structures. Implementation into the swiss standard. *SHATIS'11 International Conference on Structural Health Assessment of Timber Structures.* Lisbon.

KOSCIUK, J. Modern 3d scanning in modelling documentation and conservation of architectural heritage. *In:* JASIENKO, J., ed. Structural analysis of historical constructions, 2012 Wroclaw. 64-76.

KRALER, A., BEIKIRCHER, W. & ZINGERLE, P. 2012. Suitability of drill resistance measurements for dendrochronological determination. *World Conference on Timber Engineering.* Auckland.

LAMBORGHINI, S., MOCHI, G., VENTURI, L. & GUARDIGLI, L. Historic Timber Trusses in Europe. The case of St. Peter in Bologna. *In:* BOWEN, B., FRIEDMAN, D., LESLIE, T. & OCHSENDORF, J., eds. 5th International Congress on Construction History, 2015 Chicago. 449-456.

LANGLEY, B. 1740. *The City and Country Builder's and Workman's Treasury of Designs*.

LECHNER, T. 2013. *In situ assessment of timber structures - assessment methods and case studies.* PhD, Chalmers University of Technology.

LECHNER, T. & KLIGER, R. 2015. Practical procedure for estimating the density of timber with portable X-ray equipment. *In:* MACHADO, J. S., RIGGIO, M. & DESCAMPS, T. (eds.) *State of the Art Report: Combined use of NDT/SDT methods for the Assessment sf Structural Timber Members.* UMONS: Université de Mons.

LELONG, O., ADDYMAN, T., ARTHUR, J., DICKSON, J., HOOPER JANET, MCIVER, C. & WYLIE, D. 1998. Geilston House and garden, Cardross. Glasgow.

LEWIS, A. 2015. Town housing and planning: McGill, Gibbs and Dreghorn in early Georgian Glasgow. *The Architecture of Scotland in its European Setting: 1660-1750.* Edinburgh: in print.

LEWIS, A. R. 2006. *The builders of Edinburgh s New Town 1767-1795.* University of Edinburgh.

LLANA, D. F., IÑIGUEZ-GONZALEZ, G., ARRIAGA, F. & WANG, X. 2016. Time-of-Flight Adjustment Procedure for Acoustic Measurements in Structural Timber. *BioResources,* 11**,** 3303-3317.

LOCKHART, B. R. W. 2003. *Jinglin Geordie's Legacy: A History of George Heriot's Hospital and School*, Tuckwell PRess Ltd.

LOHRUM, B. & KING, S. 2006. Early variations of the "Sparrendach" in the "Pfettendach" – Region of South-Western Germany. *In:* DRDÁCKÝ, M. (ed.) *European Research on Cultural Heritage: State of the Art studies.* Prague: ARCCHIP ITAM.

LOURENÇO, P. B., SOUSA, H. S., BRITES, R. D. & NEVES, L. C. 2013. In situ measured cross section geometry of old timber structures and its influence on structural safety. *Materials and structures,* 46**,** 1193-1208.

LUHMANN, T., ROBSON, S., KYLE, S. & BOEHM, J. 2014. *Close-Range Photogrammetry and 3D Imaging,* Berlin, De Gruyter.

MACCHIONI, N. 2010. Species Identification. *In:* KASAL, B. & TANNERT, T. (eds.) *In-situ assessment of structural timber, RILEM State of the art reports.* Springer.

MACCHIONI, N., BERNABEI, M., BRUNETTI, M., POLLINI, C., CALICCHIO, D. & CRIVELLARO, A. 2011. Structural diagnosis on ancient timber structures: the example of the Diplomatic Room at the Royal Palace in Naples. *SHATIS'11 International Conference on Structural Health Assessment of Timber Structures.* Lisbon.

MACCHIONI, N., BERTOLINI, C. & TANNERT, T. 2010. Review of Codes and Standards. *In:* KASAL, B. & TANNERT, T. (eds.) *In-situ assessment of structural timber, RILEM State of the art reports.* Springer.

MACCHIONI, N. & PIAZZA, M. 2006. Italian Standardisation Activity in the Field of Diagnosis and Restoration of Ancient Timber Structures *In:* LOURENÇO, P. B., ROCA, P., MODENA, C. & AGRAWAL, S. (eds.) *Structural Analysis of Historical Constructions.* New Delhi.

MACDONALD, A. unpublished. Preliminary conclusions on stress calculations for roof timbers at Pinkie House, Musselburgh (June 2016).

MACGIBBON, D. & ROSS, T. 1887-92. *The castellated and domestic architecture of Scotland from the twelfth to the eighteenth century,* Edinburgh, D. Douglas.

MACHADO, J., PALMA, P. & SIMÕES, S. 2009. Ultrasonic indirect method for evaluating clear wood strength and stiffness. *Non-destructive Testing in Civil Engineering.* Nantes.

MACHADO, J. S. 2013. In Situ Evaluation of the Reference Properties of Structural Timber Members. Use of Available Tools and Information. *Advanced Materials Research,* 778**,** 137-144.

MACHADO, J. S. 2015. Reliability of prediction by combining direct and indirect measurements. *In:* MACHADO, J. S., RIGGIO, M. & DESCAMPS, T. (eds.) *State of the Art Report: Combined use of NDT/SDT methods for the Assessment sf Structural Timber Members.* UMONS: Université de Mons.

MACKECHNIE, A. 1994. *Scots Court Architecture of the Early 17th Century.* University of Edinburgh.

MADSEN, K. 2013. MEdieval church roof constructions in North Schleswig and Southwestern Jutland - examples of tradition and innovation. *Danish Journal of Archaeology,* 2**,** 3-19.

MASSARI, G. A., RIGGIO, M. & GADOTTI, F. 2010. "Respecting the Diversity"-The Timber Roof of the “Cannons Loggia” in the Thun Castle (Italy). *Advanced Materials Research,* 133**,** 1107-1112.

MCKEAN, C. 2001. *The Scottish chateau: the country house of renaissance Scotland,* Stroud, Sutton.

MCKEAN, J., MACKINTOSH, C. R. & BAXTER, C. 2000. *Charles Rennie Mackintosh: architect, artist, icon*, Voyageur Press (MN).

MCWILLIAM, C. 1978. *Lothian, except Edinburgh*, Harmondsworth ; New York : Penguin.

MESANGE, M. 1753. *Traité de charpenterie et des bois de toutes espèces,* Paris, Jombert.

MILLS, C. M. & CRONE, A. 2012. Dendrochronological evidence for Scotland's native timber resources over the last 1000 years. *Scottish Forestry,* 66**,** 18-33.

ML SHANKS 152/T6 1955. Survey of the Trades House of Glasgow and alterations by Wylie Shanks Architects *Wylie Shanks Architects.* drawings ed.: Mitchell Library, Glasgow City Archives.

ML T-TH 1/1/7 1787-98. Trades House: docquetted minute book and Collectors' Accounts, Feb 1787 - 17 May 1798. *Glasgow Trades House.* Mitchell Library, Glasgow City Archives.

ML T-TH 1/34/3 Undated. The ceiling of the great hall in Glasgow Trades Hall. *Glasgow Trades House.* Mitchell Library, Glasgow City Archives.

ML T-TH 9/4/2 1731-1811. Incorporation of Wrights: membership roll, 1731 - 1811. *Glasgow Trades House.* Mitchell Library, Glasgow City Archives.

ML T-TH 9/4/3 1811-70. Incorporation of Wrights: membership roll, 1811 - 1882. *Glasgow Trades House.* Mitchell Library, Glasgow City Archives.

MORALES CONDE, M. J., RODRIGUEZ LINAN, C. & PEDRENO ROJAS, M. A. Analysis of wooden structures with biological degradation. Study of pathologies and diagnosis of a Church roof in Seville. *In:* JASIENZKO, J. & NOWAK, T., eds. Structural Health Assessment of Timber Structures, 2015 Wroclaw. 705-715.

MORALES-CONDE, M. J., RODRÍGUEZ-LIÑÁN, C. & RUBIO DE HITA, P. 2013. Application of Non-Destructive Techniques in the Inspection of the Wooden Roof of Historic Buildings: A Case Study. *Advanced Materials Research,* 778**,** 233-242.

MUNAFÒ, P. 2002. *Le capriate lignee antiche per i tetti a bassa pendenza: evoluzione, dissesti, tecniche di intervento*, Alinea Editrice.

MUNBY, J., SPARKS, M. & TATTON-BROWN, T. 1983. Crown-post and king-strut roofs in south-east England. *Medieval Archaeology,* 27**,** 123-135.

MURDOCH, D. 2010. *My loves Bonnie Strong House*.

NAISMITH, R. J. 1985. *Buildings of the Scottish countryside*, London : V. Gollancz in association with P. Crawley.

NARDI BERTI, R., FIORAVANTI, M. & MACCHIONI, N. 2006. La struttura anatomica del legno ed il riconoscimento dei legnami italiani di più corrente impiego.

NENADIC, S. 2012. Architect-Builders in London and Edinburgh, c. 1750–1800, and the market for expertise. *The Historical Journal,* 55**,** 597-617.

NEWLAND, K. 2007. Norwegian Timber and the Scottish Great House. *Architectural Heritage,* 18**,** 35-53.

NEWLAND, K. 2010. *The Acquisition and Use of Norwegian Timber in Seventeenth Century Scotland, with reference to the principal building works of James Baine, his Majesty's Master Wright.* PhD, University of Dundee.

NEWLAND, K. 2011. The Acquisition and use of Norwegian Timber in Seventeenth-Century Scotland. *Vernacular Architecture,* 42**,** 67-83.

NEWLAND, K. 2012a. The construction chronology and significance of timber for building Panmure House, Angus. *Proceedings of the Society of Antiquaries,* 141.

NEWLAND, K. 2012b. James Baine, His Majesty's Master Wright c.1630-1704: 'an honest and ingenuous spirit...'. *Review of Scottish Culture,* 24.

NEWLAND, K. 2012c. To Norroway, To Norroway, to Norroway o'er the foam: sourcing timber for Scotland's seventeenth century building works. *In:* HAMRE, H. (ed.) *Museum Stavanger årbok.* Stavanger.

NHTG 2013. Skills Needs Analysis 2013: Repair, Maintenance and Energy Efficiency Retrofit of Traditional (pre-1919) Buildings in England and Scotland 2013. *In:* NATIONAL HERITAGE TRAINING GROUP (ed.).

NICHOLSON, P. 1797. *The Carpenter and Joiner's Assistant*, I. & J. Taylor.

NLS ACC 70/56 1711-33. Box 1: Miscellanea from St Mary's Chapel Incorporation. National Library of Scotland.

NLS MS1646 Z.02/18B 1719. Stirling Castle, November 1719, plan and sections of the Great Hall, Jelfe Andrews (Architect) and Moore Thomas (Engineer) *Military Maps of Scotland (18th century).* National Library of Scotland.

NLS MS1647 Z.02/55A 1762. Plan Elevation and Sections of the Store-House for Provisions, and Barrack-Masters Stores 1762 by William Skinner (Engineer). *Military Maps of Scotland (18th century).* National Library of Scotland.

NLS MS14493/37 1660. Transcription by Aonghus Mackechnie of works at Holyroodhouse. National Library of Scotland.

NLS MS14551/24 Undated. Contract between W. Adam and the Marques of Tweeddale for works at Yester. *Hay of Yester Papers.* National Library of Scotland.

NLS MS14551/109 1742-49. Contract between W. Adam and the Marques of Tweeddale for works at Yester. *Hay of Yester Papers.* National Library of Scotland.

NLS MS14551/115 1750. Letter from John Adam to the Marquis of Tweedale probably regarding Tweeddale House. *Hay of Yester Papers.* National Library of Scotland.

NLS MS14551/126 1753. Letter from John Adam to the Marquess of Tweeddale. *Hay of Yester Papers.* National Library of Scotland.

NLS MS14665 1735-53. Accounts of work by Thomas Dunlop and timber from William Caddell for the MArquis of Tweeddale. *Hay of Yester Papers.* National Library of Scotland.

NLS MS14665/64 1750-6. Accounts by Thomas Dunlop for repairs to Tweeddale House. *Hay of Yester Papers.* National Library of Scotland.

NLS MS14680 1779-82. Works at Tweeddale House. *Hay of Yester Papers.* National Library of Scotland.

NLS MS14716 1768-78. Repairs to roofs at Pinkie House. *Hay of Yester Papers.* National Library of Scotland.

NOWAK, T., BROL, J. & JASIENKO, J. 2013. Estimation of the strenght parameters of wood in the building structures-preliminary studies. *Annals of Warsaw University of Life Sciences-SGGW. Forestry and Wood Technology,* 83.

NOWAK, T. P., JASIEŃKO, J. & HAMROL-BIELECKA, K. 2016. In situ assessment of structural timber using the resistance drilling method–Evaluation of usefulness. *Construction and Building Materials,* 102**,** 403-415.

NRS CS96/2243 1736-47. Account book of Thomas Dunlop, wright, Edinburgh, 1736-1747, Court of Session processes. National Records of Scotland.

NRS E36/30 1671-1678. Sir William Bruce of Balcoskie: Holyrood, Stirling, Edinburgh, the Bass, 4 Mar. 1671-8 Jan. 1674, rendered 9 July 1674. National Records of Scotland.

NRS E37/24 1682. Estimate of materials required for reparation of Holyroodhouse, with notes of unfinished rooms their work to be done by Robert Mill under contract and of buildings and repairs necessary at Stirling Castle (1682). National Records of Scotland.

NRS E37/33 1699-1703. Duplicate account of work in Stirling Castle, bearing copy treasury warrant discharging Earl of Mar for sums required (1699-1703). National Records of Scotland.

NRS GD29/92 1671. Warrant by the Lords Commissioners of the Treasury to Sir W. Bruce of Balcaskie as Surveyor General to repair the roof and alleyways at Sterling Castle, provide for wright and glass-work of the rooms there (1671). National Records of Scotland.

NRS GD29/94 1679. Contract between Sir William Bruce of Balcaskie, Surveyor General, Sir William Sharpe of Stainiehill, the King's Cash-keeper, and Robert Mylne, the King's Master Mason, for the building and repair of Halyrudehouse (1679). National Records of Scotland.

NRS GD29/100 1678. Two copies of an order signed by Lauderdale terminating Sir William Bruce's appointment as Surveyor General, the building and repairing of Holyrudhouse [Holyroodhouse, Edinburgh] being completed - 30 May 1678. National Records of Scotland.

NRS GD45/18/1616/21 1694. Contracts between James, Earl of Panmure, and James Baine, the King's Master Wright, for mason, wright, plaster and stone work at Brechin Castle. Petition by Baine defending his work. National Records of Scotland.

NRS GD45/18/1616/25 1694. Contracts between James, Earl of Panmure, and James Baine, the King's Master Wright, for mason, wright, plaster and stone work at Brechin Castle. Additional artickles of work done by Ja:baine (consented to) att brechin Castle and valued by Tobias bauchop november 1694. National Records of Scotland.

NRS GD124/15/207/3 1700. Letter to the Earl of Mar from the Earl of Seafield. Difficulty in obtaining money to repair Stirling Castle - 9 Apr 1700. National Records of Scotland.

NRS GD124/15/216/2 1701. Letter to the Earl of Mar from the Marquis of Annandale. Annandale has urged the Lords of Treasury to do something for the Castle of Stirling - 11 Apr [1701]. National Records of Scotland.

NRS GD124/15/471 1707. Letter to the Earl of Mar from Mr James Smith, surveyor of Her Majesty's works, in Edinburgh. He describes the dismal state of the Palace of Holyroodhouse and the Castle of Stirling (1707). National Records of Scotland.

NRS GD124/15/506/23 1707. Letter to the Earl of Mar from the Earl of Glasgow. Sensible of Mar's diligence in the above matter. Payment made for repair of Stirling Castle - 19 Jun 1707. National Records of Scotland.

NRS GD124/15/567 1707. Letter to the Earl of Mar from Col John Erskine, his step-father, at Alloa. Family matters. Negotiations with Balgowan. Repairs to Stirling Castle necessary - 16 May 1707. National Records of Scotland.

NRS GD421/5/2 1633-42. Records of George Heriot's Trust, Edinburgh, Accounts and other Financial Papers of George Heriot's Hospital and Trust, Treasurer's accounts. National Records of Scotland.

NRS GD421/10/68 1685. Detailed account and discharge by Thomas Sandilands, wright, to the treasurer of George Heriot's Hospital for £683 Scots for timber and wright work performed on the chapel and lodge (or summer house) in the Easter garden, 16 Jan 1685. *Records of George Heriot's Trust, Edinburgh, Administrative records of Heriot's Hospital and school statutes, foundationers, staff building, housekeeping.* National Records of Scotland.

OLDRIEV, W. T. 1916. The ancient Roof of Glasgow Cathedral. *Proceedings of the Society of Antiquaries of Scotland,* 50**,** 155-172.

OSTENDORF, F. 1908. *Geschichte des Dachwerks,* Leipzig-Berlin.

OTTENHEYM, K. 2007. Dutch Influences in William Bruce's Architecture. *Architectural Heritage,* 18.

OXFORD ENGLISH DICTIONARY. 2016. *Wright, noun* [Online]. Available: http://www.oed.com/view/Entry/230697?rskey=3GJesC&result=1&isAdvanced=false - eid [Accessed 20/02/2015.

PAIN, W. 1796. *The Practical House Carpenter; Or, Youth's Instructor*, William Norman, bookseller and stationer, no. 75, Newbury-Street.

PALAIA, L., MONFORT, J., SÁNCHEZ, R., GIL, L., ÁLVAREZ, A., LÓPEZ, V., TORMO, S., PÉREZ, C. & NAVARRO, P. 2008. Assessment of timber structures in service, by using combined methods of non-destructive testing together with traditional ones. *9th International Conference on NDT of Art.* Jerusalem.

PALLADIO, A. 1570. *I quattro libri dell'architettura*.

PARISI, M. A., CHESI, C. & TARDINI, C. 2013. Seismic Vulnerability of Timber Roof Structures: Classification Criteria. *Advanced Materials Research,* 778**,** 1088-1095.

PARK, H. S., LEE, H. M., ADELI, H. & LEE, I. 2007. A New Approach for Health Monitoringof Structures: Terrestrial Laser Scanning. *Computer-Aided Civil and Infrastructure Engineering***,** 19-30.

PEDDIE, J. Description of an old timber building in the Lawnmarket, Edinburgh. Proceedings of the Society of Antiquaries of Scotland, 1883. 4.

PIAZZA, M. & RIGGIO, M. 2008. Visual strength-grading and NDT of timber in traditional structures. *Journal of Building Appraisal,* 3**,** 267-296.

PIGNATELLI, O. 2010. Dendrochronology. *In:* KASAL, B. & TANNERT, T. (eds.) *In-situ assessment of structural timber, RILEM State of the art reports.* Springer.

PODESTÀ, S., POMPEJANO, F. & STAGNO, G. 2013. The Wooden Roof of Banesa e Skendulate in Gjirokastra, Albania: The Role of the Diagnostic Test Campaign in the Structural Safety Evaluation. *Advanced Materials Research,* 778**,** 911-918.

POMPEJANO, F., PODESTÀ, S. & CHESI, C. 2015. Preliminary studies on the structural behaviour of traditional timber roofs in Gjirokastra, Albania. *In:* JASIEŃKO, J. & NOWAK, T. (eds.) *Structural Health Assessment of Timber Structures.* Wrocław, Poland.

PRICE, F. 1733. *The British Carpenter or a treatise on carpentry*.

RCAHMS DP 043860 1959. Neidpath Castle Digital copy of west elevation and section looking East and North elevation and section looking South. Copy of PBD 258/19.: Royal Commission on the Ancient and Historical Monuments of Scotland.

RCAHMS DP 043862 1964. Neidpath Castle Reconstruction drawing: first floor plan. Copy of PBD 258/29.: Royal Commission on the Ancient and Historical Monuments of Scotland.

RCAHMS DP 143824 2012. Oblique aerial view of Drochil Castle, looking to the E. *RCAHMS Aerial Photography Digital.* Royal Commission on the Ancient and Historical Monuments of Scotland.

RCAHMS DP 161383 2013. Darnaway Castle. Ground floor. Hall. Hammerbeam roof.: Royal Commission on the Ancient and Historical Monuments of Scotland.

RCAHMS DP 222837 2015. Oblique aerial view of Darnaway Castle, looking NE. *RCAHMS Aerial Photography Digital.* Royal Commission on the Ancient and Historical Monuments of Scotland.

RCAHMS LOR/M/17/5 1953. Plans and elevations showing additions and alterations. Details showing new floor to painted gallery. Details showing roof over painted ceiling and catwalk.: Royal Commission on the Ancient and Historical Monuments of Scotland.

RCAHMS LOR/T/1/5 1928. Plans, sections and elevations of verandah, repairs to North wing roof and coal cellar. Plans and sections of new drive and forecourt. Royal Commission on the Ancient and Historical Monuments of Scotland.

RCAHMS MLD 69/29 1947. Pinkie House. Section and elevations. Copies C 39421 P, C 39421 S.: Royal Commission on the Ancient and Historical Monuments of Scotland.

RCAHMS SC1202662 Undated. Dundee, Claypotts road, Claypotts Castle. View of plans of castle. Copy of A 50130.: Royal Commission on the Ancient and Historical Monuments of Scotland.

RCAHMS SC1324316 1971. Dundee, Claypotts road, Claypotts Castle. General view of angle tower. Copy of G 81173 S.: Royal Commission on the Ancient and Historical Monuments of Scotland.

RCAHMS SC 383456 1970. Torthorwald, Cruck-framed Cottage. Interior. General view, Copy of DF 1112 *Historic Buildings and Monuments/Scottish Development Department photographs.* Royal Commission on the Ancient and Historical Monuments of Scotland.

RCAHMS SC 433080 1998. Darnaway Castle. Photographic copy of drawing showing part view and plan of the timber framed roof of the Great Hall. Royal Commission on the Ancient and Historical Monuments of Scotland.

RCAHMS SC 738897 1959. Stirling, St John Street, Church Of The Holy Rude. View of the timber roof of nave.: Royal Commission on the Ancient and Historical Monuments of Scotland.

RCAHMS SC 830680 1927. Perth, St John's Place, St John's Kirk Of Perth And War Memorial. Details of choir roof as existing with annotations. Scanned image of D 4976 CN. *Ian G Lindsay.* Royal Commission on the Ancient and Historical Monuments of Scotland.

RCAHMS SC 937335 1963. Drochil Castle. Scanned image of view from W, Copy of PB 812. Royal Commission on the Ancient and Historical Monuments of Scotland.

RCAHMS SC 943434 Undated. View of Douglas Castle from South. Copy of B 13800.: Royal Commission on the Ancient and Historical Monuments of Scotland.

RCAHMS SC 989070 1969. Dysart, Panhall, 1 Pan Ha', Bay House. Scanned image of drawing showing reconstruction: perspective elevation; sections showing painted ceilings; ground floor plan; first floor plan and pediment. Royal Commission on the Ancient and Historical Monuments of Scotland.

RCAHMS SC 1047690 1886. Linlithgow, High Street, Town House Of The Knights Of St John. Photographic copy of cutting showing interior perspective view.: Royal Commission on the Ancient and Historical Monuments of Scotland.

RCAHMS SC 1164646 Undated. Dunglass Collegiate Church. View from NE, Copy of EL 1838. *Historic Buildings and Monuments/Scottish Development Department photographs.* Royal Commission on the Ancient and Historical Monuments of Scotland.

RCAHMS SC 1171792 Undated. Dunglass Collegiate Church. Interior. View of choir from W, Copy of A 47776. *Historic Buildings and Monuments/Scottish Development Department photographs.* Royal Commission on the Ancient and Historical Monuments of Scotland.

RCAHMS SC 1201162 1888. Interior-detail of roof during alterations. *Scottish Colorfoto.* Royal Commission on the Ancient and Historical Monuments of Scotland.

RCAHMS SC 1209320 1922. Interior-general view of Throne Room in Holyrood Palace. *Scottish Colorfoto.* Royal Commission on the Ancient and Historical Monuments of Scotland.

RCAHMS SC 1223494 Undated. Kinross House. Plan of first, second and third floors and vaults. Insc: "Sir John Bruce's House at Kinross". Copy of KRD 5/1 P.: Royal Commission on the Ancient and Historical Monuments of Scotland.

RCAHMS SC 1327346 1952. Aberdeen, Broad Street, Provost Skene's House, Interior. General view of interior featuring men at work. Copy of AB 1808.: Royal Commission on the Ancient and Historical Monuments of Scotland.

RCHAMS DPM 1900/67/2 1909. Glasgow Cathedral. Details of roof construction over nave, nave aisles and choir. *Dick Peddie and McKay.* Royal Commission on the Ancient and Historical Monuments of Scotland.

RENTOKIL 1973. Letter proposing insecticidal treatment of the main roof space and provision of a thermal kilt. HES.

RENWICK, R. 1911. Extracts from the records of the burgh of Glasgow, vol. 6, 1739-1759.

RIDOUT, B. 2000. *Timber decay in buildings: the conservation approach to treatment*, Taylor & Francis.

RIGGIO, M., ANTHONY, R. W., AUGELLI, F., KASAL, B., LECHNER, T., MULLER, W. & TANNERT, T. 2014. In situ assessment of structural timber using non-destructive techniques. *Materials and Structures,* 47**,** 749-766.

RIGGIO, M., MACCHIONI, N. & RIMINESI, C. 2016. Structural health assessment of historical timber structures combining non-destructive techniques: The roof of Giotto's bell tower in Florence. *Structural Control and Health Monitoring***,** 1-18.

RIGGIO, M., PARISI, M. A., TARDINI, C., TSAKANIKA, E., D'AYALA, D., RUGGIERI, N., TAMPONE, G. & AUGELLI, F. Existing timber structures: proposal for an assessment template. *In:* J., J. & T., N., eds. 3rd International Conference on Structural Health Assessment of Timber Structures, 2015a Wroclaw. Dolnośla˛skie Wydawnictwo Edukacyjne, 100-107.

RIGGIO, M., PRANDI, F., DE AMICIS, R. & PIAZZA, M. 2013. Use of high resolution digital images and NDT imaging techniques for the characterization of timber structural elements. *Nondestructive testing of materials and structures, RILEM Bookseries,* 6.

RIGGIO, M., SANDAK, J. & FRANKE, S. 2015b. Application of imaging techniques for detection of defects, damage and decay in timber structures on-site. *Construction and Building Materials,* 101**,** 1241-1252.

RILEM 2010. In Situ Assessment of Structural Timber: State-of-the-Art, Challenges and Future Directions. *In:* TANNERT, T. & KASAL, B. (eds.) *RILEM State of the Art Reports.*

RINN, F. 2012. Basics of micro-resistance drilling for timber inspection. *holztechnologie***,** 24-29.

ROBINSON, M. 1999. Concise Scots Dictionary. Edinburgh: Polygon.

ROCK, J. 2015. Cockenzie House - New research (October 2015). Unpublished.

ROCK, J. 2016. *Newhailes New Research* [Online]. Available: https://sites.google.com/site/newhailesnewresearch/home [Accessed 21/10/2016.

RODRÍGUEZ LIÑÁN, C., MORALES CONDE, M. J., RUBIO DE HITA, P. & PÉREZ GÁLVEZ, F. 2015. Application of non-destructive techniques in the inspection of wooden structures of protected buildings: the case of Ntra. Sra. De Los Dolores Church (Isla Cristina, Huelva). *International Journal of Architectural Heritage,* 9**,** 324-340.

ROSS, R. J. 2010. *Wood handbook : wood as an engineering material,* Madison (WI USA), Dept. of Agriculture, USDA Forest Service, Forest Products Laboratory.

ROSS, R. J. & HUNT, O. M. 2000. Stress Wave Timing Nondestructive Evaluation Tools for Inspecting Historic Structures. Madison, WI: US: Department of Agriculture, Forest Service, Forest Products Laboratory.

ROSS, R. J., PELLERIN, R. F., VOLNY, N., SALSIG, W. W. & FALK, R. H. 1999. *Inspection of Timber Bridges Using Stress Wave Timing Nondestructive Evaluation Tools - A guide for USe and Interpretation,* Madison (IL USA), US Department of Agriculture, Forest Service, Forest Products Laboratory.

ROSS, T. & BROWN, B. 1916. The Magdalen Chapel, Cowgate, Edinburgh. *Old Edinburgh Club,* 8.

ROWAN, A. 1984. The building of Hopetoun. *Architectural History***,** 183-209.

ROWAN, A. 1990. William Adam's Library. *Architectural Heritage,* 1**,** 8-33.

RUDDOCK, T. 1995. Repair of two important early Scottish roof structures. *Proceedings of the Institution of Civil Engineers. Structures and buildings,* 110**,** 296-307.

RYKWERT, J. 1985. *The brothers Adam: the men and the style,* London, London : Collins.

SALMON, W. 1767. *Palladio Londinensis*, J. Rivington; R. Baldwin; L. Hawes, W. Clarke, and R. Collins; W. Johnston; S. Crowder; T. Longman; B. Law; E. and C. Dilly, and C. Ware and Company.

SANDAK, A., SANDAK, J. & RIGGIO, M. 2015a. Methodology and protocols for routine assessment of wooden members with spectroscopy. *In:* MACHADO, J. S., RIGGIO, M. & DESCAMPS, T. (eds.) *State of the Art Report: Combined use of NDT/SDT methods for the Assessment sf Structural Timber Members.* UMONS: Université de Mons.

SANDAK, J., SANDAK, A. & RIGGIO, M. 2015b. Multi sensor approach combined with multivariate analysis for assessment of timber structures. *In:* MACHADO, J. S., RIGGIO, M. & DESCAMPS, T. (eds.) *State of the Art Report: Combined use of NDT/SDT methods for the Assessment sf Structural Timber Members.* UMONS: Université de Mons.

SANG-JOON, L., KWANG-MO, K. & JUN-JAE, L. unpublished. Improvement of the ultrasonic and X-ray CT techniques for field application. Department of Forest Sciences, Seoul National University Seoul, Republic of Korea.

SCAMOZZI, V. 1615. *L'idea dell'architettura universale*.

SCAN. 2015. *Scottish Archive Network onli catalogue* [Online]. Available: http://www.scan.org.uk/.

SCHUEREMANS, L. 2009. Assessing Timber Roof Structures. Methodology and Case Studies

from a Belgian Viewpoint. *Conference Series on Theoretical and Practical Issues on Built Heritage Conservation.* Tusnad.

SCOTLAND, H. E. 2010. Managing change in the historic environment. Edinburgh: Historic Environment Scotland.

SCOTTISH ARCHIVE NETWORK. 2016. *Online Catalogue* [Online]. Available: http://catalogue.nrscotland.gov.uk/scancatalogue/search.aspx [Accessed 24/12/2016.

SCOTTISH VERNACULAR BUILDINGS WORKING GROUP 1976. *Building construction in scotland: some historical and regional aspects,* Edinburgh, Scottish Vernacular Buildings Working Group.

SCOTTISH VERNACULAR BUILDINGS WORKING GROUP 1992. *Materials and traditions in Scottish building: essays in memory of Sonia Hackett,* Edinburgh, Scottish Vernacular Buildings Working Group.

SERAFINI, A. 2013. *Structural and historical assessment of the 17th century timber roof in house No. 414/I in Prague Old Town.* Advanced Masters in Structural Analysis of Monuments and Historic Constructions, Czech Tenchical University.

SERAFINI, A. & GONZALEZ LONGO, C. 2015a. The design and construction techniques of eighteenth century timber roofs in Scotland: Glasgow Trades Hall and Tweeddale House in Edinburgh. *In:* BOWEN, B., FRIEDMAN, D., LESLIE, T. & OCHSENDORF, J. (eds.) *5th International Congress on Construction History.* Chicago.

SERAFINI, A. & GONZALEZ LONGO, C. The Roof Structure of George Heriot's Hospital Chapel and the Roof Design of its

period in Scotland (in review). The architecture of Scotland in its European setting: 1660-1750, 2015b Edinburgh.

SERAFINI, A. & GONZALEZ LONGO, C. Seventeenth and eighteenth century timber roof structures in Scotland: design, pathologies and conservation. *In:* VAN BALEN, K. & VERSTRYNGE, E., eds. 10th International Conference on Structural Analysis of Historical Constructions, 2016 Leuven. Taylor and Francis.

SERAFINI, A., RIGGIO, M. & GONZALEZ LONGO, C. 2016. A database model for the analysis and assessment of historic timber roof structures. *International Wood Products Journal***,** 1-6.

SERLIO, S. 1545. *Tutte l'opere d'architettura et prospetiva,* Venice.

SHAW, J. 1990. Dutch and Scotch Pantiles. Some evidence from the seventeenth and early eighteenth centuries. *Scottish Vernacular Buildings Working Group,* 14**,** 26-29.

SHUAIQI, H., KE, L. & XUDONG, B. 2015. Wood Species Recognition Based on SIFT Keypoint Histogram. *8th International Congress on Image and Signal Processing (CISP).*

SIA 269/5 2009. Erhaultung von Tragwerken - Holzbau. Zurich: Swiss Society of Engineers and Architects SIA.

SIMPSON, J. 2007. The Evolving Stair - The development of the stair in Scottish architecture. *Architectural Heritage,* 18**,** 99-113.

SLAVID, R. 2011. Investigating timber in historic buildings. *The Timber Industry Yearbook.* TRADA.

SM ADAM 7/225 1755. Edinburgh Assembly Rooms and Musical Society: designs for concert hall by James Adam. *Robert and James Adam office drawings.* SIr John's Soane Museum London.

SM ADAM 48/25 1791. Glasgow Trades Hall section front to back by Robert Adam. *Robert and James Adam office drawings.* SIr John's Soane Museum London.

SMITH, J. 1736. *A specimen of ancient carpentry,* London.

SMITH, J. 1958. Medieval roofs: a classification. *Archeological Journal,* 115**,** 111-149.

SMITH, J. A. 1870-2. Notice of the shingled roof of the tower of the Canongate Tolbooth, Edinburgh. *Proceedings of the Society of Antiquaries of Scotland,* 9**,** 162-7.

SNOW, J. 2013. Case Study 11: Newtongrange, Installation of roof and coom insulation and secondary glazing. *Historic Environment Scotland Refurbishment.*

SOBRA, K., FONSECA FERREIRA, C., RIGGIO, M., D'AYALA, D., ARRIAGA, F. & ARIA, J. R. 2015. A new tool for the structural assessment of historic carpentry joints. *In:* JASIEŃKO, J. & NOWAK, T. (eds.) *Structural Health Assessment of Timber Structures.* Wrocław, Poland.

SOUSA, H. S., BRANCO, J. M. & LOURENÇO, P. B. 2015. Hierarchical modelling of timber reference properties using probabilistic methods: Maximum Likelihood Method, Bayesian Methods and Probability Networks. *In:* MACHADO, J. S., RIGGIO, M. & DESCAMPS, T. (eds.) *State of the Art Report: Combined use of NDT/SDT methods for the Assessment sf Structural Timber Members.* UMONS: Université de Mons.

SOUSA, H. S., SØRENSEN, J. D., KIRKEGAARD, P. H., BRANCO, J. M. & LOURENÇO, P. B. 2013. On the use of NDT data for reliability-based assessment of existing timber structures. *Engineering Structures,* 56**,** 298-311.

STAMP, G. & SAYER, P. 1999. *Alexander 'Greek' Thomson*, Laurence King.

STELL, G. 1981. Crucks in Scotland: a provisional list. *In:* LONDON COUNCIL FOR BRITISH ARCHAEOLOGY (ed.) *Cruck construction; an introduction and catalogue by N. W. Alcock with sections by P. V. Addyman, F. W. B. Charles, A. I. Gailey and D. McCourt, R. de Z Hall. G. I. Meirion-Jones, J. T. Smith and G. P. Stell.* London.

STELL, G. 1992. Timber in historic Scottish buildings. *In:* SONIA, H., GEOFFREY, S., ANNE, R. & SCOTTISH VERNACULAR BUILDINGS WORKING GROUP (eds.) *Materials and traditions in Scottish building: essays in memory of Sonia Hackett.* Edinburgh: Scottish Vernacular Buildings Working Group.

STELL, G. 2004. Timber in Scottish historic buildings. *In:* KLEBOE, J. (ed.) *Timber and the built environment Conference.* Edinburgh: Historic Scotland. Technical Conservation Research and Education Group.

STELL, G. & BAILLIE, M. 1993. The Great Hall and Roof of Darnaway Castle, Moray. *Moray: Province and People, Edinburgh***,** 163-179.

STEVENS CURL, J. 2006. *A Dictionary of Architecture and Landscape Architecture*, Oxford University Press.

STRACHAN, S. R. 2008. *The Laird's Houses of Scotland: from the Reformation to the Industrial Revolution, 1560-1770.* PhD, University of Edinburgh.

SUCHÝ, L., KRUŠINSKÝ, P., BABJAKOVA, Z. & ĎURIAN, K., Z 2008. Historické krovy sakrálnych stavieb Turca. Žilinskú Univerzitu V Žiline, Stavebnú Fakultu, Katedru Pozemného Stavitel'stva a Urbanizmu.

SUMMERSON, S. J. N. 1953. *Architecture in Britain, 1530 to 1830,* Penguin Books, Penguin Books.

SUMMERSON, S. J. N. 1993. *Architecture in Britain, 1530 to 1830,* Penguin Books, Penguin Books.

SUTHERLAND, F. 2005. Glasgow Trades Hall historical report.

SZABÓ, B. & KULIN, M. 2005. *Dicţionar ilustrat de structuri portante istorice: Illustrated dictionary of historic load-bearing structures*, Kriterion/Utilitas.

TABRAHAM, C. J. 1995. *Fortress Scotland and the Jacobites*, London : B.T. Batsford ; Edinburgh : Historic Scotland.

TAMPONE, G. 1996. *Il restauro delle strutture di legno*, Hoepli Editore.

TAMPONE, G. Mechanical failures of the timber structural systems COMOS International Wood Committee XVI International Symposium, 2007 Florence, Venice and Vicenza.

TAMPONE, G. 2016. *Atlante dei dissesti delle strutture lignee-Atlas of the failures of timber structures*, Nardini.

TANNERT, T., ANTHONY, R. W., KASAL, B., KLOIBER, M., PIAZZA, M., RIGGIO, M., RINN, F., WIDMANN, R. & YAMAGUCHI, N. 2014. In situ assessment of structural timber using semi-destructive techniques. *Materials and structures,* 47**,** 767-785.

TCH ACCOUNT BY DEAS & CO 1757-8. Uncatalogued account of timber bought from Haig Deas & Co. for Touch House. Private archive at Touch House.

TCH ACCOUNT BY PATERSON 1757. Transcription of uncatalogued account of timber bought by Mr Paterson for Touch House (10 September 1757). Private archive at Touch House.

TCH ACCOUNT OF MATERIALS Undated. Uncatalogued account of materials for Touch House. Private archive at Touch House.

TCH LETTER TO MR SETON 1751. Uncatalogued letter from timber merchant to Mr Seton (27 September 1751). Private archive at Touch House.

TDH 1/899 1856. Survey and Alterations to Glasgow Trades Hall roof structure by the Architect Charles Wilson in 1856: plan and sections. Private archive in Trades Hall basement.

THELIN, C. & LINSCOTT, K. 2008. Structural definition and comparison of early medieval roof structures. *6th International Conference on Structural Analysis of Historical Construction.* Bath.

THEODOSSOPOULOS, D. 2015. Mannerist explorations in the work of the “fashionable architect” John Douglas in 18th century Scotland. *The Architecture of Scotland in its European Setting: 1660-1750.* Edinburgh: in print.

THOMSON, A. 1991. *The Scottish timber trade, 1680 to 1800.* University of St Andrews.

TOMASI, R., PEZZO, M. I. & PIAZZA, M. 2008. Rehabilitation of an historical theatre in Italy. *Annali Museo Civico di Rovereto,* 23**,** 89-102.

TORATTI, T. 2011. Proposal for a failure assessment template. *Engineering Structures,* 33**,** 2958-2961.

TRADA 2012. Lessons in History. *The Magazine for Trada members.* TRADA.

TSAKANIKA, E. 2007. Byzantine and Post-Byzantine Historical Timber roofs in Greece. Typical failures, misunderstanding of their structural behaviour, restoration proposals. *In:* ICOMOS (WOOD COMMITTEE) (ed.) *16th International ICOMOS Conference and Symposium “From material to structure”.* Florence, Venice and Vicenza.

TWH DRAWINGS/PICTURES 1980s. Uncatalogued drawings and pictures of survey and repair works carried out in 1980s at Tweeddale House. Private archive at Touch House.

UNI 11035 2003. Legno strutturale - Classificazione a vista di legnami italiani secondo la resistenza meccanica: terminologia e misurazione delle caratteristiche. Milano: UNI.

UNI 11118 2004. Beni culturali - Manufatti lignei - Criteri per l'identificazione delle specie legnose. Milano: UNI.

UNI 11119 2004. Beni culturali - Manufatti lignei - Strutture portanti degli edifici - Ispezione in situ per la diagnosi degli elementi in opera Milano: UNI.

UNI 11130 2004. Beni culturali - Manufatti lignei - Terminologia del degradamento del legno. Milano: UNI.

UNI 11138 2004. Beni culturali - Manufatti lignei - Strutture portanti degli edifici - Criteri per la valutazione preventiva, la progettazione e l'esecuzione di interventi. Milano: UNI.

UNI 11141 2004. Beni culturali - Manufatti lignei - Linee guida per la datazione dendrocronologica del legno. Milano: UNI.

UNI 11161 2005. Beni culturali - Manufatti lignei - Linee guida per la conservazione, la manutenzione e il restauro. Milano: UNI.

UNI 11182 2006. Beni culturali - Materiali lapidei naturali ed artificiali - Descrizione della forma di alterazione - Termini e definizioni. Milano: UNI.

URQUHART, D. 2007. Guide for practitioners: conversion of traditional buildings - application of the Scottish building standards. Edinburgh: Historic Environment Scotland.

VALERIANI, S. Historic carpentry in Rome. Proceedings of the First International Congress on Construction History: Madrid, 20th-24th january 2003, 2003. Instituto Juan de Herrera, 2023-2034.

VALERIANI, S. Monaci, dardi e colonnelli. Genesi e caratteristiche delle capriate italiane. Santiago Huerta (Hsrg.): Actas del Cuarto Congreso Nacional de Historia de la Construcción, Cadiz, 2005. 1039-1049.

VALERIANI, S. 2006. The roofs of Wren and Jones: a seventeenth-century migration of technical knowledge from Italy to England.

VAN DEN BULCKE, J., BOONE, M., VAN ACKE, J., STEVENS, M. & VAN HOOREBEKE, L. 2009. X-ray tomography as a tool for detailed anatomical analysis. *Annals of Forest Science,* 66.

VANDENABEELE, L., BERTLES, I. & WOUTERS, I. 2016. Baltic shipping marks on nineteenth-century timber: their deciphering and a proposal for an innovative characterization of old timber. *Construction History,* 31**,** 157-175.

VANDESANDE, A. & VAN BALEN, K. An operational preventive conservation system based on the Monumentenwacht model. *In:* BALEN, V. & VERSTRYNGE, eds. Structural Analysis of Historical Constructions – Anamnesis, diagnosis, therapy, controls, 2016 Leuven. Taylor & Francis, 217-224.

VILCHES CASALS, M., LABÈRNIA BADIA, C. & RODRÍGUEZ TRUJILLO, V. 2015. Assessment through NDT of the state of timber structures of the historic buildings of Catalonia. *In:* MACHADO, J. S., RIGGIO, M. & DESCAMPS, T. (eds.) *State of the Art Report: Combined use of NDT/SDT methods for the Assessment sf Structural Timber Members.* UMONS: Université de Mons.

VITRUVIUS POLLIO, M. 1556. *Dell'architettura di M. Vitruvio Pollione libri diece*, Baduel.

WALKER, B. 2006. Getting your Hands Dirty: A Reappraisal of Scottish Building Materials, Construction and Conservation Techniques. *Architectural Heritage,* 17.

WALKER, F. A. 2000. *Argyll and Bute*, London : Penguin Books ; in association with the Buildings of Scotland Trust.

WANG, X. P., TEDER, M. & WACKER, J. 2013. Condition Assessment of the Timber Structures of a Century-Old Industrial Building Using a Nondestructive Inspection Procedure. *Advanced Materials Research,* 778**,** 840-848.

WEMYSS, C. 2014. *The Noble Houses of Scotland,* Germany, Prestel.

WILLIAMS, J. 2015. Assessing structural timber elements. *The Timber Industry Yearbook.* TRADA.

WILLIAMSON, E. 1990. *Glasgow*, New Haven ; London : Yale University Press ; Penguin.

YEOMANS, D. T. 1986a. Early carpenters' manuals 1592-1820. *Construction History***,** 13-33.

YEOMANS, D. T. 1986b. Inigo Jones's Roof Structures. *Architectural History,* 29**,** 85-101.

YEOMANS, D. T. 1987. Historic development of timber structures. *Timber in Construction* [Online]. Available: https://http://www.trada.co.uk/images/onlinebooks/F8A457ED-8137-4FD0-B7B9-7ABA5718A761/.

YEOMANS, D. T. 1992. *The trussed roof: it's history and development*, Scolar Press.

YOUNG, M. 2014. Thermal imaging in the investigation of solid masonry structures. *The Building Conservation Directory***,** 23-26.

ZAHID, I., GRGURINOVIC, C., ZAMAN, T., DE DEYZER, **R.** & CAYZER, L. 2012. Assessment of technologies and dogs for detecting insect pests in timber and forest products. *Scandinavian Journal of Forest Research,* 27**,** 492-502.

ZANINI, G. V. 1629. *Della architettura,* Padova, Francesco Bolzetta.