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Forestry Commission

In partnership with Scottish Enterprise

green oak

in construction

peter ross christopher mettem andrew holloway




Green oak in construction

by
Peter Ross, ARUP
Christopher Mettem, TRADA Technology
Andrew Holloway, The Green Oak Carpentry Company

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TRADA Technology Ltd
Chiltern House
Stocking Lane
Hughenden Valley
High Wycombe
Buckinghamshire HP14 4ND

t: +44 (0)1494 569600
f: +44 (0)1494 565487
e: information@trada.co.uk
w: www.trada.co.uk

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The authors

Peter Ross BSc, DIC, CEng, MICE

Formerly an Associate Director of Ove Arup and now, on retirement, a consultant to the firm, he is a well-known timber designer of both new-build schemes and historic repairs, including the new roof at York Minster (Case Study 9.5). He is President of TRADA, a member of the BSI Timber Committee and was Technical Secretary of the 1994 edition of Eurocode 5.

Christopher Mettem MSc, C Eng, FIWSc

Chief Research Engineer, TRADA Technology, and BSI Technical Secretary Structural Timber Codes and Standards. He has led many government, European Commission and industry-funded research projects in the field of timber engineering. In recent years he has been focussing on information repackaging, knowledge transfer, teaching, technical writing and photographic illustrating.

Andrew Holloway BA(Hons)

Founder and owner of The Green Oak Carpentry Company. He was the carpenter-builder of the multiple award-winning 2002 Weald and Downland Gridshell (Case Study 9.8) and more recently of the Savill Building, Windsor Great Park, winner of the 2006 Wood Awards Gold Award. Additionally the Company was awarded the 2006 Best Use of British Timber Award for the Savill Building and Chithurst Monastery (*Figure 2.10*). He is an experienced City and Guilds qualified timber frame carpenter, with wide-ranging crafts skills and key strengths in design.

Photographs

Cover photographs: main The Green Oak Carpentry Company; inset left to right 1, 2 The Green Oak Carpentry Company; 3 P Ross, 4 The Green Oak Carpentry Company.

Frontispiece: The Green Oak Carpentry Company.

Other photographs are acknowledged as they appear throughout the book.

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1 Introduction

Green oak can be defined simply as oak which has been freshly cut. Thus green oak construction is the craft of forming a building frame with members of green oak. It is not a new craft, but dates back many centuries and was used by generations of carpenters to make the historic barns, houses and church roofs which can be seen up and down the land. Neither is the craft confined to history – it is very much alive today, and has provided the stimulus for the production of this book.

Figure 1.1 Oak logs
Photo: Forest Life Picture Library

So what is the difference between working with green oak and modern timber construction? Today, most timber used for building is seasoned either by kiln or air-drying. This dissipates the movements which occur as the timber gradually loses its excess moisture before it is used for fabrication. Why not simply do the same with oak?

There are four basic problems with the use of seasoned oak for framing work, all of which relate to the properties of the material. In detail they are:

Figure 1.2 Prefabricated sections of green oak framing ready for delivery to site
Photo: C J Mettem

- Hardness
  Even using power tools, seasoned oak is much more difficult to cut and shape than green. Anyone who has pruned roses will appreciate the difference between a green shoot and a dead branch.

- Drying time
  Oak dries very slowly and typical frame members, say between 150 mm and 200 mm thick, will take some six to eight years of air-drying to lose excess moisture. Even drying the material in modern kilns would not achieve a reduction in this time for oak of such thickness. Since oak frames have always been individually designed there are no stocks of material and so a project would effectively be on hold for this period.

- Drying movement
  Oak also has a large coefficient of drying shrinkage and so seasoned members would require a second cut after drying to true up the faces and to make the joints, which must fit accurately.

- Fissures
  Seasoned oak has a marked tendency to fissure. Fissures complicate the cutting of joints and make edge moulding particularly difficult.

The consequence of all this is that a frame in seasoned oak, whether medieval or modern, is simply not a commercial proposition. Green oak, in contrast, makes great sense, giving advantages of programme – the timber can be used immediately, conversion is simpler – only one cut is required, and working is easier.

Photo not available in PDF edition

Figure 1.3 The natural fissures which develop in a green oak frame as the timber dries.

However, it has to be borne in mind that the drying movements of the timber, which might otherwise have taken place in a kiln or timber yard, will now occur in service. It is an obvious requirement that the frame should nevertheless remain stable, with no slackness developing in the joints, and that the building envelope – the walls and the roof - should retain their integrity.

Photos not available in PDF edition

Figure 1.4 here and opposite page. Moffat House utilises a green oak structure for the upper floors on a steel framed storey below, combining modern and traditional materials and techniques to create a unique home.
Architects: Bl@st Architects
Framer: Carpenter Oak and Woodland

The authors have attempted to set out the methods by which these aims can be realised. It is hoped that the more general parts of the text will be of interest to clients who are thinking of commissioning a green oak frame, both as an introduction to the subject, and to understand through the illustrations how a green oak frame behaves over time. The more detailed chapters on material properties, frame forms and enclosure will be of use to designers and specifiers, while engineers will be assisted by new grading rules, more relevant to work in green oak than those in the current hardwood standard. The rules define two grades for general framing work and three associated structural grades, which can be directly related to design stresses, tabulated in both permissible stress and limit state format.

Photos not available in PDF edition

It should be said that this book is not a complete history of timber construction, an engineering design handbook, or a manual of framing techniques, for the simple reason that they are all subjects of books in themselves. Nevertheless, it gives an overview of the whole process of designing a building based on a frame of green oak, providing advice and encouragement to all those engaged in a small, but thriving, sector of the building industry.

2 Green oak past and present

2.1 The medieval period

Timber has been used as a building material since the earliest times. Indeed, throughout the whole of the medieval period, oak dominated the field of construction on the basis of both its durability and its general availability. While much of this building stock has been lost, a significant number survive today, some five hundred years or so after they were built.

Aisled barns (*Figure 2.1*) exist in most areas of the country and are examples of a form which originally served also as a church or a house. However, cruck frames (*Figure 2.2*), where two halves of a curved trunk are set against one another to create an arch, are possibly the most immediately recognisable form of historic timber construction.

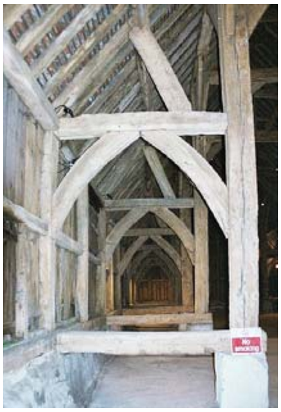


Figure 2.1 Aisle at Harmonsworth Barn, Middlesex.
Photo C J Mettem

Figure 2.2 Cruck framing
above and centre: Midlands cruck barn, now at Avoncroft Museum
right: The Red Lion, Weobley
Photos C J Mettem

Traditional buildings (*Figure 2.3*), which consist essentially of an open frame structure with diagonal braces, often have a first floor which is 'jettied' or projected over the ground floor construction. They developed in various regional styles, such as the close vertical studs seen mainly in the south of England, or the square panels, sometimes with a decorative infill, typical of the north and west.

Whilst many of these buildings are of a simple, domestic form, grander buildings, generally with masonry walls, still relied on oak for their roofs. In addition to the great monastic barns (*Figure 2.4*), and six thousand or so churches, the hammerbeam roofs of historic palaces mark the highpoint of medieval carpentry (*Figure 2.5*).

Figure 2.3 Traditional framing
above and centre: Little Moreton Hall, Cheshire
Photos: C Mettem
right: Close vertical studs, Lavenham, Suffolk
Photo: P Ross

Figure 2.4 Great Coxwell Barn, Oxfordshire. Interior: aisle and posts

Photo not available in PDF edition

Figure 2.5 Hammerbeam roof, Eltham Palace

The local traditions of stone building in Scotland and Wales may give a superficial impression that oak framing was confined to England, but examples can be found from all areas. In Wales, in Aberconwy House, (14th Century, *Figure 2.6*), and in Powys Castle (12th Century and onward) original medieval oakwork can be seen. In Ireland, where in the past many properties were destroyed or deserted, restorations based on archeological research have been carried out, such as the new oak roof for the fortified tower house at Ballytarsna Castle, Co. Tipperary (Ref: 37). In Scotland, the roof of the Great Hall at Edinburgh Castle (*Figure 2.7*), still stands and was used as a reference for the recent reconstruction of the roof of the Great Hall at Stirling Castle (see Case Study, 9.2).

Figure 2.6 Aberconwy House
Photo: C J Mettem

Photo not available in PDF edition

Figure 2.7 Hammerbeam roof of the Great Hall, Edinburgh Castle

To obtain their material medieval carpenters generally went to the nearest wood, felled the most suitable trees and converted the trunks to the required sizes by cleaving, hewing or sawing. Only for the most demanding projects, such as the octagonal lantern over the crossing at Ely Cathedral (1328-37), was it necessary to extend the search for trees of the necessary dimensions. This near-to-site conversion of the log resulted in components which were easier to lift and transport to the workplace. Off-cuts were converted into boards and pegs or cleft to make wall and roof battens, the bark was collected for tanning leather, and branches were chopped up for charcoal-making. Hence the total process can be seen as an efficient utilisation of the whole resource (Ref: 39). Even the joints were resolved without the use of metal, by forming a mechanical interlock between the pieces which was then locked by pegs. These joints, could, of course, be undone, making the alteration and adaptation of the original frame a relatively easy operation, and there are contemporary records of complete frames being sold, dismantled and re-erected.

Figure 2.8 King post truss. Roof of Trinity College, Cambridge.
Photo: Jewell Harrison

As explained in Chapter 1, the freshly-cut or 'green' timber had a high moisture content, and a 'vocabulary' of construction developed which accommodated the movements resulting from the drying process. The drying fissures on the surface of the members have always been accepted as part of the character of the work, minimised by the selection and location of the piece, and sometimes disguised by the judicious addition of sectional mouldings.

Joiners, making doors, windows or panelling, could not be as tolerant of drying movements as the carpenters building the frames. They generally used timber which had been sawn and then seasoned by air drying. Most timber yards contained a few logs of high quality, through and through sawn and stacked under cover, which would have dried out in a year or two.

2.2 The post-medieval period

The late medieval period saw the growth of towns. Within these closely-packed conurbations an individual house fire could easily become a general conflagration. Following the Great Fire of London in 1666, the Building Bylaws specified the use of brick for external walls. This material was also more appropriate for the new classical style, and so by the end of the seventeenth century most buldings had walls of masonry with timber floors and roofs. The timber was now protected from the direct effects of the weather so structural elements could be made more cheaply in imported softwood, as oak had become more scarce. Increasing use was made of metal for connections and tension members (*Figure 2.8*).

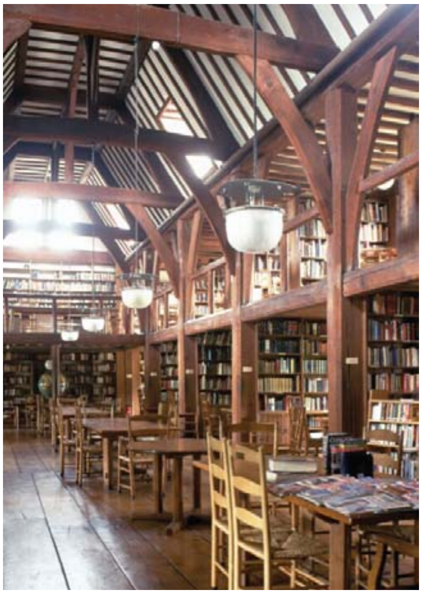


Figure 2.9 The Memorial Library, Bedales School. Architect: Edward Gimson, 1921
Photo: P Ross

The major use for large oak sections was in shipbuilding; a use which lasted until the nineteenth century, when iron, and then steel, replaced timber for all but small vessels. By the end of the nineteenth century, there was relatively little structural work undertaken in oak, apart from traditional open roofs in Gothic Revival churches and city halls. However, designers in the Arts and Crafts movement (*Figure 2.9*) favoured the material in work for wealthy clients.

2.3 The present day

The development of the formaldehyde group of adhesives in the mid-twentieth century resulted in the increasing use of glued laminated construction (glulam). Individually seasoned laminations, usually of softwood, are glued together to give a beam of virtually any size, but made of dry timber. Glulam provides an economic design solution for medium-to large-span roof structures set within the weatherproof envelope of the building. As a consequence, very few structures were built in oak in the mid twentieth century, when its use was largely confined to high-quality joinery alongside other temperate and tropical hardwoods.

However, from the 1970s onwards, there has been a gradual revival of interest in green oak structures, made by specialist carpentry companies using traditional methods of construction and fabrication, (*Figure 2.10*). These clearly show their method of construction and principles of stability; what might in building terms, be called structural honesty. See Chapters 5, 6 and 7. However, there can be a certain ‘ shock of the old’, when clients more used to looking at kiln dried softwoods and manufactured veneered boards have to accept that drying movements, and in particular surface fissures, are not ‘defects’ but system characteristics. This revival of interest has also initiated some research, looking for instance in more detail at the strength of pegged joint assemblies (see Appendix III).

Figure 2.10 (and next page) Modern green oak structures
Framing and photos: The Green Oak Carpentry Company
below: Completed frame before enclosure

top: One and a half storeys using a modern two-tier cruck frame
centre: One and a half storeys with gallery; principal frames use raking struts from the tie beam
bottom: a simple crown post roof

top: Chithurst Monastery, Hampshire. A modern hall, resembling a traditional Sussex barn (Photo: Wood Awards)
centre: Tithe Barn at Great Fosters Hotel, Surrey. Reconstruction of a traditional roof
bottom: A garden room extension using joinery infill panels

Figure 2.11 (above and left) Pilton Barn, Glastonbury. Reconstruction of roof destroyed by lightning
Framing: McCurdy & Co
Architect: Caroe and Partners
Photos: Wood Awards / McCurdy & Co

Figure 2.12 'Downsian gothic' trusses at St George's Hall, Windsor
Photo: Giles Downes, Siddell Gibson Architects

Later Chapters and the Case Studies illustrate the great range of projects which are currently being carried out in green oak. At one end of the range are the historical reconstructions, such as Pilton Barn (*Figure 2.11*) or the Globe Theatre (Case Study 9.1). Here the primary aim has been to achieve an authenticity of form and detail, based on extensive historical research.

Other projects have re-visited past styles, but interpreted them more freely, in the manner of the Victorians; perhaps the best known being the new roof to St Georges's Hall, Windsor, reconstructed following the fire in 1992. The surviving walls determined the basic frame layout, while the trusses themselves were re-invented in 'Downsian Gothic' after the roof's designer Giles Downes (*Figure 2.12*).

Much recent work is based on historic models, such as those shown in Chapter 5, which are then fitted out and clad, often in a contemporary style (see, for example, Case study 9.3). However, in some ways the more interesting projects are those where the principles of design in green oak have been applied to engineered structures, generally using metal connections. These include the York Minster roof, Bedales School Theatre and Darwin College Study Centre (Case Studies, 9.5, 9.6 and 9.7), all of which were the subject of conventional structural analysis.

Late in the twentieth century, huge advances in computer technology enabled designers to draw, analyse, and in some cases to fabricate projects of extreme geometrical and analytical complexity. The Weald and Downland Gridshell (Case study 9.8) marks a step change in our ability to create exciting, and at the same time reliable structures, while allowing the efficient design and fabrication of more modest projects.

The advantages of green oak framing as a method of construction still hold good today. Although oak is more expensive than softwood, it has an attractive figure, and the natural durability of the heartwood allows exterior use, where it weathers over time to a silver grey. Even with the benefit of modern power tools, green oak is still much easier to cut and shape than seasoned oak.

The gradual rise in concern for environmental issues has also favoured green oak, which locks up carbon, has a low embodied energy, requires no preservative treatment and can be sourced from sustainably-grown forests. Today the oak frame is an accepted building form, capable of being weatherproofed and insulated in accordance with present-day regulations, while at the same time providing a link to the buildings of the past.

3 The supply of green oak

It is generally believed that oak is one of the more expensive timbers, and for seasoned material of joinery quality this is true. To get some idea of the economics of green oak construction in relation to other species, however, it is useful to compare material costs and also to look at the other factors which should be taken into account in an overall assessment.

3.1 Timber supply

3.1.1. Softwoods

The softwood forests of northern Europe, America and Canada consist largely of trees in groups of similar age and species, which can thus be clear felled and converted to size on production lines. As a result, spruce (whitewood) and pine (redwood) are undoubtedly the cheapest option for structural work. The material is kiln-dried and graded to national standards within the range of strength classes C16-C27 defined in BS EN 338 (Ref: 15) (see Section 6.3.2). It is normally supplied in a range of standard sizes (in 25 mm increments) up to 75 mm by 250 mm in cross-section and up to 6 m long. The indicative costs shown in Section 3.3 include a wastage factor of 30%. Both spruce and pine have low drying movements, but are non-durable.

Figure 3.1 Top: Drying kilns and timber yard at a modern British softwood sawmill
Above: Logs and finished timber entering and leaving a British softwood sawmill
Photos: BSW Timber Ltd

The softwoods most readily available in larger framing sizes (ie up to 250 x 250 mm) are larch and Douglas fir, available from imported stock, or more recently, from UK sources. Depending on the timescales from production at the sawmill to installation in the building, the material could be partially air dried. The indicative costs given in Section 3.3 include a 40% wastage factor.

The only softwood with a durable rating (according to BS EN 350-2 (Ref: 17)) is western red cedar (WRC) imported from North America, which commands a correspondingly high price despite its modest strength (C14 - C24). It is used predominantly for cladding and small domestic structures. A limited quantity of WRC from UK sources is available, though this only classed as moderately durable in BS EN 350-2.

3.1.2 Temperate hardwoods

The primary use of the temperate hardwoods is for joinery work, with oak meeting much of that demand. Oak has strengths in the range D30 – D40, and the heartwood (unlike the majority of the temperate hardwoods and oak sapwood) is durable.

Figure 3.2 Delivery of oak into a green oak framing yard
Photo: Green Oak Carpentry Company

Air-dried planks of oak are available up to about 100 mm thick (occasionally 125 mm thick) at costs which reflect oak's slow drying rate. In view of this thickness limitation, unseasoned or green oak is the only practical option for most framing work, which routinely requires thicknesses of 150 mm of more.

No green oak stocks are held, as there are no 'standard' framing sizes and the way in which it is used means that it is best freshly sawn. Orders are cut from the log, and prices are usually based on the net volume after conversion. Since price is also dependent on the specified grade, it is prudent to limit this to the minimum compatible with the function of the piece (see Chapter 6).

Oak as a timber is European-wide. Whilst UK supplies are readily available, merchants may offer stocks of, for example, French origin. Pieces up to 300 x 300 mm x 6 – 7 m long can easily be obtained, and larger sizes supplied on special enquiry (with a proportionate increase in price).

A possible alternative species to European oak is sweet chestnut, where the heartwood is also durable, and with broadly similar properties, but it is less stable and, in the larger sections required for framing, may be more expensive.

3.1.3 Tropical hardwoods

The UK, along with many other countries of the world, imports a range of tropical hardwood species. Exporting countries generally impose a ban on the export of logs, and so most timber arrives as planks with thicknesses ranging from 25 mm to 100 mm and widths dependent on the log diameter. Tropical hardwoods used for joinery are typically available in lengths up to 4.2 m but a small range of timbers used for civil engineering is available in very long lengths, about 6 m being common but twice this length not unknown. Many species are rated as durable or very durable, with a medium to high strength range (D30 - D70).

Figure 3.3 Sea defences being constructed using greenheart

Tropical hardwoods (*Figure 3.3*) are generally darker in colour than softwoods, in the red to brown range, and have generally low drying movements. The best known species, such as mahogany and teak, are destined almost exclusively for joinery use. The cost comparison given in Section 3.3 includes a selection which might be used for structural work. These would be subject to the thickness limitation noted above, although ekki is obtainable up to a thickness of about 250 mm. Most timber would be supplied with moisture contents in the range 18% - 24% but the heavy civil engineering species are supplied and used green. The indicative costs assume a waste factor of 50%, but do not include a premium for timber certified as coming from a sustainable source, the purchase of which should be subject to enquiry on availability.

3.2 Environmental issues

The last thirty years have seen the gradual rise in awareness of environmental issues, the most fundamental being sustainable development, energy conservation and the relation between carbon emission and global warming. The world's forests are central to these issues, being both a supplier of oxygen and a carbon sink. Concern regarding non-sustainable rates of felling, primarily of the tropical hardwoods, led to the United Nations Conference on Environment and Development; "the earth summit", held at Rio de Janeiro in 1992. The Rio Declaration and the Forest Principles laid down the principles of sustainable forestry management.

3.2.1 Sustainability

It is now generally accepted that timber is a good choice as a construction material on environmental grounds, being the only renewable structural material, and having a low embodied energy. It is advisable, however, to check that the rate of cutting of the supply forest can be permanently sustained. Obviously it is not possible for the final purchaser of the timber to determine this directly and therefore reliance must be placed on some form of certification system.

Figure 3.4 Examples of certification marks

Certification is a method by which forestry and timber processing operations are independently assessed against various environmental, economic and social criteria, which are based on the principles laid down in the Rio declaration. If they compare favourably they are certified by an organisation, such as the Canadian Standards Association (CSA), Forest Stewardship Council (FSC), the Programme for the Endorsement of Forest Certification Schemes (PEFC) or the US Sustainable Forests Initiative (SFI). Material offered as certified should be able to be traced back by a 'chain of custody' to the forest from which it was cut. The government has set up a Central Point of Expertise on Timber (CPET) to give guidance on the procurement of sustainable timber for the public sector.

During 1999, every Forestry Commission woodland in England, Scotland and Wales (around 40% of British forests) was assessed against the FSC recognised UK Woodland Assurance Standard (UKWAS) by an independent auditor. As a result, Forestry Commission woodlands now meet the Forest Stewardship Council requirements. The Forestry Commission selected the FSC label for all of its timber because it is recognised by many consumers and is supported by most environmental groups. An increasing area of privately owned woodland throughout the UK has also been certified by the FSC as being sustainably managed.

Inevitably there are costs to be borne by foresters in obtaining certification, and these become more significant for the owners of small woodlands. Recently, streamlined auditing procedures for small woods (100 hectares or less) have been successfully introduced, together with schemes for group certification. It is hoped that these procedures will encourage the take-up of certification schemes by all UK forest owners. It should be noted in any case that with few exceptions the felling of trees in the UK is controlled. This requires a felling licence (issued by the Forestry Commission in England, Scotland and Wales or the Forest Service, Northern Ireland) which will generally only be issued if various conditions, such as replanting, are to be met.

Figure 3.5 top: Oak plantation Hamsterley Forest, Kielder
above: Old oak, New Forest
right: Upland native oak woodland, mid Wales
Photos: Forest Life Picture Library

3.2.3 Life cycle impacts

In making an environmental assessment of a particular design, it is usual to look at the environmental impacts of the components under the various life cycle headings. The assessment outlined below is for seasoned timber and green oak.

Environmental impacts of green oak construction		
Forestry:	Felling	If the forest is sustainably managed, then the net growth energy is 'zero', and felling uses only a small amount of energy
Transport:	Forest to sawmill Sawmill to fabricator Fabricator to site	Transport is required at these three stages. Since in comparison with other structural materials, timber is relatively lightweight and pieces can be close-stacked, transport energy is not often a major item. It obviously reduces the closer the three locations are to one another
Processing:	Sawmill cutting	Seasoned timber is generally cut to standard sizes and then re-cut or planed to final sizes. Green oak needs only a single cutting operation to final sizes
	Drying (seasoned timbers of small sections)	Most seasoned timber is kiln-dried, which requires a certain energy input
	Green oak	No energy requirement (nor for air-dried material)
Fabrication:	Assembly	Traditional frames of oak are more labour-intensive to fabricate than softwood frames, but have no requirement for metal fasteners
	Applied treatments	Oak, being durable, requires no preservative treatment, and is generally used without formaldehyde adhesives or applied finishes
	Frame erection	Since most traditional frames were erected with hand labour, the modern equivalent requires little mechanical assistance, although crane erection may be used for speed and convenience
In-use:		Given good detailing, the durability of oak and the absence of applied finishes make an oak frame virtually maintenance-free for its service life
End of life:	Re-use	For hundreds of years timber frames have been adapted, altered and re-used. The most famous historic example is probably the dismantling of the Globe Theatre on its site and re-erection on the South Bank of the Thames in 1599 (see the Globe case study). It is only necessary to ensure that the infill construction does not in some way inhibit this inherent capability
	Disposal	Since oak has not been treated with applied preservatives there are no limitations on disposal

Thus the traditional oak frame, the oldest of the current building methods, emerges as a top scorer in an environmental assessment. However, environmental design is about the whole building and not a selected element. Over recent years several environmental house designs have been completed, based on a contemporary use of a green oak frame. These often incorporate additional aspects of energy economy and sustainability.

3.3 Costs

3.3.1 Material costs

Figure 3.6 gives cost comparisons on a volumetric basis of the common timbers used in construction. It is based on the prices at which these would be supplied by a merchant to a fabricator in 2005 together with an allowance for waste as noted in Section 3.1. The relative costs are, of course, approximate, since the supply price for any particular contract will depend upon the size of the order and the fabricator's particular requirements, including the specified grade and visual quality. Nevertheless, this helps to build up a picture of relative costs.

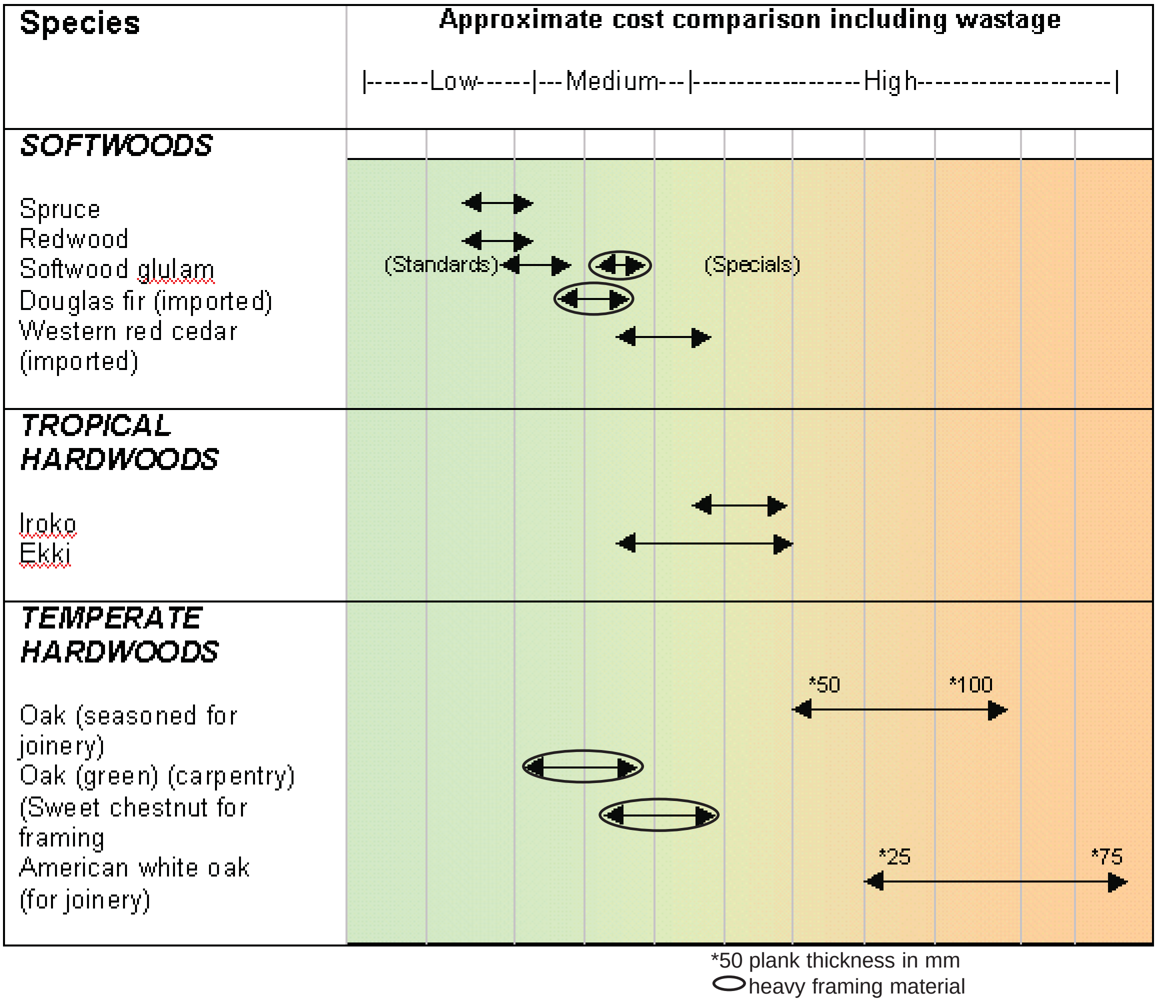


Figure 3.6 Cost comparison of timbers commonly used in construction

3.3.2 Fabrication and erection costs

Fabrication and erection costs are difficult to quantify, since they relate to the form of construction rather than to the particular species. Traditional frames tend to be more labour intensive to fabricate, due to the cutting of the joints, but contemporary frames may incur more metalwork costs.

Traditional frames are relatively easy to erect since they evolved in an age when most material had to be manhandled into place. However, fabrication and erection costs in total are now probably equal to two or three times the supply costs of the material, and largely independent of species. Thus any cost differential between oak and other potential green framing species is considerably reduced when considering the contract as a whole.

3.3.3 Cost summary

The results of the comparison shown in Figure 3.6 are thus rather surprising. There are three ways of approaching framing with members of large cross-section in a traditional form: using softwood glulam that may have to be fabricated to order, Douglas fir, or green oak, and the costs of these materials are seen to be roughly comparable.

However, oak also possesses the following advantages:

- the heartwood is naturally durable (no need for preservatives)
- the timber can be exposed both internally and externally (no need for finishes)
- it has an attractive figure and very good weathering qualities.

4 The properties of oak

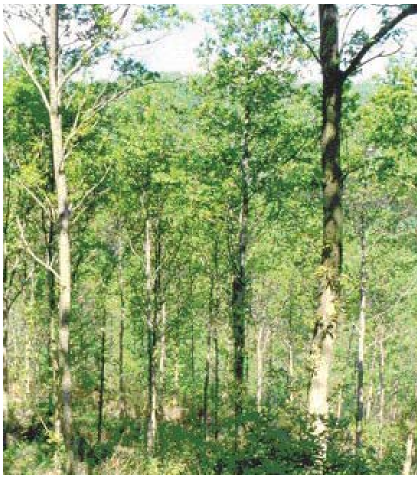


Figure 4.1 top: Softwood growth: mature Scots pine and regenerated young pines
centre: Hardwood growth: oak woodland, planted 52 years before photograph and thinned about 40 years later
above: Oak (foreground, right) showing adventitious re-growth at damaged branch positions
Photos: Forest Life Picture Library

Timber, in common with all organic materials, has a particularly complex structure. In order to understand the properties of oak, it is useful first to look at the way in which a tree grows.

The two broad divisions into which trees are classified are the softwoods, confined mainly to the temperate zones, and the hardwoods, which in turn are classified into temperate and tropical groups depending on the region in which they grow. The softwoods are a relatively small number of cone-bearing or coniferous species, with evergreen needles or scale-like leaves, which grow generally as a single stem to the top of the tree.

Temperate hardwoods, such as oak, are naturally widely branched, unless grown in close proximity to other trees, and broad-leaved, most shedding their leaves in cold weather. Hardwoods are also capable of regenerating lost branches, and since the economic value of the tree is almost always in the trunk, these factors make the management of an oak forest for timber production a more demanding process than softwood production (*Figure 4.1*).

4.1 The living oak tree

All trees are perennial plants capable of secondary thickening, that is, they add yearly growth to the previous year's wood. The main part of the tree is the trunk, which supports the branches and leaves forming the crown. The bark protects the cambium layer, where growth takes place. The trunk itself is made of cells, which are generally elongated in shape.

The majority of cells are orientated parallel to the direction of the trunk. The dimensions vary between species, but they are typically 100 times as long as they are wide and some 4,000,000 of them may be contained within a 25 mm cube of wood. Scattered throughout the wood are groups of cells (5-10% by volume) aligned radially, called rays. No cells run tangentially. The structure of wood is thus markedly anisotropic, ie its properties differ in different directions.

Most of the twigs and branches of the crown are primarily sapwood. In the trunk of the tree, however, the older cells nearer the centre cease to conduct sap, because of their distance from the living, actively dividing cambium, and accumulate extractives. They are then referred to as heartwood, which in many species, including oak, is darker in colour than sapwood (*Figure 4.2*). The toxicity of these extractives makes the heartwood much more durable than the sapwood, which is classified as 'not durable' (see Section 4.4).

Growth takes place while environmental conditions are suitable. In temperate climates, following the dormant winter season, the early wood is characterised by relatively rapid growth, which has a different texture to the latewood. This annual cycle produces a distinctive pattern of growth rings which can be seen most clearly in the transverse section.

The trunk of the tree has three basic functions and the cellular structure of the wood has developed to perform these:

- support for the crown
- storage of food materials from the spring growth
- conduction of water, dissolved mineral salts and carbohydrates between the roots, the leaves and storage cells.

The true oaks belong to the genus *Quercus*, which has more than two hundred separate species and a number of hybrids. Most are found in the northern hemisphere and are mainly trees, although some are shrubs. The main species producing European oak timber are:

Quercus robur L. pedunculate oak
Quercus petraea Liebl. durmast or sessile oak.

Figure 4.2 Oak log after felling showing clear differentiation between sapwood and heartwood.
Photo: Forest Life Picture Library

Both species occur naturally throughout Europe, including the British Isles, and extend into Asia Minor and North Africa. The timber is known as English, French, Polish, Slavonian, or Swedish oak, etc. according to its commercial supply origin. The trees reach a height of 18 m to 30 m, or a little more, depending upon growth conditions, which also affect the length of the trunk. When drawn up to reach the light in forests at the expense of their branches, this may be 15 m or so in length, but in open situations, the tree branches much lower down. Mature diameters can be up to 1.5 m.

4.2 Timber properties

There is no essential difference in the appearance of the wood between the two species of European oak. The sapwood of a mature log is normally 25 mm to 75 mm wide, and lighter in colour than the heartwood, which is yellowish-brown. Quarter-sawn surfaces show a distinct silver-grain figure, due to the broad rays. The annual growth rings are clearly marked by alternating zones of earlywood, consisting of large pores, and dense latewood. Hence, oak is known as a ring porous timber.

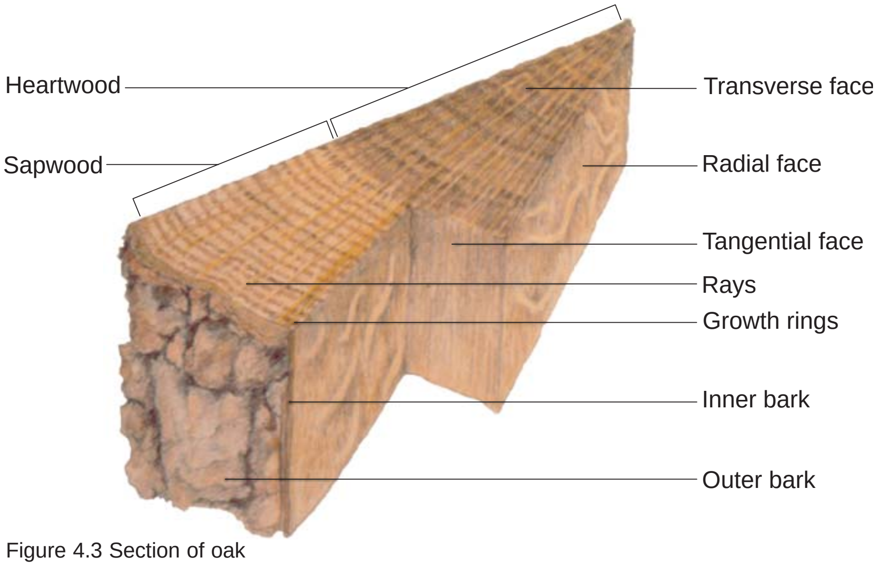


Figure 4.3 Section of oak

Conditions of growth govern the character of the timber to a great extent. The growth conditions in the various countries which export oak vary considerably. The Baltic countries, and northern Poland, for example, produce oak which is generally hard and tough. However, further south, the growth conditions become more favourable to the production of milder, more uniformly-grown timber.

Hence the weight of oak varies substantially according to its source. That from the Baltic region, western Europe, and Great Britain being about 720 kg/m^3 and that from central Europe about 672 kg/m^3 on average, after drying. French sources (Ref:1) recognise two density categories – between 550 and 650 kg/m^3 for “medium-heavy”, and between 700 and 800 kg/m^3 for “heavy”; these categories being based on mass and volume at 12% moisture content.

4.3 Moisture content and drying movement

4.3.1 Moisture content

Like all living things, trees exist in a state of moisture imbalance with their surroundings, and have a constant need to absorb water through their roots. The moisture content (MC) of a timber sample is defined as the ratio of contained water to the weight of dry wood. The heartwood of a freshly cut oak could well have a moisture content of 80%, with even higher values in the sapwood and branches. The cell walls are saturated, and the remaining water is held in the cell cavities.

When the tree is felled, growth ceases, and the trunk starts to lose moisture from its surface. The ‘free’ water in the cell cavities is lost first, until a state is reached when the cell cavities are empty but the cell walls are still saturated. This moisture content is called the fibre saturation point (FSP). The FSP for oak is around 30%, but the value differs slightly between species. As the moisture content continues to fall, the cell walls begin to lose moisture, resulting in shrinkage across their width at a rate, from FSP to zero moisture content, which is roughly linear. Eventually, for a given air relative humidity (RH) the moisture content will stabilise at a value known as the equilibrium moisture content (EMC). The relationship between air RH and timber EMC is shown in *Figure 4.4*.

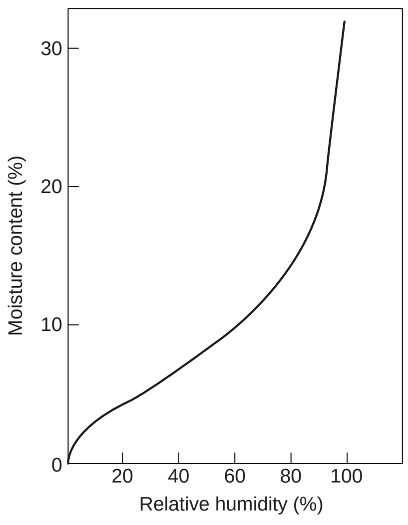
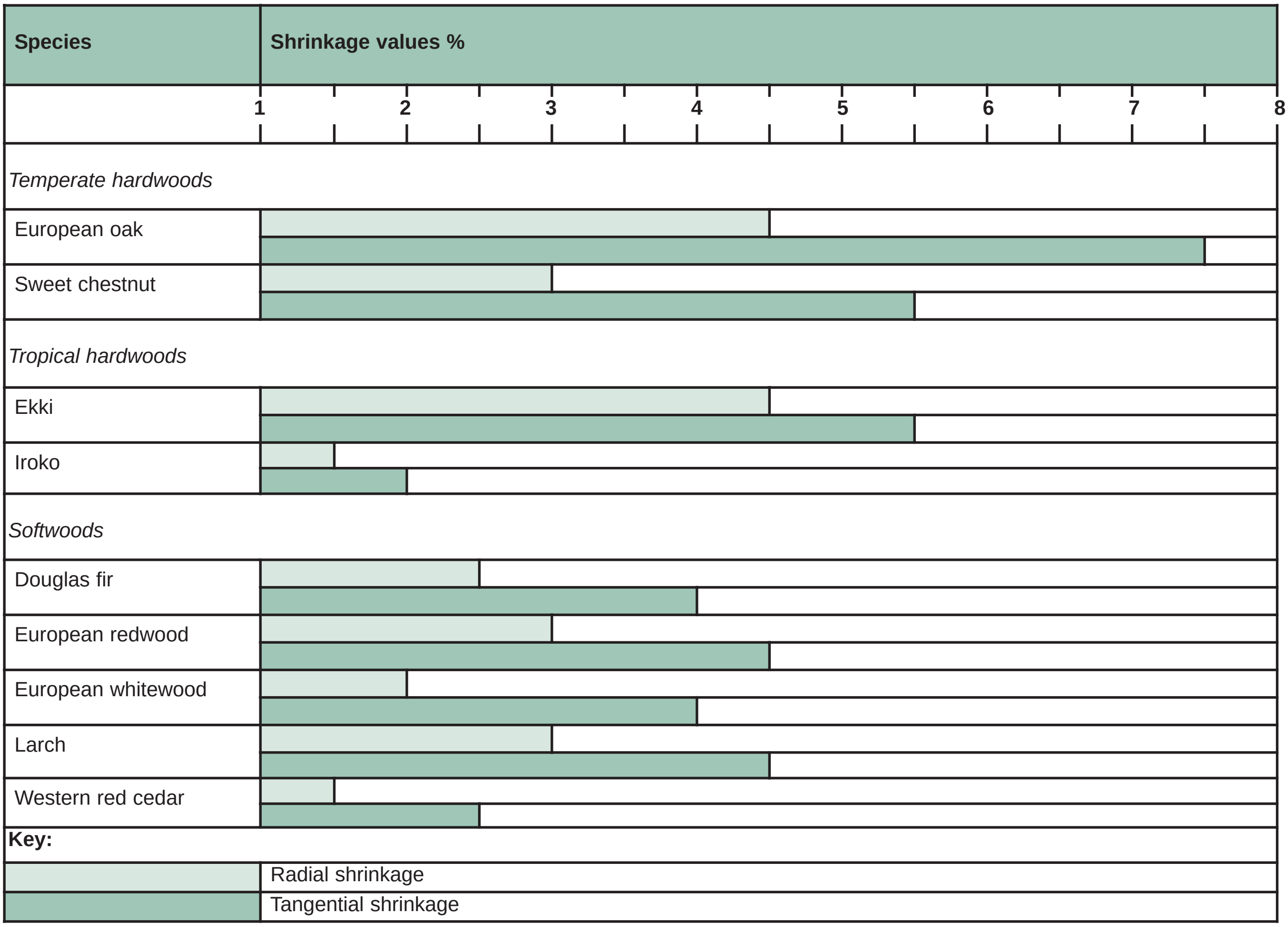


Figure 4.4 Typical relationship between relative air humidity at 20° C and the equilibrium moisture content of timber

It can be seen that the moisture content of oak in an internal, heated environment, where the RH will typically be around 40-50%, will eventually stabilise at 7 - 10%. In an unheated, protected environment (RH 50%-85%) the EMC will be 12 - 14%. Timber which is directly exposed to sun and rain will obviously have a fluctuating moisture content, from 12% to over 20%, at least in the outer layers subject to direct wetting and drying.

The result of this drying is to cause the timber to shrink, but the anisotropic structure of the wood gives very different effects in the three directions. Along the grain (the direction stabilised by 95% of the cells) the total shrinkage for all species from green to oven-dry is around 0.15%, which for practical purposes can be ignored. For oak, the radial shrinkage from green to 10% MC (the direction partly stabilised by rays) is around 4.5%, with a corresponding tangential shrinkage (the direction with no stabilising cells) of around 7%. These shrinkage movements are significantly higher than most of the common softwoods; typical values are given in Table 4.1.

Table 4.1 Shrinkage values for some common species drying from green to 12% moisture content (from BRE Handbook of Hardwoods (Ref: 34))

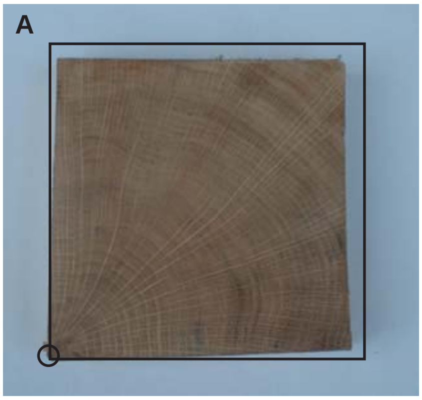


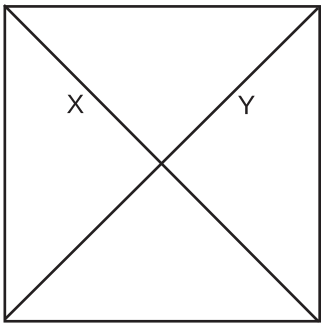
The effect of this shrinkage on a particular piece of oak depends on its proportions and position within the log. As an aid to predicting the distortion, it is helpful to imagine that as the piece dries, the growth rings tend to straighten out.

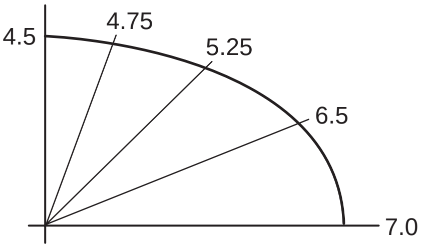
Figures 4.5 and *4.6* show some short (20 mm) slices cut from a green oak log, and allowed to dry down to 10% moisture content. *Figure 4.5* illustrates the distortion which occurs on drying sawn sections. The original green section is superimposed in black on each photograph and the position of the heart is indicated by a circle. *Figure 4.6* shows five adjacent slices of oak trunk containing the heart, which were cut green, and allowed to dry out.

Figure 4.5 Results of drying on green oak sawn sections

Sample A
Sample A is effectively a ‘quarter’ of a log. The differential shrinkage rates have pulled it to a diamond shape, but there is no restraint to the shrinkage, and so the sample shows no fissures, and very little distortion of the faces
The published drying shrinkage values from green to 12% moisture content for oak are 4.5% radial and 7% tangential. The values for intermediate angles are plotted using an elliptical relationship. The actual shrinkage of the specimens is illustrated and the heart or centre of the tree is circled
The diagonal Y is a radial line and the calculated shrinkage is thus 4.5%. The diagonal X is a combination of tangential shrinkage at the centre and shrinkage at 45° to the tangent at the corners, giving an average calculated value of 5.75%. Both actual values are close to the calculated values

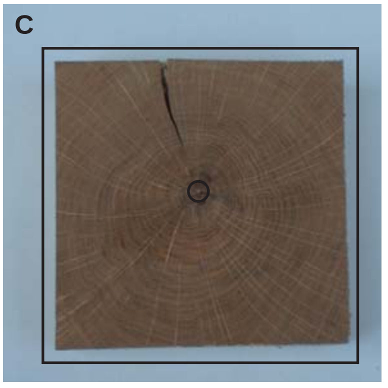






Sample B
Sample B effectively halves the log. Some distortion of the faces is evident, together with some minor fissures. The presence of the heart close to one face has caused some distortion and minor fissuring

Sample C
Sample C shows that the effect of the higher tangential shrinkage on a complete log section is to produce one major fissure, reaching to the pith, and several minor fissures. These effects can also be seen in relatively thin members, such as floorboards or cladding



Sample D Quarter sawn

Sample E Flat sawn

Sample F Flat sawn, includes heart

If boards are 'quarter sawn' (sample D), they remain virtually distortion-free during drying, but flat (tangentially) sawn boards (sample E) tend to cup. Including the heart in a relatively thin board, sample F, will weaken it considerably

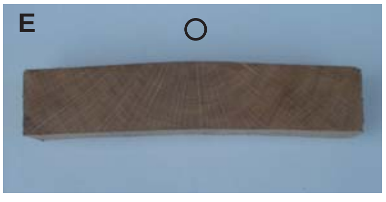
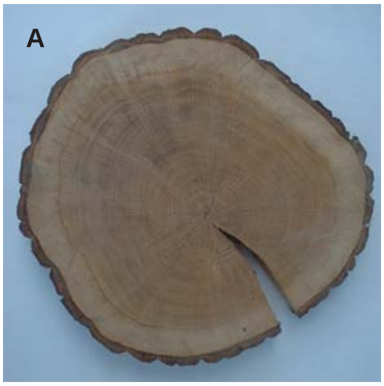
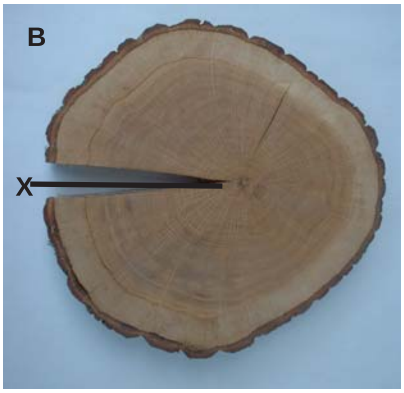


Figure 4.6 Effect of drying on slices of oak trunk

Sample A
Tangential shrinkage has caused a fissure to develop along the shortest line between the heart and the bark, the 'principle of least work' in the field of biology



Sample B
Sample ‘B’ was pre-cut along line X, the longest distance from the heart to the bark. This has acted as a release for the circumferential strains, and the first fissure has duly opened along this line, The principle of pre-cutting can be used to induce the major fissure to occur on a face which is perhaps hidden, or visually unimportant



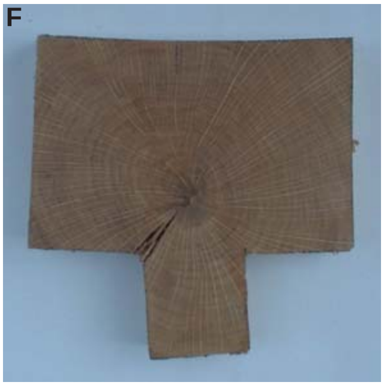
Sample C

Sample D

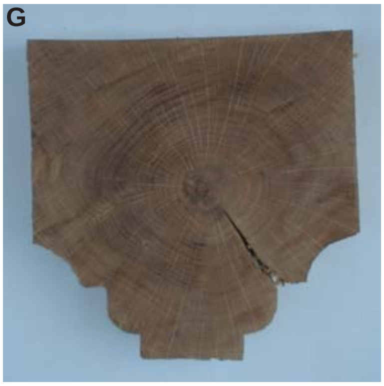
Sample E

Samples C to E explore the effect of a centre hole as a method of minimising fissures. In sample E, a hole which is only 1/5th of the trunk diameter has almost persuaded the slice not to split at all (see Case Study 9.1: Globe Theatre)

Sample F again demonstrates a fissure along the 'shortest line' principle of A, in this case resulting a pronounced distortion of the section



Sample G might represent the cross-section of a moulded floor beam. Here the fissure occurred at the root of a re-entrant profile, where it is hardly noticeable



4.3.2 Movement

So far we have discussed the shrinkage which occurs as green timber dries to its equilibrium moisture content. However, the moisture content and hence the dimensions of timber will change if its surrounding temperature and humidity conditions change. This is known as movement. The degree of movement exhibited by timbers varies with species; oak is classified as a 'medium movement' timber.

The movement of timber in relation to the ambient RH is reversible. If the ambient humidity of the air increases for a period of time, or the piece gets wet, the moisture content of the outer layers will increase, with some consequent radial and tangential swelling, but for these, and any subsequent movements, the rates of movement are roughly half the initial values. Thus, drying fissures may get narrower if the timber is re-wetted, but will never close completely.

All of the pieces shown in *Figures 4.5* and *4.6* were deliberately cut as short sections, and as a consequence dried out relatively quickly along the grain to the cut faces. Even so, the process took between two and three months. Actual framing members are long by comparison, and would have to lose most of their moisture from the side faces. The old carpenter's rule for drying of 'a year for every inch of thickness', will give some idea of the time which it takes to air-dry freshly-cut oak. As a guide, a 100 mm x 100 mm section might require four years, and a piece 150 mm x 150 mm six years or more.

Figure 4.7 'Sticked and stacked' logs
Photos: John Boddy Timber Ltd

The loss of moisture from the external faces also means that there is a moisture gradient across the section. As the moisture content of the outer layers falls below the FSP they start to shrink, producing tangential tensile stresses which may overcome the very modest strength of the timber in this direction, and cause several small fissures to develop. As drying progresses it is likely that one of these fissures will extend to the pith. The fissure tends to occur along the weakest line, which is the shortest distance from the pith to the surface. Thus, it is almost always found that the depth of a drying fissure is not more than half the depth of the piece. In general, the only case where drying fissures will occur through the full depth of the piece (when they are known as splits) is at each end. Due to the more rapid loss of moisture from the end grain, the whole cross-section tends to shrink against the restraint provided by the still-wet body of the piece.

So far, we have looked at the effects of drying shrinkage on the cross-section. As we have seen that shrinkage along the grain is negligible, a small test-piece with perfectly straight grain should effectively remain straight while drying out. For full-size framing members however, some variation in slope of grain along the piece is likely, bringing with it the possibility of drying distortion along the length. Thus fresh-sawn logs which are to be dried are 'sticked and stacked' (*Figure 4.7*) to allow air circulation, while using the self-weight of the stack to prevent drying movement.

4.4 Durability

All plants have some position within the food chain. Celery, for instance, can be broken down into starches and sugars by the relatively feeble human digestive system, whilst herbivores such as cattle are able to eat grasses and leaves within grazing height. Nevertheless, the substances of the trunk – cellulose, hemicelluloses and lignins – are combined in such a way that only a relative handful of fungi and insects have discovered a method of using timber as a food source, and then only under certain conditions.

The timber in a building has existed in three very different states:

- the growing tree
- the felled log, or as timber undergoing seasoning
- in service as a building element.

The prevention of fungal or insect attack in the first two states is primarily the responsibility of the forester and the merchant. The building designer is concerned with the possibility of attack after the timber has been installed and since not every piece may be attack-free at the time of construction, the frame-maker has the responsibility of selection (see Appendices I and II).

4.4.1 Fungal attack

The spores of fungi are microscopic and myriads are widely distributed by air currents. To germinate they need:

- a food source
- oxygen
- a suitable ambient temperature range
- adequate moisture.

Within a building, the chances of germination of a spore landing on timber will therefore depend primarily on the moisture content of the timber. If this is below 20%, growth of fungi will not occur. Above this level and up to an optimum of about 35-45% moisture content, there is a good chance that some spores will eventually germinate. The mycelium, made up of exceedingly fine tubes called hyphae, then grows through the cells of the host timber, feeding on it, and causing decay.

It was noted in Section 4.1 that the heartwood of timber contained extractives. The toxicity and proportion of these extractives in each species largely determines its natural durability.

In European standards, a classification system for durability has been established. Originally this was based on tests carried out by cutting 50 mm x 50 mm stakes of various species, driving them into the ground, and testing them at yearly intervals for failure, (*Figure 4.8*). More recently, these so-called 'graveyard tests' have been supplemented by various biological laboratory tests set out in BS 350-1 (Ref: 16). From the results, timbers of different species are classified into five durability classes, defined in BS EN 350:

1 - very durable
2 - durable
3 - moderately durable
4 - slightly durable
5 - not durable.

The classification of some common structural species is given in Table 4.2.

Figure 4.8 'Graveyard' tests
Photo: © BRE

Table 4.2 Durability ratings of the heartwood of common species (from BS EN 350-2 (Ref: 17))

Species	**Natural durability class against fungi**				
	5 Not durable	**4** Slightly durable	**3** Moderately durable	**2** Durable	**1** Very durable
Temperate hardwoods					
European oak				■	
Sweet chestnut				■	
Tropical hardwoods					
Ekki				■	
Greenheart					■
Iroko				■	■
Softwoods					
Douglas fir - North American timber			■		
Douglas fir - cultivated in Europe		■	■		
European redwood (pine)		■	■		
European whitewood (spruce)		■			
Larch		■	■		
Western red cedar - North American timber				■	
Western red cedar - Timber cultivated in the UK			■		

As can be seen, the heartwood of oak is classified as 'durable', a better rating than all but one of the softwoods, and exceeded only by a few species of tropical hardwoods. The sapwood of all species (containing no extractives) is either 'not durable' (as in oak) or, at best, 'slightly durable'.

In view of the poor durability of most softwoods, treatment processes have been developed to impregnate the outer layers of the timber with preservatives. The effectiveness of the treatments, however, depends upon the permeability of the species. Oak is very resistant to such treatments, but, because of its natural durability, does not have need of them. The few 'very durable' tropical hardwoods include greenheart which is resistant to marine borers, and its superiority to oak is mainly relevant to applications such as dock and harbour work.

4.4.2 Insect attack

In the UK, there are only a few species of beetle which attack timber. Larvae hatch from eggs laid on the surface of the wood, and then bore into it, creating tunnels as they feed and develop, before leaving through holes on the surface when they finally emerge as adult insects. The heartwood of oak is very resistant to insect attack in the British Isles. When an area of attack is discovered in installed oak, it is generally found that the area has been damp for a sufficient period of time for rot to have developed, or that the piece contained sapwood. However, even dry sapwood is vulnerable to attack by the powder post beetle (*Lyctus* spp) and this should be taken into account if sapwood is included in material for internal use within a building frame.

In summary, oak is one of the most durable of the temperate hardwoods, and its heartwood can be used with confidence for both internal and external structures. The special durability of such tropical species as greenheart or ekki relates mainly to their resistance to attack by marine borers in structures such as piers or jetties.

4.5 Strength properties

To get some idea of the strength of oak, it is useful to look first at the results of bending tests on small (20 mm square) 'clear' samples (that is, sound, straight-grained and without fissures or knots) which can be carried out relatively easily in the laboratory. The test arrangements are described in BS 373 (Ref: 4) and typical results are shown in *Figure 4.9*, where the extreme fibre stress in bending is plotted against the corresponding strain. The slope of the graph is the modulus of elasticity (E), a measure of stiffness. Tests are carried out on a series of both green (above FSP) and dry (10% MC) samples, and it is clear from the results that oak, in common with other timbers, gains in strength and stiffness as it dries out – the modulus of elasticity of the green timber, E_{green}, is some 80% of E_{dry}.

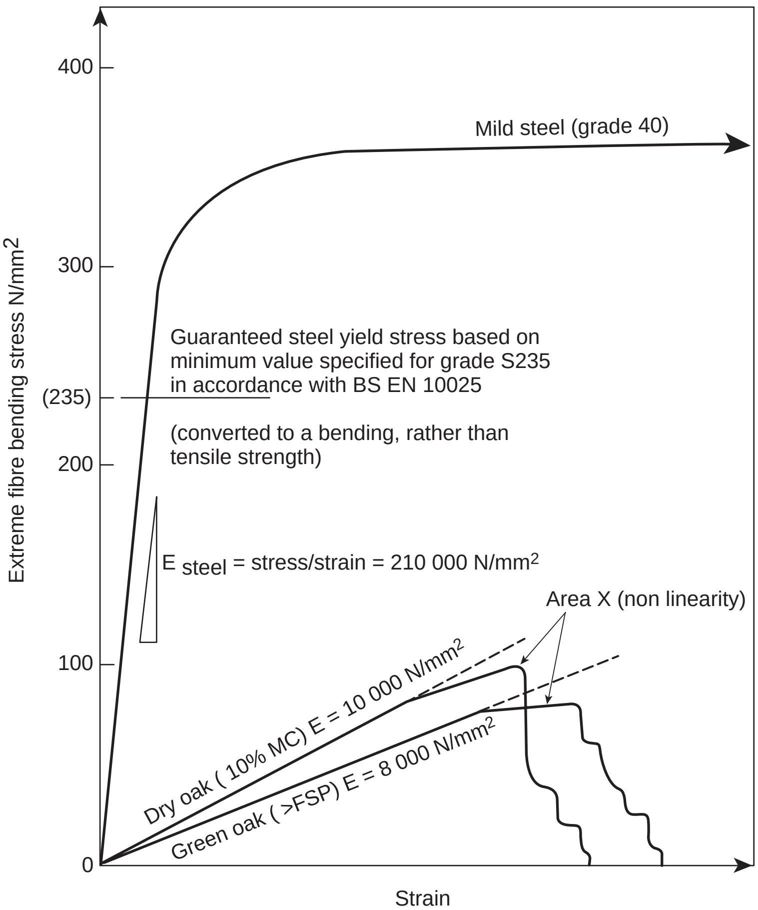


Figure 4.9 Comparative stress/strain behaviour of oak and plain carbon steel

The results are averages of about 260 tests. All timber has a certain variability in its properties (mainly stemming from a variation in density, which in turn is the result of inevitable variations in growth conditions). The coefficient of variation of the bending strength of clear green oak is around 15%. The results of a similar test on a specimen of mild steel of the same dimensions are also plotted in *Figure 4.9* for comparison. It is interesting to note that while steel is over three times as strong as oak, it is ten times heavier. Thus the strength/weight ratio of clear dry oak (in common with most other timbers) is much superior to steel, and it was for this reason that the early aviators built their machines in wood rather than metal. However, steel is some twenty times as stiff as oak, and has a ductile failure (the flat part of the graph which extends well off the page), whereas oak shows only a small flattening of the curve (area x) before a relatively sudden brittle failure. It is also true that timber loses some strength under sustained loading – the equivalent 'fifty-year' results would be about 30% down.

Similar tests can be done to establish compressive and shear strengths and the results are shown in *Figure 4.10*. But, as we have seen, timber is very anisotropic (*Figure 4.3*). The perpendicular to grain (cross-grain) properties are markedly lower; some 10%-15% of the parallel to grain properties (both for oak and for other species generally). These results place oak in a medium to high strength category – stronger than the softwoods, and exceeded in strength by only a few of the tropical hardwoods.

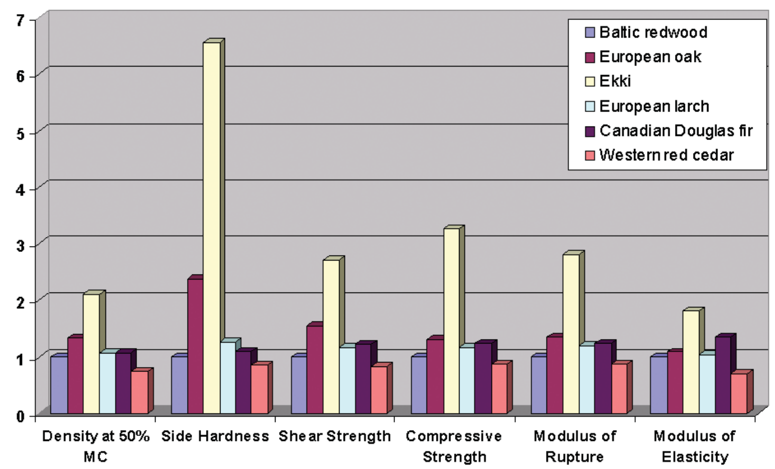


Figure 4.10 Green oak strength properties compared with other green timbers

It is, however, almost impossible to obtain clear timber of a size which can be used for construction purposes, and so all framing timber will contain characteristics which reduce its strength and stiffness. These are principally:

- knots
- slope of grain
- wane (loss of corner profile)
- fissures and splits (also known as shakes and end checks).

Limits on the size or extent of these defects are generally defined by selection or by more formal grading rules, dealt with in more detail in Chapter 6 and in the Appendices.

4.6 Creep deflection

All timber beams, including those made of oak, are subject to 'creep'; that is an increase in deflection over time under a constant load. The effect is largely dependent upon changes in the moisture content of the timber. Thus a seasoned timber beam installed in a dry environment will exhibit little creep deflection. A beam which is initially green, installed in the same environment, will exhibit more creep, while most creep will be evident in a beam of green timber exposed to the weather, with constant wetting and drying.

To demonstrate the effect, a small beam of green oak was loaded for six months in an internal heated environment (*Figure 4.11a*). From an initial value of 12 mm, the deflection increased over time, but at a decreasing rate. Six months later, the beam, now dry, had deflected by 31 mm. The creep component of the deflection, 19 mm, is around 1.6 times the initial deflection under load, and remained as a permanent set when the beam was unloaded (*Figure 4.11b*).

This degree of creep might seem large, but the test had been deliberately designed to highlight the effect. The beam had a high span-to-depth ratio, and the full load was maintained for the whole of the test period. If floor beams are proportioned according to traditional rules, or designed in accordance with the code of practice, the creep component of the deflection will be relatively small.

Guidance on the estimation of creep deflection is given in Eurocode 5 (Ref: 20), and the rules are summarised in Appendix III.3. These suggest that the long-term creep deflection of a green oak beam will vary from 1.6 times to 2 times the initial permanent load deflection, depending on whether the beam is inside or outside the building envelope. In this context, the 'permanent' load has two components - the dead load of the structure, and the 'quasi-permanent' load, defined as the notional average live load over time.

An example is given (in AIII.3.1) of a principal house floor beam, 250 mm deep and spanning four metres. In this case, the initial deflection under permanent load of 3.5 mm, will increase over time by 5.5 mm, or thereabouts. Since a four metre beam is unlikely to be perfectly straight when cut, good practice would be to install the beam 'bow up', hence minimising the final effect of creep. It should be remembered that while the actual amount of creep deflection is small, it will occur after fittings and fittings have been installed, and might have to be considered, for instance, in the location of tall cupboard units.

Figure 4.11
a, top: A plank of green oak, 100 mm wide by 20 mm deep, spanning 1.2 m with a central point load
b, above: After six months the plank had dried out. With the load removed, a residual deflection of 19 mm remained

4.7 Working qualities

The working properties of timber vary with density and moisture content. Green oak is generally easy to work but the dried material is described as medium to difficult. Cutting edges always need to be kept sharp.

4.8 Chemical properties

Oak is an acidic timber which tends to promote the corrosion of metals in contact with it in the presence of moisture. The timber itself is also subject to blue-black staining which is formed by a reaction of iron with tannin in the presence of moisture.

Figure 4.12 Tannin exudation on European oak cladding boards

Oak contains large amounts of tannin, which when green timber is used externally, will bleed from the wood as it dries. This appears as a black deposit, variable in intensity that will be gradually washed down by rainfall (*Figure 4.14*). The tannin can stain porous surfaces below the cladding, such as brick walls or paving, and can cause corrosion in steel. Exudation can continue for many months and it is sensible to use corrosion-resistant fixings (such as stainless steel) and to protect surfaces below during this period. This has significant implications for building design as discussed in Section 6.4.5.

4.9 Behaviour in fire

When timber is heated, gases are released; mainly incombustible carbon dioxide and combustible carbon monoxide. It is the gas which first burns, and not the timber itself. For the vapours to ignite there is normally a source of ignition. This happens at around 250-300°C. If there is no ignition source, but the temperature increases, then spontaneous ignition may occur, as happens when a fire radiates heat onto a remote piece of timber. Once ignited, the burning vapours heat up adjacent timber and the process continues. The heat transfer from the flame to unburnt material is mainly by radiation from the flame, and convection from the burning vapours. Changing the orientation of a burning match from the horizontal to the vertical demonstrates the different modes of heat transfer. Because timber is a good insulant, conduction of heat back into the unburnt material plays a minor role.

Figure 4.13 Charred oak. A Globe Theatre (see Case Study 9.1) joint after fire testing. The oak has suffered little charring; this is apparent as the shape of the elements is clearly defined. The assembly was subsequently successfully tested to verify its remaining strength
Photo: Jon Greenfield

As the gases burn off, the residue, charcoal, is largely pure carbon. The charcoal intumesces during its formation, expanding in volume and creating microscopic voids. It is an excellent insulant and the timber a short distance behind the charring layer is virtually undamaged. This has the effect of controlling the rate at which combustion occurs, and many tests have shown an approximately linear relationship between charring depth and time, which, for a particular temperature, is known as the charring rate. The charring rate depends upon the density of the timber.

European oak is more dense than the average structural softwood and structural design codes therefore permit advantage to be taken of a slower charring rate. For example, BS EN 1995-1-2 (Ref: 21) cites a rate of 0.5 mm/min for European oak, compared with 0.65 mm/min for European spruce or redwood.

The design of oak structures in relation to fire regulations is covered in Section 5.2.5.

5 Design of green oak structures

Whilst some clients for buildings may be clear from the outset that they want a green oak structure, it is more usual for the designer to take the client through a decision process. The first step is to decide whether timber is an appropriate material for the structure, and then to consider the possibility of using green oak. This chapter outlines the first steps in the second part of that process, considering the options for frame design, the various performance criteria and looking at examples of historic construction forms as models for today (see also Case Studies, Chapter 9 and Section 2.3).

5.1 The design of the frame

5.1.1 The architectural 'language' of framing

It should be borne in mind that the use of an oak frame as a load-bearing structure imposes a certain discipline on the building layout. The frame outline should be part of the overall building concept, rather than something imposed on the plan at a late stage in the design. Later in this chapter, examples are shown of traditional buildings, and many can be seen to consist of a series of bays, defined by cross-frames at regular intervals, which are linked together by the longitudinal members. On plan this generates a rectangular grid, with posts at the intersections (*Figure 5.1a*) and results in a structure which is relatively straightforward to detail in terms of the joints. Traditionally, in buildings of regular bay spacing this dimension was something in the order of 12-16 feet (3.6-4.8 m). This was guided by timber length and also by the practicalities of use, including convenient opening sizes. Modern designs are not obliged to follow this practice, but the implications of departure from this convention should be considered since maintaining such a discipline often leads to economy.

However, traditional buildings are not confined to a rigidly repetitive grid. It is possible to add to, or modify the outline (*Figure 5.1b*). The spacing of the cross-frames may be varied, provided that the longitudinal members are appropriately sized for the spans which result (*Figure 5.1c*). Circular or segmented layouts are also possible (*Figure 5.1d*); the Globe Theatre (see Case study 9.1), for example, is a twenty-sided polygon.

With the benefit of engineering analysis, further variations are possible (see Rowses Farm, Appendix 1.2.2). Bedales School (see Case Study 9.6), apart from being symmetrical, has no pronounced grid, demonstrating that green oak may be used for contemporary design as well as following traditional models.

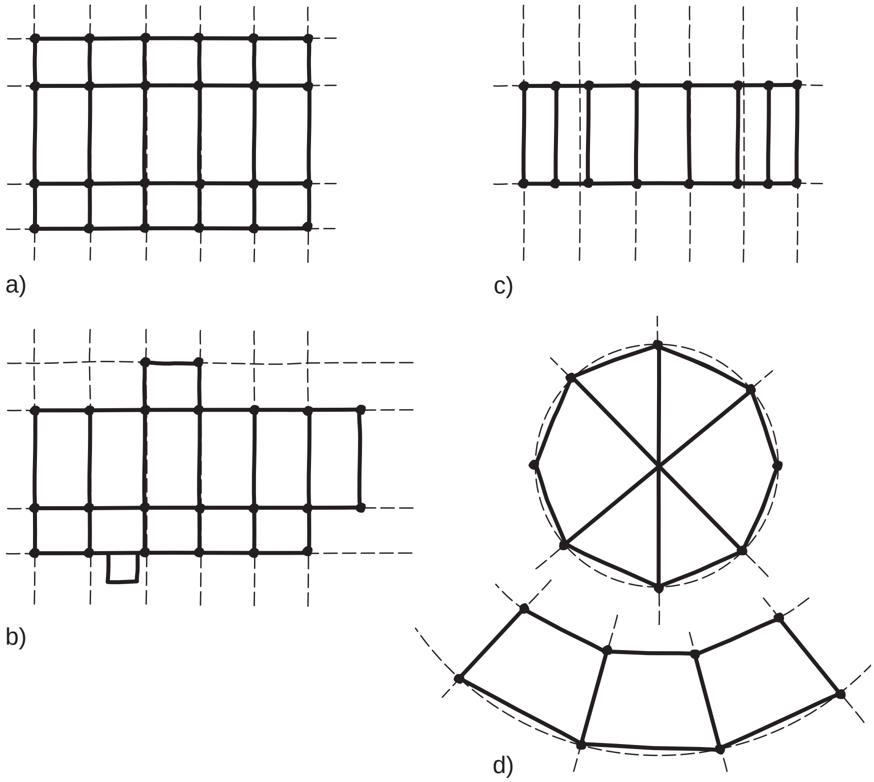


Figure 5.1 The architectural language of framing

Figure 5.2 Approach A Frylands Cottage- A green oak building in traditional vernacular style and scale, framed with traditional pegged joints.
Photo: The Green Oak Carpentry Company

5.1.2 The structural design of the frame

There are essentially two approaches to the procurement of green oak frames, depending upon the method by which they are designed and the way in which building regulation approval is sought.

Approach A applies to traditional frames, often using pegged carpentry joints. The frame is fabricated and erected by skilled and experienced craftsmen.

Approach B applies to more ambitious designs where the frame form results in longer spans and/or heavier loading requiring formal engineering calculations. Metal connections are often employed and fabrication and erection should be undertaken by experienced contractors.

There is a third approach, relating to unusual or innovative structures, where new techniques of construction may require particular justification, perhaps involving tests or prototypes. These projects are generally outside the scope of this book's advice, but the Weald and Downland Museum's Gridshell is included as a Case Study (9.8) example of this type.

Structures covered by Approach A should be essentially domestic in scale, with no abnormal spans or loading (*Figure 5.2*), and might be chosen from the medieval forms illustrated in Section 5.3.1. For such structures, an engineer's Certificate of Approval is normally provided for building regulations purposes. This allows exemption from a requirement for formal code-based calculations on the basis that the design is founded on the long usage of "….. well-tried and traditional methods of construction which have been employed successfully over a long period of time." (Clause 1.1 (Scope) of BS 5268-2: 2002 (Ref: 7)). Timber selection is by the framer, who could base this on the carpenters' framing selections GF/SF described in Chapter 6 and Appendix I.

Approach B includes an overall structural analysis with calculations submitted for building regulations approval. The calculations are based on the recommendations given in the structural design codes, BS 5268-2 or the Eurocode series, specifically BS EN 1995 (Ref: 20) for timber. Examples in the Case Studies include York Minster (9.5), Bedales School Theatre (9.6 and *Figure 5.3*) and Darwin College Study Centre (9.7). The timber may be specified according to the selections noted above but for critical members the Green Oak Strength Grading Rules should be used, as described in Chapter 6 and Appendix II.

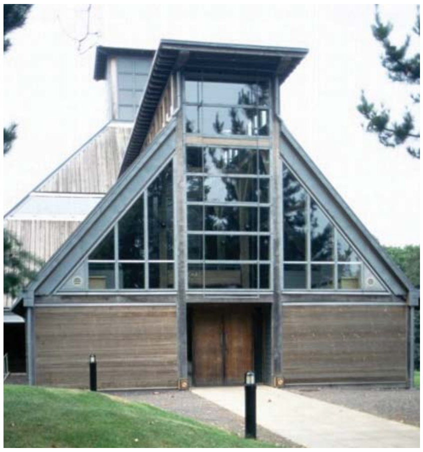


Figure 5.3 Approach B - The Olivier Theatre, Bedales School
Photo: P Ross

It is important that responsibility for a green oak frame is taken by a construction professional, generally an engineer or a technically informed architect, who is knowledgeable about the behaviour of the material. Where formal strength grading becomes part of the framing process, this professional needs to agree with the carpentry contractor or timber building manufacturer as to exactly when and how it is to be achieved. It is essential to apply the method not only at the design stage for calculation data, but also in the workshop (see Section 6.3.4).

The Globe Theatre, Southwark, London, *Figure 5.4* (see Case Study 9.1), exemplifies another type of project where more precise control of grading was necessary for certain elements. In this instance, skilled craftsmen used traditional carpentry methods to construct the individual frame elements. However, the building includes internal structures that support large numbers of visitors, whilst the site is an exposed riverside embankment close to an estuary, with consequentially high wind loading.

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Figure 5.4 The Globe Theatre, Southwark.

For further guidance, *Figure 5.5* summarises the decision process.

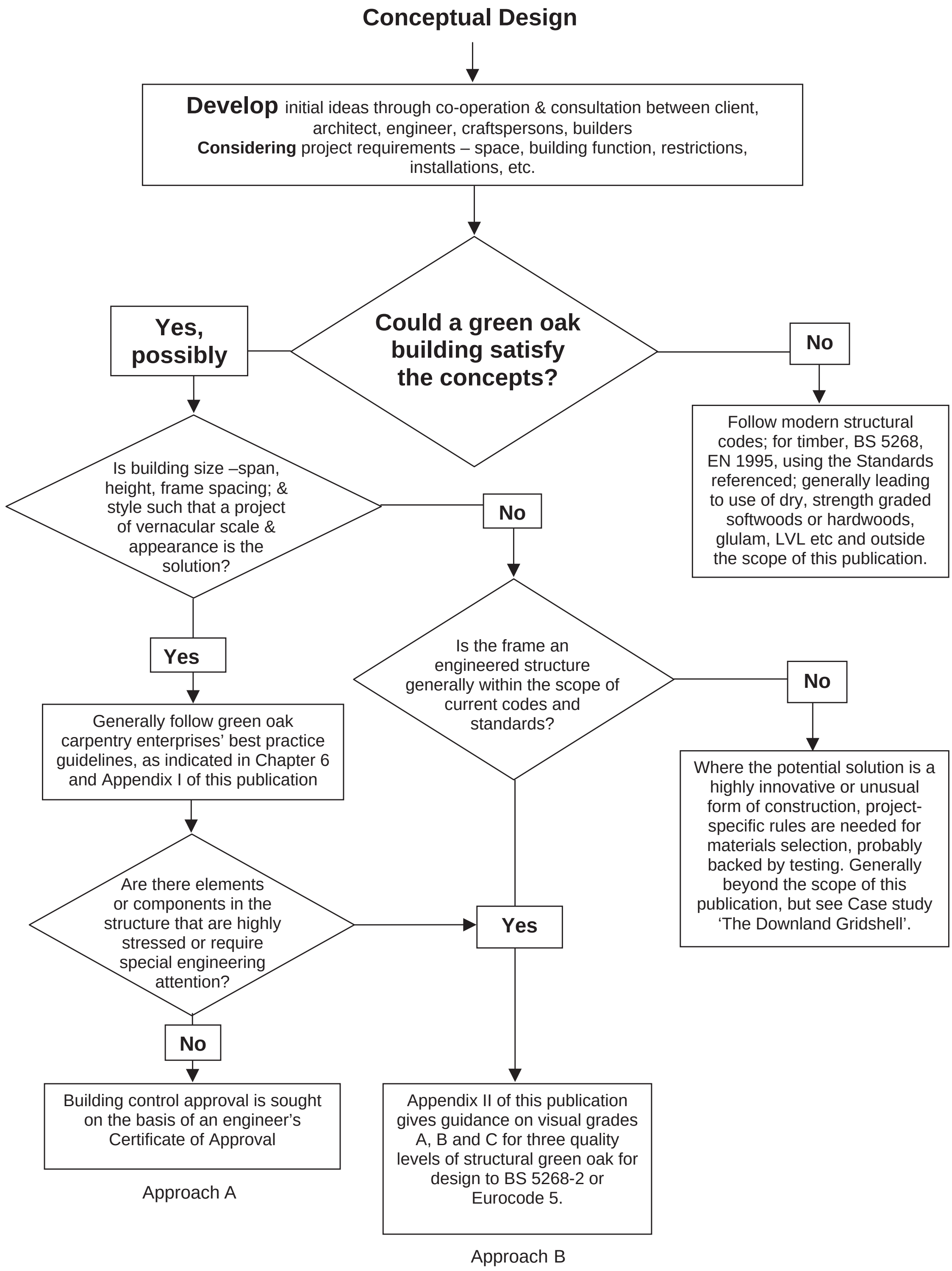


Figure 5.5 The decision process for selecting a project in green oak heavy framing

5.2 Performance of the structure

Adequate performance of a structure should be ensured by compliance with various design criteria under the following headings:

- strength and stability
- serviceability
- durability
- appearance
- fire.

Some criteria will be laid down in the building regulations or structural codes, whilst others need to be agreed between the designer and the client. For structures made of green oak, the criteria are discussed in more detail below.

5.2.1 Strength and stability

For reasons of safety, it is obviously important that a structure has adequate strength (so that it will not fall down) and stability (so that it will not fall over). In most cases it will be necessary to provide supporting evidence to this effect in a building regulation submission. In order to present engineering calculations, strength, stiffness and density properties are required, see Appendix III.

As discussed in Chapter 4, the strength of green oak is significantly lower than its dry strength and the engineer must take this into account. Although green timber in a normal building environment will eventually dry out and achieve its full strength, it is unfortunately not possible to make bargains with the weather – the design wind speed or snow load may occur shortly after construction, when the timber is still green.

Stability is more likely to be overlooked as a design case than strength. By reference to the examples in Section 5.3, it is obvious that most vernacular frames achieve stability in both directions by bracing members, which effectively triangulate the structure. These braces are generally in opposing pairs, as the tension capacity of a pegged joint is small, and the stabilising force in either direction may be provided predominantly by the brace which is on the compression side.

Some modern frames may rely on bending resistance at the joints to ensure stability. Such cases need careful engineering analysis to ensure that the joints have adequate strength and stiffness, particularly where fasteners such as bolts are used in green timber which subsequently dries out.

5.2.2 Serviceability

Serviceability is a general term associated with structural deformations under load - the most obvious examples being the deflection of beams and vibration of floors. Serviceability is not usually a safety issue, and the calculation of deformation is not then strictly required for a regulation submission. The Eurocode series of structural design codes generally permits the design criteria to be agreed between the construction professionals and the building owner, although for small routine projects, published recommendations, such as those included in the National Annex, may be followed without special consultation. Further information on serviceability design is given in Appendix III.

As discussed in Chapter 4, the potential deflection of beams is a significant factor in green oak design for two reasons:

- the Modulus of Elasticity (ie the measure of stiffness) of green oak is significantly lower than dry
- in addition to the elastic (ie recoverable) component of deflection, green oak is subject to creep (non-recoverable) deflection, (see Section 4.6).

Figure 5.6 Caerphilly Castle Visitor Centre. The prominent cantilevers of the canopy are a case where special care was taken to control the vertical deflections of green oak beams. This included prediction of creep using the Eurocode methods
Photo: Davies Sutton Architects

These factors are controlled by avoiding over-ambitious span/depth ratios for beams, as is normal in most vernacular designs. However, the building owner should be made aware that some degree of creep deflection will inevitably take place. In some situations this may be especially significant (*Figure 5.6)*.

The designer also needs to consider deformations in relation to:

- their potential to affect the performance of non-structural elements such as partitions, doors and fitted furniture
- vibration or excessive 'liveliness' of floors
- their visual acceptability.

Horizontal, or sway deformations of frames should also be considered in relation to:

- their structural acceptability (sway stiffness)
- potential damage to non-structural elements, eg glazing.

The other serviceability issue for green oak is the effect on performance of drying movements. Shrinkage and movements of the cross-section are inevitable and must be considered within the design, see Section 5.4. Most vernacular structures accommodate these movements without loss of structural performance, but they may affect adjacent elements, such as plastered panels or window frames.

Distortion along the length of a member may occur as bow, spring or twist (see Appendix II.4.6) and combinations of these are also possible. Since distortion occurs as the oak dries, it is not completely avoidable, but careful grading and selection will keep it to acceptable levels. Traditional structures generally have arrangements and details that accommodate the movements associated with drying distortion. These include:

- ends that are free to take up modified positions, eg within pegged joints
- members that are controlled by mass along their length, eg sole plates
- triangulated bracing attached by flexible pegged joints
- cross-sectional dimensions of bending members that are generally square or near square.

5.2.3 Durability

The durability of oak heartwood and the vulnerability of the sapwood have already been discussed in Section 4.4. When a frame is set entirely within the weatherproof envelope of the building and protected from moisture which might emanate from the ground, the external walls, or the roof, the timber will eventually dry down to a moisture content of around 10%-14%. Under these conditions there will be no risk of either dry or wet rot developing, and there is no reason to exclude sapwood on this account. However, even dry sapwood is prone to attack by *Lyctus brunneus* beetle larvae. Since sapwood is generally found on the arrises, or edges, of a piece, its gradual removal is unlikely to reduce the grade strength unacceptably. However, the appearance of the fine, flour-like bore dust produced may alarm building owners so this possible consequence of allowing sapwood in the timber specification should be discussed with them at the design stage.

If a framing member is partly exposed to the weather, such as on the external wall of the building, no sapwood should be allowed on the exposed faces, and permanent contact between any timber member and the ground should also be avoided. For a fully exposed structure such as a bridge, or deck, sapwood should be excluded completely.

The 'design life' of oak heartwood within a building (given appropriate maintenance of the fabric), could confidently be stated to be limitless. Where the oak is exposed to rain, it is difficult to give a notional life-span, because this will depend greatly on the details of construction. The design should encourage water to run off the structure, avoiding potential water traps. The detailing of external structures for durability is discussed in more detail in Chapter 8.

5.2.4 Appearance

There are few structural systems in which the logic of construction is more clearly expressed than the oak frame. This, combined with the visual appeal of the timber itself, is the main motive for a purchaser. Consequently, the appearance of the completed frame is very important. Some aspects need consideration early in the design process and should be made clear to building owners when they commission a green oak structure.

Appearance in terms of knots, grain, surface rings and ray patterning is influenced by the quality of the timber specified as well as by the method of conversion. These topics are discussed further in Chapter 6.

Whilst the timber is still green it will be clear of fissures, but fine checks will develop quite rapidly, soon to be followed by larger fissures (*Figure 5.7)*. These could alarm a building owner who is unaware that this will occur and it is thus very important that the construction professionals communicate thoroughly over these aspects. They are discussed extensively in Sections 4.3 and 5.4.

Figure 5.7 Significant fissure in a post in Bedales School library, built in 1921
Photo: P Ross

For posts, the option of excluding boxed heart in order to minimise the occurrence of fissures may not be feasible in terms of the required member size, and to insist on finding an exceptional piece goes against the principle of utilising the smallest log appropriate for the purpose. Another option is to pre-cut the post (thus pre-determining the position of the fissure) as shown in *Figure 4.6 (b*), ideally on a concealed face. The building owner should also be made aware that slight distortions in the length will occur on drying, although the designer's aim is to control these.

The method of conversion will also show as surface texture and there may be a need to remove any stain which develops between conversion of the timber and completion of the frame. Many green oak framing companies employ sand blasting to clean internal timbers once the building has been made weathertight.

Although most frames are left without applied finishes, a limited range of surface treatments is described in Section 6.4.6.

5.2.5 Design for fire protection

The behaviour of timber in fire is described in Section 4.6 and requirements relating to the design of structures in relation to fire are laid down in building regulations (Refs: 25, 36, 40). These have, until recently, been largely prescriptive, although in England and Wales a 1996 amendment allowed the application of fire engineering principles to increase the options available to the designer.

The regulations require the survival of the structure for a defined period, which is determined according to the height and the purpose group classification of the building. For an oak frame, this leads to two design parameters:

- a period of fire resistance
- control of the surface spread of flame.

5.2.5.1 Fire resistance

The required period of fire resistance for structural elements varies from zero for roofs (as long as they are not required to stabilise the walls) to 30 minutes or a maximum of 60 minutes for buildings likely to be based on timber framing. The two approaches to achieving these periods are:

- to design fire-surviving timber elements and connections, or
- to protect the timber with suitable material.

It is, of course, perfectly possible to protect timber with a material such as plasterboard (as is done for most modern timber-framed buildings), but, as discussed in 5.2.4 above, the expression of the oak is generally an aim of the design. The alternative is to size the member so that after the requisite period there is still enough residual timber to carry the design load for a short while. This method of design is described in more detail in BS 5268-4 (Refs: 8,9) and BS EN 1995-1-2 (Ref: 21). Advantage can be taken of the higher density of European oak compared with a typical structural softwood.

Pegged joints have been shown not to reduce the period of fire resistance. Bolted or screwed joints with exposed heads will fail prematurely, due to loss of strength in the steel and the conduction of heat into the centre of the timber. Hence, if such fasteners are used for elements requiring a period of fire resistance, they are generally inset and plugged. A selection of methods to achieve this is given in the above-mentioned structural codes.

5.2.5.2 Surface spread of flame

Untreated oak falls into surface spread of flame Class 3 (to BS 476-7 (Ref: 5)). Regulations may require Class 1 surfaces for larger rooms (or Class 0 for circulation spaces in some buildings) but a proportion of the surface is allowed to be of a ‘lower’ (ie numerically higher) class. Since the actual frame is generally a small proportion of the total wall and ceiling area, it is not usually necessary to apply a flame retardant coating to the exposed timber surfaces. However, the use of a flame retardant may have to be considered where, for instance, timber panelling is also used.

The national classification system quoted above is based on testing to British Standards. It is being replaced by a European classification system for the reaction to fire performance of products. The classifications are set out in BS EN 13501-1 (Ref: 22) and the requirements in relevant building regulations.

5.3 Historical forms as models for today

This section shows a selection of historic frames from various periods with the aim of illustrating those forms of most use as models for present-day green oak designers. The section is divided into three broad categories:

- The Medieval Period
  This was typified by complete frames, generally in oak, exposed to view from within and without, and with the various members joined by timber dowels in mortice and tenon, side-lapped and end-spliced joints. See Section 5.3.1.

- The Seventeenth/Eighteenth Centuries
  Apart from agricultural buildings, such as barns, most structures now had walls of brick. Timber was still used to construct roofs and floors, but since it was now largely protected from the weather, there was less need for the durability of oak, which was also becoming scarcer. Hence, increasing use was made of softwood, mainly imported from northern Europe and America. See Section 5.3.2.

- The Nineteenth Century
  There were further developments of eighteenth century forms, with longer span trusses, and an increasing use of metal components for joints and tension members. See Section 5.3.3. Revivals of this architectural style are sometimes used oak structures, but in general this era is less of an inspiration for green oak structures than for softwood designs.

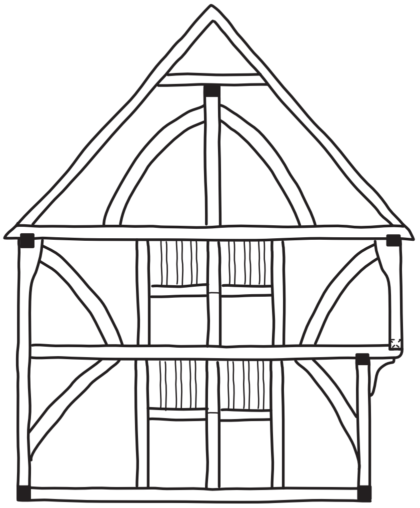


Figure 5.8 Medieval framing

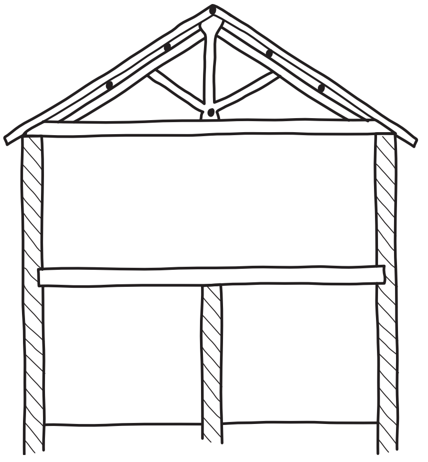


Figure 5.9 Typical 17th and 18th Century construction

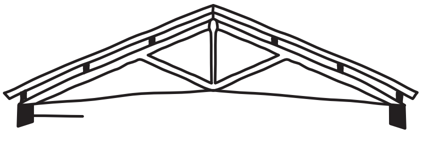


Figure 5.10 Typical 19th Century roof truss

5.3.1 The Medieval Period

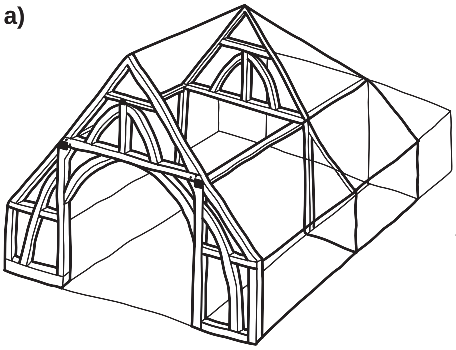
5.3.1.1 Barn structures

The barn, *Figure 5.11a* to *c*, was originally an all-purpose structure, which could also be used to form a house or church. It developed into a recognisable basic form, which included:

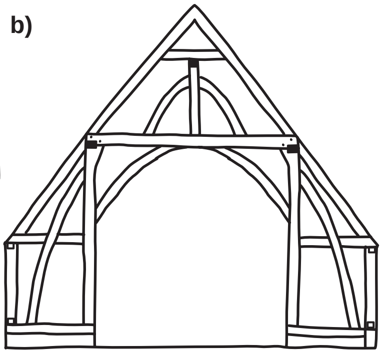
- A modular frame with distinct bays.
- A steep roof of 45° or more, pitch, originally for thatch, later for tiles.
- A centre "nave", with aisles on each side and an eaves roof level that might be little more than head height.
- Hipped or half-hipped ends were common in some regions.

Innumerable variations on this basic form can be seen up and down the country. The frame members meet in the same plane and are joined by variations of the mortice and tenon (see Section 5.3.1.6). Loads are passed from member to member, primarily in end compression, with shear on the tenon blade. Pegs provide general robustness to the structure.

a)



b)



c)

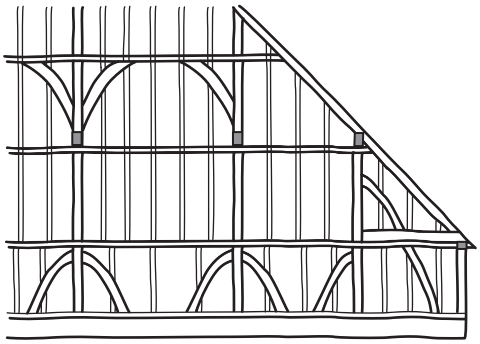


Figure 5.11 Aisled barn 15th Century

The simplest form of the single-storey building, although not necessarily the earliest, was the cruck frame (*Figure 5.12*). Trunks were split in two and turned to rest against one another providing the stability of an arch or triangle.

Triangulation also ensures the stability of the hammer beam frame (*Figure 5.13*), with hammer beams corbelled over curved braces and supporting the hammer posts. This ingenious design could produce the same profile as the barn truss, without the intruding aisle posts.

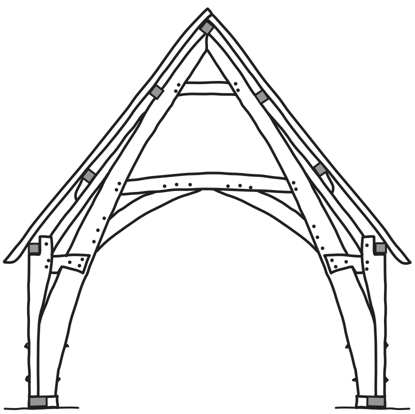


Figure 5.12 Base cruck

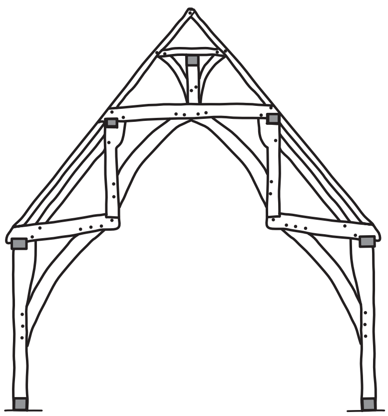


Figure 5.13 Hammer beam

5.3.1.2 Two storey structures

Whilst the open hall provides a fine architectural effect, many users of the contemporary frame require a two-storey structure. A great variety of model forms can be seen, most relying for stability on bracing members and transverse frames with full height storey posts. An example is shown in *Figure 5.14*.

The most recognisable characteristic of the medieval timber frame, however, is the jetty, where the first floor joists cantilever over the ground floor frame to project the upper storey. Apart from adding visual interest, the jetty gives some weather protection to the floors below. A designer using this form today should ensure that adequate anchorage is provided to the inboard ends of the floor joists to resist the uplift created by the weight of the first floor wall and the roof loading on the cantilever.

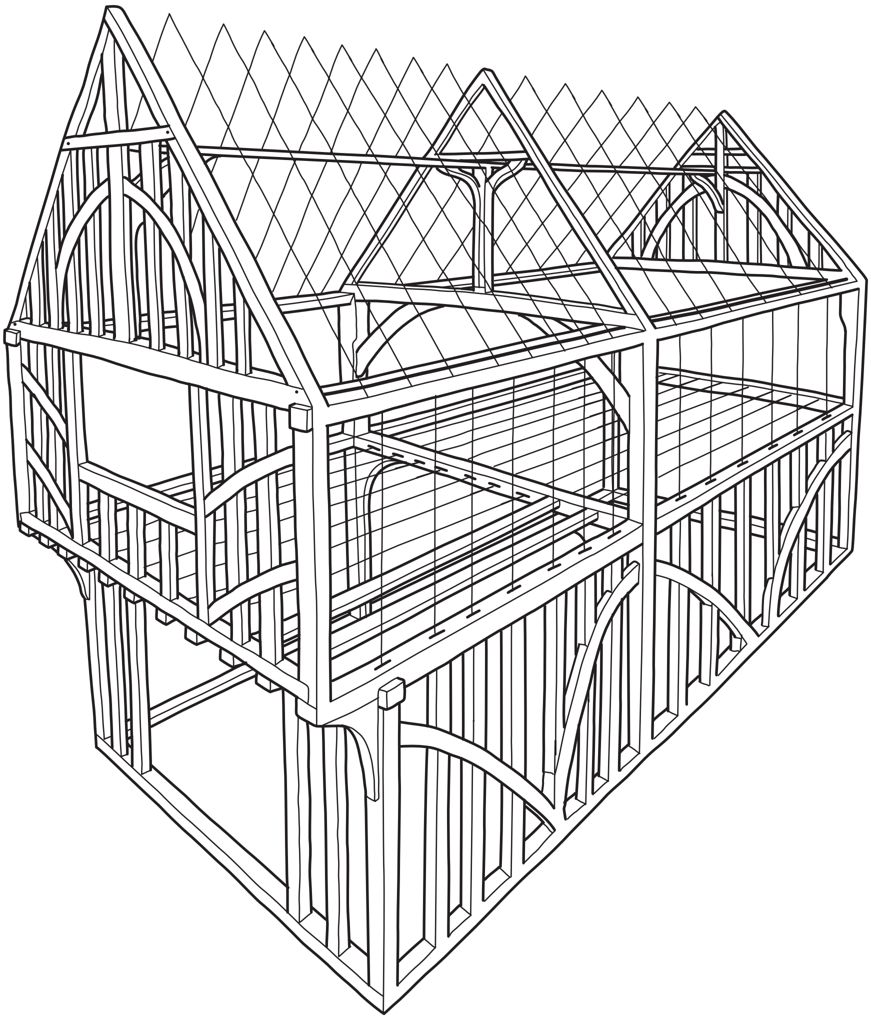


Figure 5.14 Two storey structure [Drawing after Hewitt (Ref 29)]

5.3.1.3 Storey and a half structures

The two frames, the interrupted tie truss (*Figure 5.15*) and the sling braced truss (*Figure 5.16*), have medieval roots, but their main advantage in contemporary work is to achieve a two-storey building with a relatively low eaves height. This frame is often combined with dormer windows to the first floor.

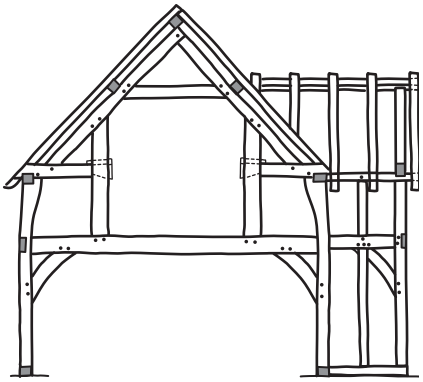


Figure 5.15 Interrupted tie trusses
Dropped tie with a porch bay to one side

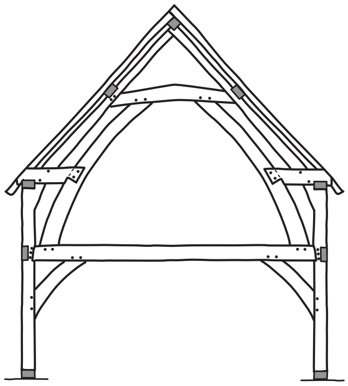


Figure 5.16 Sling braced truss

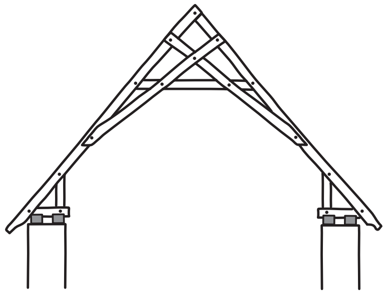


Figure 5.17 Scissors brace

5.3.1.4 Roofs

The medieval churches of the UK provide some six thousand worked examples of (mainly) open framed roofs, no two of which are identical. A large number of basic forms exist. The earlier roofs have steep pitches and oversailing eaves, whilst many of the fifteenth century have shallow pitches (following the introduction of lead), which discharge into gutters concealed behind upstand masonry parapets.

The basic framing forms vary from close-coupled common rafters (*Figure 5.17*) to principal trusses with purlins spanning between. *Figure 5.18* shows a crown-post roof where the post, which is in compression, bears on a robust bottom tie, which also has to have bending strength, but which virtually eliminates outthrust on the clerestory walls. If echoed in a modern design, attention needs to be paid to the longitudinal stability of the structure which was often lacking in medieval roofs, which relied instead on support from masonry gables.

The arch-braced collar truss (*Figure 5.19*) remains a popular form, but unless it is adequately buttressed, it requires the pegged joints between the braces and the rafters to resist a significant tensile force which may initiate splitting in the thin tenon section. Most present day framers will add discreet bolted connections directly between the tie and the rafters.

Shallow-pitched roofs (*Figure 5.20*) are often supported on principal beams which might have roll mouldings. A central post supports tilted rafters, sometimes with a decorated spandrel infill.

The most famous roofs, with single or double hammer-beams and roll-mouldings to virtually every member, are probably too ambitious for current applications, but remain the high point of medieval church carpentry.

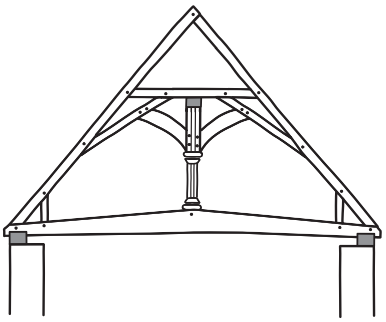


Figure 5.18 Crown post

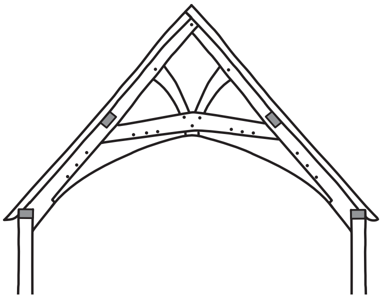


Figure 5.19 Arched brace collar truss

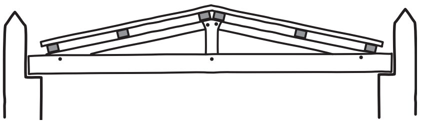


Figure 5.20 Post and beam

5.3.1.4 Floors

Medieval floor structures were generally formed with common joists at close spacing supported by what are now termed principal members (summers). The spans were generally moderated by the insertion of bridging beams and spine beams (*Figure 5.21*a). All members were square, or squareish, in cross-section, and the structure was 'open', with no underlain ceiling.

Original floorboards are occasionally found, laid parallel and let into edge rebates in the joists (b), plain edged and fixed with nails. More often they were laid across the joists as in modern practice. The joists were tenoned into the bridging beam (c), and at the perimeter of the building either tenoned into a girding beam, or supported on a ledger pegged to the main frame (d). The bridging beam might have a simple edge chamfer (e) or a more ambitious moulding (f). The intersection of bridge beams, both of which were moulded, presented a challenge to the carpenter, analogous to the junctions in stone window tracery.

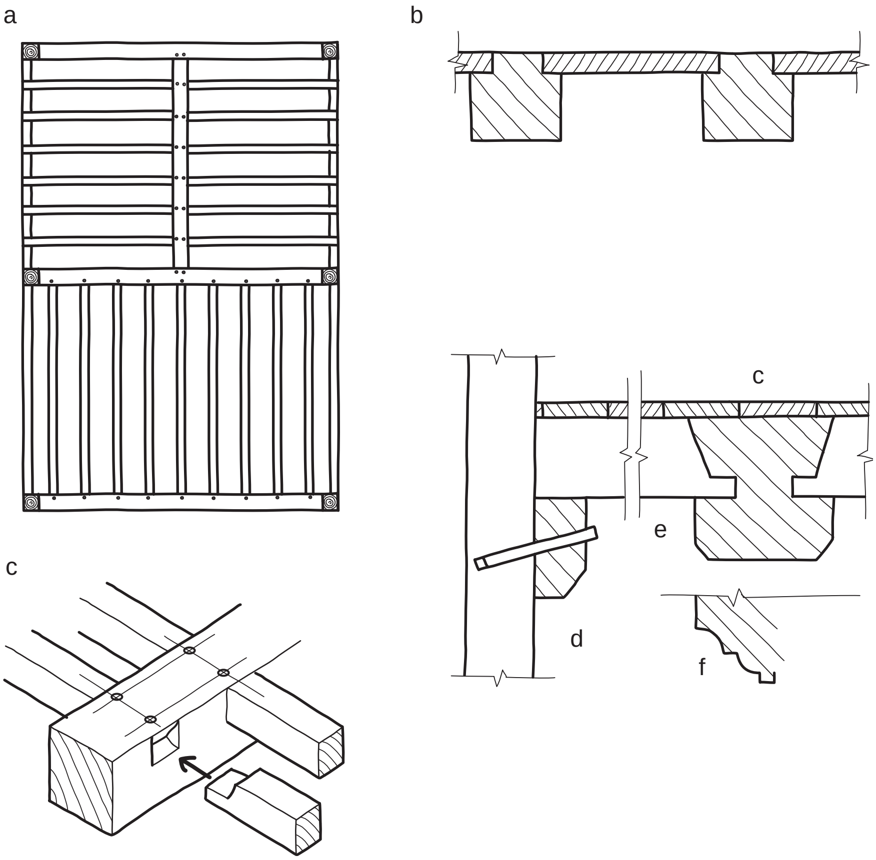


Figure 5.21 Typical medieval floor structure

Whilst medieval floor framing can be used as a model for contemporary construction, the use of simple boarding for the floor, with no ceiling below, would need detailed consideration of modern acoustic and fire resistance requirements. These are considered in Chapter 7 (Example 7).

5.3.1.6 Framing joints

A small selection of traditional framing joints is illustrated, chosen as those most often used by framers today. In general they:

- are entirely of timber
- rely on mechanical interlock as the principal method of load transmission
- use pegs as a tightening and locking mechanism.

The joints can be grouped as described below. Typical locations of joints within a building are shown in *Figure 5.33*.

The mortice and tenon (*Figure 5.22*) was the basic compression joint of the medieval and indeed earlier periods.

Compression loads are passed from one member to another through bearing between tenon and mortice shoulders. Shear loads pass through side bearing on the tenon (a). The pegs, made out of seasoned oak, draw the frame together (b).

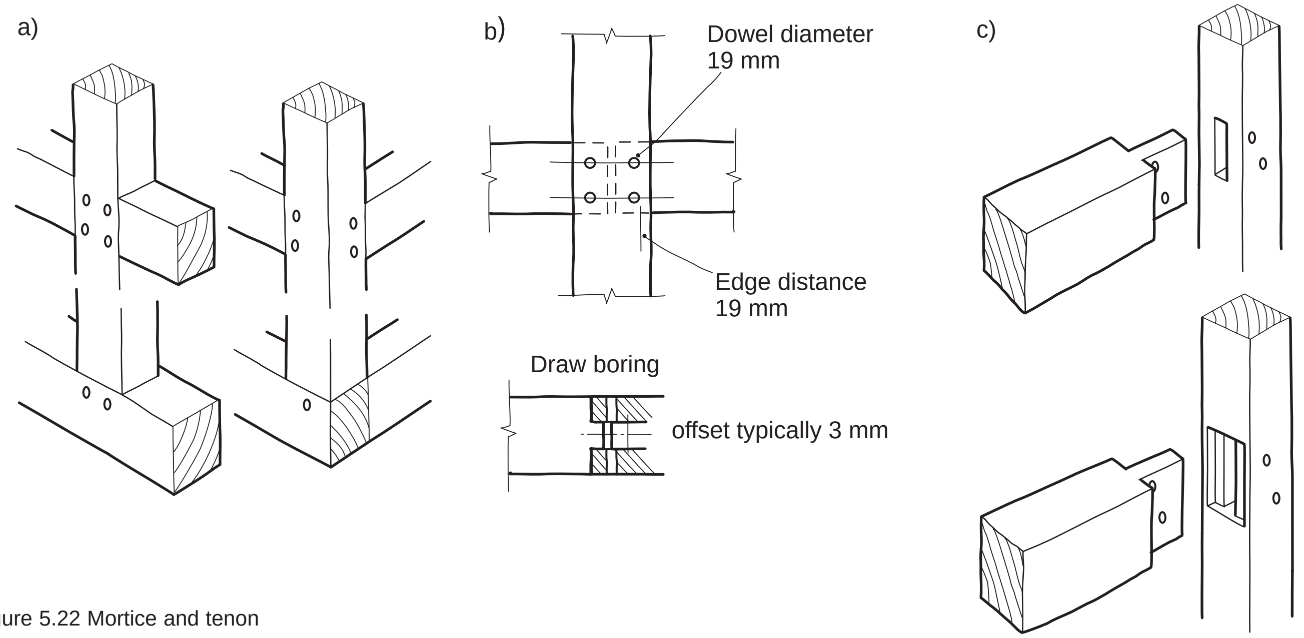


Figure 5.22 Mortice and tenon

The basic through mortice and tenon transmits only moderate loads because the tenon blade has only a modest bearing on the lower mortice wall and there are further limitations, for example in shear resistance.

An improvement introduced by the late medieval period, and still preferred, is to house the tenoned ends into the morticed post sides, giving greater bearing support (c). As illustrated, there is ample long grain on each side of the post mortice to deter mortice face split-out; another potential weakness. However, if the balance of member sizes differs, or if two beams need to enter the post at right angles to one another, then the beam ends are reduced in breadth.

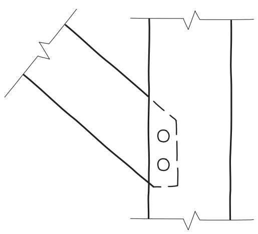


Figure 5.23 Brace with tenon into post mortice

The conventional joint for an angled brace is another variation of the mortice and tenon (*Figure 5.23*).

Lap joints

Lap joints form a group in which one timber is fastened at an angle to another.

The notched lap (*Figure 5.24*) achieves a small degree of tensile strength through the notch, although calculations to prove this are generally unnecessary since the braces on the compression side of the wind load can usually provide sufficient resistance.

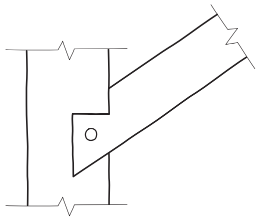


Figure 5.24 Notched lap

End laps which provide more tensile resistance include the wedged dovetail tenon (*Figure 5.25*) and the wedged tenon (*Figure 5.26*). The wedge in the latter joint has considerable tightening power, and can mobilise significant bending resistance in the joint as well as tension resistance. Both wedges can be re-driven to take up drying shrinkage. Tie beams can be joined to wall plates by the lapped dovetail (*Figure 5.27a*) or by a simple cogged joint (*Figure 5.27b*).

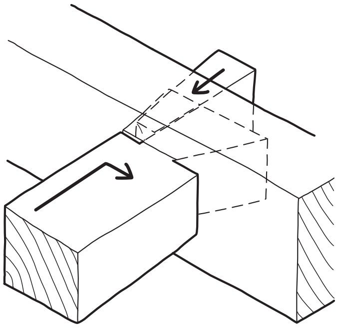


Figure 5.25 Wedged dovetail tenon

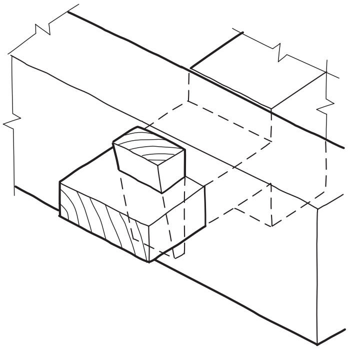


Figure 5.26 Wedged through tenon

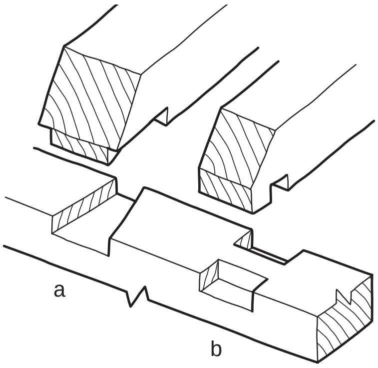


Figure 5.27 Tie beams: a Dovetail b Cog

It has already been noted that, in general, medieval framers avoided the need to transmit significant tensile forces through pegged joints. However this need arises where an A-frame truss is required with a raised collar (assuming that the truss feet are not abutted, in which case the truss is an arch in disguise).

The collar brace (*Figure 5.28*) requires multiple pegs, but the relatively thin tenon is then vulnerable to splitting along the peg line. Most modern framers will offer the joint discreet assistance with a bolt or other metal connection along line 'X'.

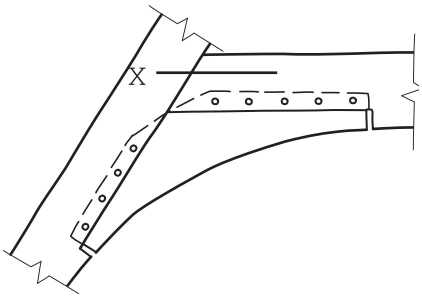


Figure 5.28 Collar brace

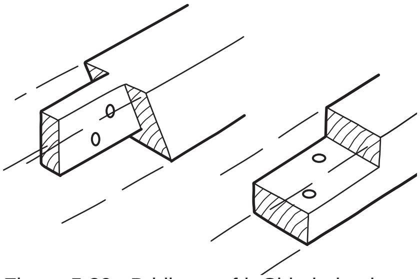


Figure 5.29a Bridle scarf b Side halved scarf

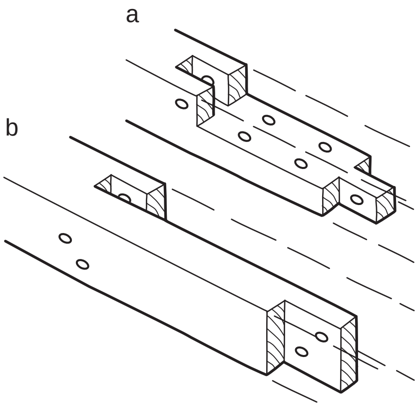


Figure 5.30a Edge-halved scarf b Face-halved scarf

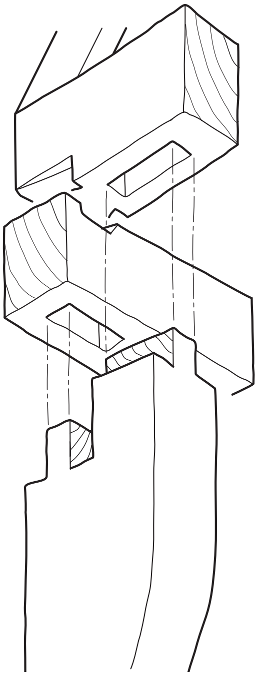


Figure 5.31 Tie beam lap dovetail assembly

Scarf joints

A scarf joint connects individual pieces to provide a member longer than can be provided in a single piece. Common examples are wall plates (*Figure 5.33*) and purlins.

The scarf is usually placed at points of low bending stress, eg close to a brace support. There the load is principally in shear, which can be resisted by the bridle scarf (*Figure 5.29a*) or a simple side-halved scarf (*b*).

Providing a scarf joint which has a degree of bending resistance requires a longer overlap between the members. Those in common use today (chosen from a very large range of medieval examples which are included in Hewitt (Ref 29)) are the edge-halved scarf with bridled abutments (*Figure 5.30a*) and the face-halved and bladed scarf (*b*). The latter joint is stiffer, since it retains the full depth of the pieces throughout, but for strength both scarfs rely on the shear resistance of pegs which only result in some 15 - 25% of the strength of an unjointed section.

The tie beam lap dovetail assembly

This particularly complex joint (*Figure 5.31*) occurs where a post supports a roof truss, while stabilised laterally by the wall plate. To allow all this to happen, the post is locally widened (referred to as the jowl). As the oak dries, there is shrinkage of the dovetail. Whilst this will not result in failure of the joint, the movement may initiate a small split in the head of the post. Modern framers will often substitute a cog (*Figure 5.27b*) for the dovetail, which significantly reduces the effect of the drying movement.

The jetty assembly

A typical detail (*Figure 5.32*) is shown at the location of a main post. This uses part of the detail shown in *Figure 5.31* twice - once to support the jetty beam from below, and again, inverted, as the base to the first floor post. The jetty beam needs to be anchored against uplift at its far end.

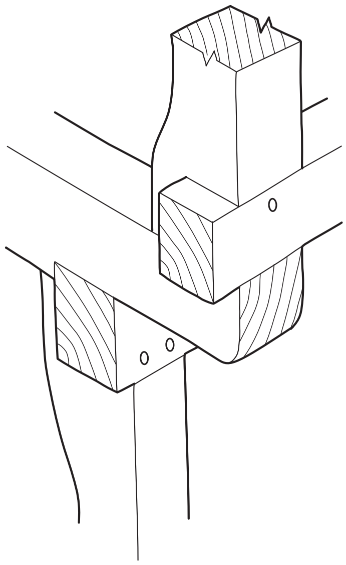


Figure 5.32 Jetty assembly

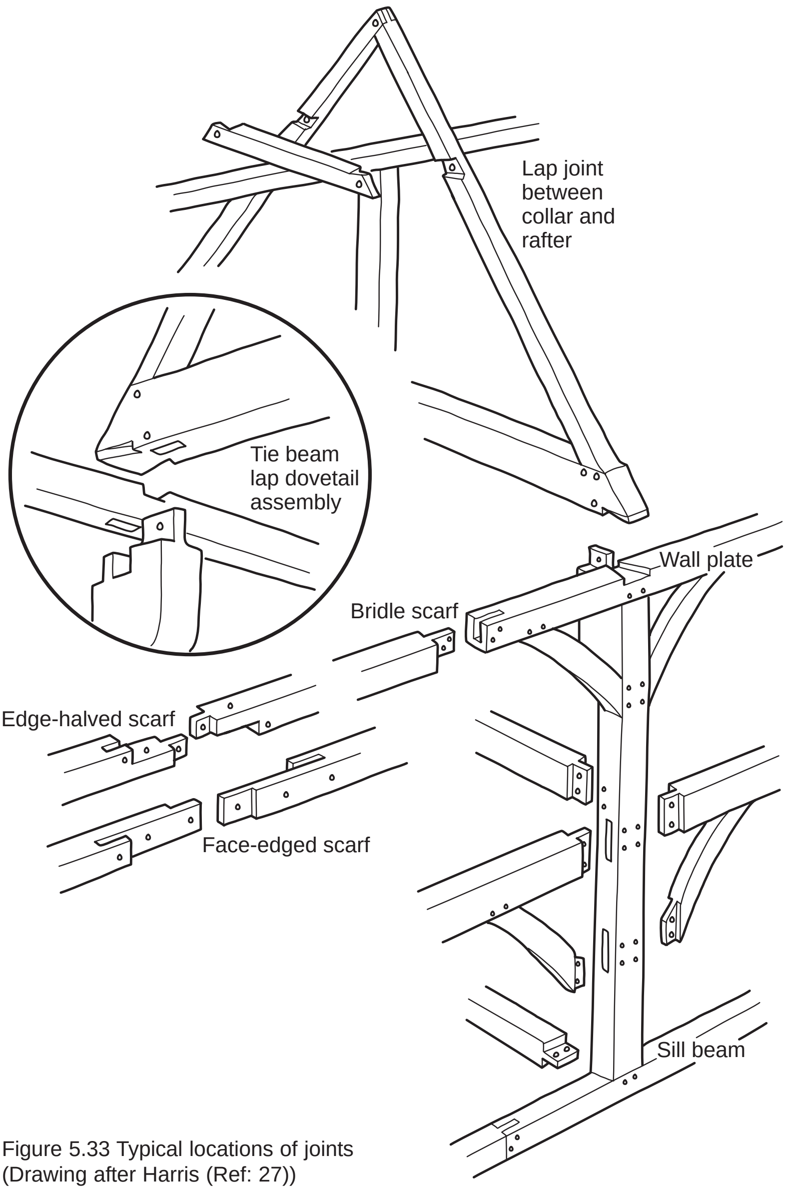


Figure 5.33 Typical locations of joints
(Drawing after Harris (Ref: 27))

Pegs and pegged joints

From *Figure 5.33* it can be seen that all the traditional frame joints are held together by pegs. As noted in Section 5.3.1.6, the various loads on the building from gravity and wind are passed from one member to another mainly in direct compression, for example by the shoulders of a tenon, with the tenon blade dealing with shear forces. The pegs, however, perform three important functions; they:

- draw the contact surfaces of the joint together and hold them tight
- ensure the general robustness of the frame
- (occasionally) act in tension for frame stability (eg an arched braced collar truss (*Figures 5.19 and 5.28*))

Manufacture of pegs

A clear round butt of green oak is cleft into quarters, using an axe or wedges. The resulting 'cake-shaped' blanks are cleft again, and from these wedges billets are cut and the pegs are finally shaped on a shaving horse. A typical large 12 inch (300 mm) long, 1 inch (25 mm) diameter peg will taper down to around 13/16th of an inch (20 –22 mm) just before the point, which has the proportions of a blunt pencil tip. Smaller pegs, ¾ inch (19 mm) diameter are common. Hand cutting follows the grain and hence maximises strength, but pegs are sometimes made by driving a squared-off blank through a circular die, which will also follow the grain, albeit with no taper. Whichever method is used, the fabricated pegs are then thoroughly dried before use.

Draw boring

In the mortice and tenon joint (*Figure 5.22*), and others of similar form, the pegs are generally driven into holes which have been draw bored; that is the hole in the tenon is off-set by about 1/8 inch (3 mm) towards the shoulder (*Figure 5.22b*). The action of driving the peg home draws the two members together, and, if the shoulders have been well cut, results in a robust and rigid joint, with the peg effectively locked into position. For a lap joint, such as simple notched lap (*Figure 5.24*), the necessary restraint for the peg is often obtained by 'driving a square peg into a round hole', as the saying goes.

Figure 5.34 Draw boring a tenon in a raking brace

Edge distances

The amount of solid timber between the peg hole and the face of the timber: the 'edge distance' in engineering terms (*see Figure 5.22*), is generally set at the peg diameter. Engineers are sometimes concerned that the value is well below the code recommendations for fasteners, but it must be remembered that the peg is oak and not steel, and that the distance must be minimised to avoid shrinkage loosening the peg. Peg strength is considered in more detail in Appendix III-5.

5.3.2 The seventeenth and eighteenth centuries

By the seventeenth century, the majority of buildings had masonry walls with only the horizontal elements (the floors and roof) in softwood, both now usually hidden from view by plaster ceilings.

The roofs were generally supported by king post trusses (*Figure 5.35*), strictly, a classical invention. The king post itself is in tension, while all the joints are ingeniously arranged to be in compression, with the exception of the joint between the post and the bottom tie, which originally used a long double-pegged or through-tenon. A mid-span support to the tie was necessary, as it now took the weight of the ceiling.

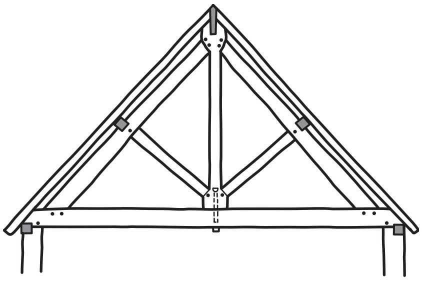


Figure 5.35 King post truss

Although the trusses were in softwood and not usually on view, they are a handsome form, and there is no reason why they cannot be used as a model for an exposed oak roof. The principal variation is the queen post truss, *Figure 5.36*.

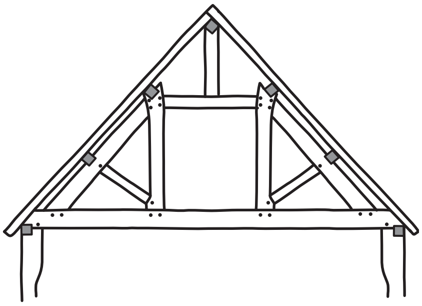


Figure 5.36 Queen post truss

5.3.2.1 Joints

The joints for these trusses (*Figure 5.37*) were still medieval in general form, in that the members are in the same plane, and joined by pegged mortices and tenons (a). The eighteenth century saw the introduction of various forms of iron strap-work (b) and a bolted connection between the post and tie (c). As an alternative, the gib-and-cotter joint (d) allowed drying shrinkage to be taken up by driving home the cotters (wedges) between the gibs (u-shaped metal pieces).

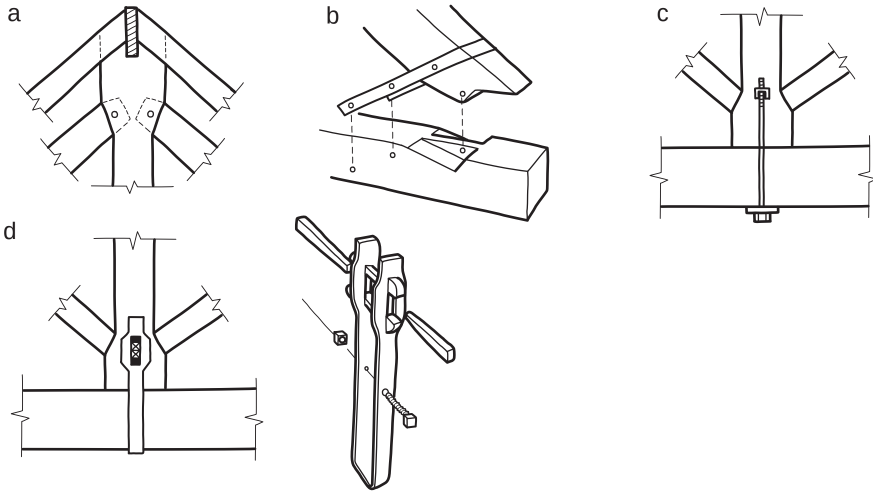


Figure 5.37 Joints in trusses

5.3.3 The Nineteenth and Twentieth Centuries

The main influence on structural development in the nineteenth century was the Industrial Revolution, with a demand for, among other things, larger buildings. Extra bays were added to roof trusses (*Figure 5.38a*) and joints were reinforced by wrought iron straps and cast shoes. Increasing use was made of composite trusses (*Figure 5.38b*) in which only the compression members were in timber and the tension members were made from iron rods.

Towards the end of the nineteenth century, the development of mass production techniques for nails and bolts, with corresponding cost reductions led to a fundamental change in the construction of industrial trusses. Instead of abutting members in a single plane, as had previously always been done, truss members were simply lapped and then bolted or nailed together (*Figure 5.39a* and *b*). The truss was now totally reliant on metal connectors for strength, but the joint was equally strong in tension or compression. As a consequence, trusses which followed examples in iron, such as 'N' or Warren trusses were now possible forms for timber.

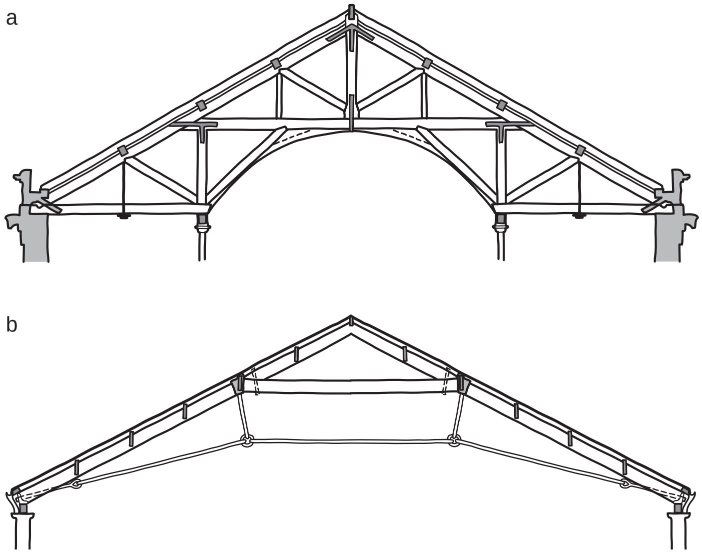


Figure 5.38 Nineteenth Century trusses

a

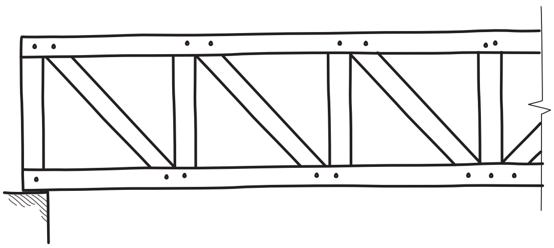


Figure 5.39 Bolted and nailed trusses

b

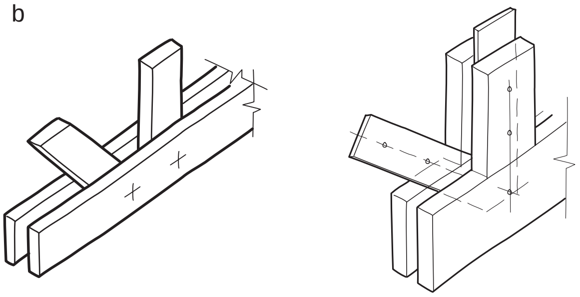


Figure 5.40 Flitch plate joint

In the twentieth century, with the development of steelwork and the potential for the installation of plain dowelled fasteners of steel in the timber, profiled flitch plates could be used at joints, effectively concealed within the timber profile (*Figure 5.40*). This returns the adjacent members to common planes, improving the appearance.

5.4 Drying movements

The effect of drying shrinkage on the cross-section of typical frame members is illustrated in *Figures 5.41 and 5.42*. The timescale of this shrinkage will depend upon the dimensions of the individual members, but typically posts and beams of oak, 100 mm to 200 mm in thickness, within a heated building should be ‘dry’ (ie achieve a moisture content of 10 - 12%) within five to eight years.

Faces of members exposed to rain will continue to experience small cyclical movements due to surface wetting and drying. Longitudinal drying movements may, for practical purposes be ignored. The magnitude of cross-grain shrinkage will vary, depending upon the relative proportion of radial or tangential grain in the face, and the occurrence of fissures, which dissipate the overall shrinkage. Taking all this into account, the average net value of cross-grain shrinkage, at typical positions as shown in the diagrams, may be taken as around 4% of the face dimension.

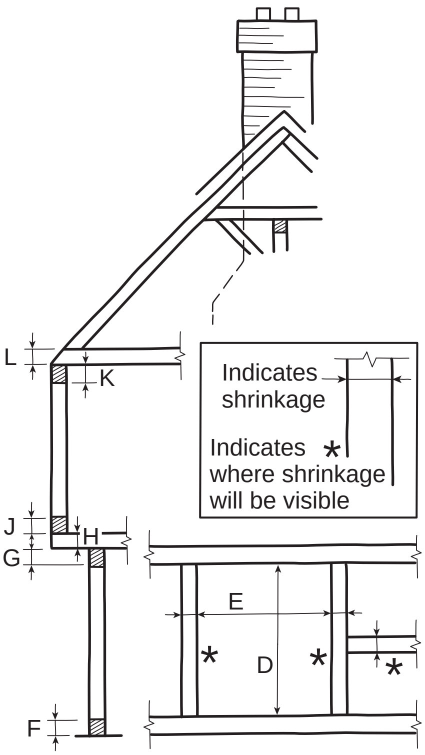


Figure 5.41 Effect of frame shrinkage

5.4.1 Overall settlement

The effect of shrinkage is cumulative from ground level upwards *(Figure 5.41)*. The mass of the structure itself causes settlement so the shrinkage is always taken up. Thus the level of the first floor will eventually drop by the total shrinkage of F+G+H. This will affect the fit of a staircase linking ground and first floors. The ridge line will drop by the shrinkage of F+G+H+J+K+L. There may be a total thickness of some 1.25 metres of timber in cross grain, with a potential settlement of some 50 mm or so. This may well be significant, if, for instance, the ridge piece is built into a brick chimney.

5.4.2 Infill panels

The height of a panel, D is controlled by the longitudinal grain of the adjacent posts and so there will be little, if any, movement. However, the dimension, E, will increase by the lateral shrinkage of the posts. The effect of frame shrinkage on the various forms of enclosure is dealt with in more detail in Chapter 7.

5.4.3 Joint shrinkage

The effect of shrinkage on joints is shown in *Figure 5.42*.

The 'bite' of a peg which has been draw-bored is generally sufficient to overcome the small shrinkage, A, at a square-cut joint. For splayed joints at the end of, for example, a brace or principal rafter, the shrinkage, B, will often result in the opening of a small wedge-shaped gap. A dovetailed joint will relax slightly due to the shrinkage of the dovetail within the housing member, C.

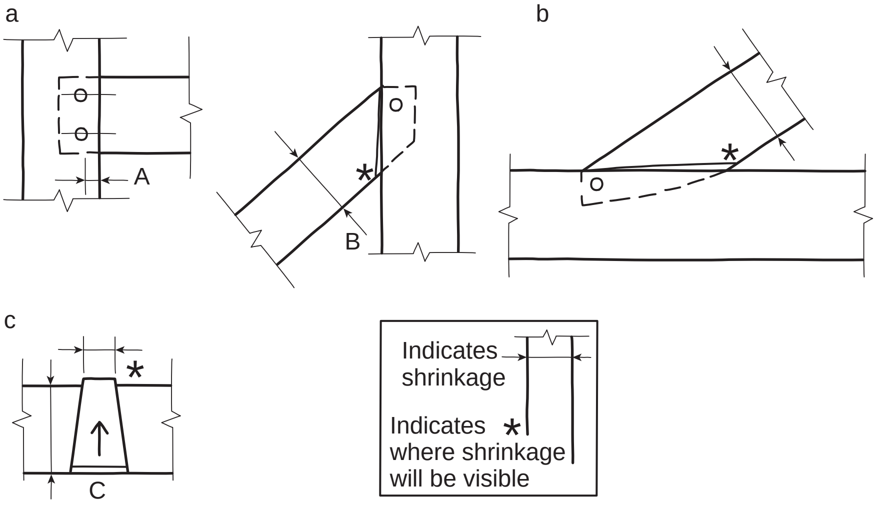


Figure 5.42 Shrinkage at joints

Shrinkage at exposed joints may exacerbate potential water traps already present, for example where a brace-to-post joint is in an inverted position *(Figure 5.43)*. Local cladding over the bracing may obviate the problem. Further discussion of protective detailing is given in Chapter 8.

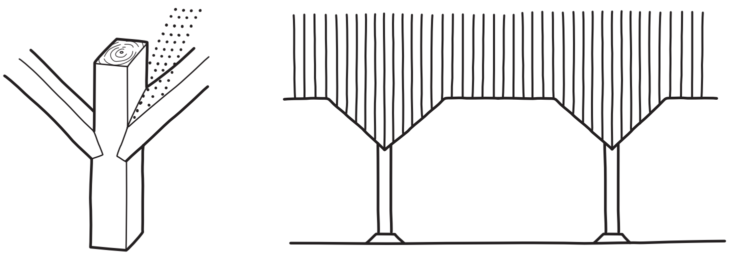


Figure 5.43 Water trap at exposed joint

6 The green oak framing process

6.1 The traditional approach

Fortunately, nowadays one can visit many historic frames built with green oak. The tree-like nature of the structures themselves is often evident, especially in the case of aisled mediaeval barns, whose framing can clearly be read and understood. Looking at their exposed internal timbers, it quickly becomes apparent that the requirement for certain sections and lengths dominated the carpenter's choice. If insisting on using only clear, straight grained material, the job would have been impossible, and in any case, this was unnecessary.

Rackham's research (Ref: 38) provides insight into medieval carpenters' attitudes to quality and concludes that the earlier carpenters "expected timbers to be shaped more or less like trees" (*Figure 6.1*). This gives us an insight into the way in which they viewed their material, accepting many features that might now be called 'defects.'

Photos not available in PDF edition

Figure 6.1 For the principal posts of buildings such as the Barley Barn, Cressing Temple, Essex (above right and left), there was a need for exceptional oaks. Extensively researched, the structure dates from 1205 – 1230 AD. At the same site, the Wheat Barn (right) dates from 1257 – 1280; hence these two buildings are amongst the oldest carpentered oak frames still in use in the British Isles
Photos: Barley Barn: © Cressing Temple, part of Essex County Council
Wheat Barn: C J Mettem

Curved timbers were also essential, such as in the exposed wind braces and wall bracing of many vernacular frames. Crucks are another obvious example, although many remain hidden within structures that superficially do not appear to be of timber.

Carpenters still take considerable trouble to obtain stock of the correct curvature and grain orientation (*Figure 6.2)*. For this, they have to return to an integrated approach to supplies, often making contact directly with woodland owners and managers. For the jowl post, for example, the thickening at the head is traditionally obtained from a timber cut to include part of the root buttresses. Unfortunately, in modern practice, this useful region of the log is often removed. The need to seek out suitable naturally curved or shaped oaks still taxes modern carpenters (*Figure 6.3)*. There is no possibility of bending or laminating curved green oak components, therefore naturally-grown forms are essential, and these now provide a valuable outlet for timber that a few decades ago would have been left to rot in the woods.

Although today's green oak carpentry enterprises retain the hand-built tradition, such work also needs recourse to hand-held powered equipment such as heavy-duty chain mortisers, electrically-driven planes and guided circular saws. The extraordinary revival of interest in heavy framing has led to a growing demand for skilled labour, and powered tools are essential to complete the work economically and within an acceptable timescale.

The sawn timbers on which carpenters work are often slightly off-square, bowed, and occasionally slightly twisted ("in wind"). Modern carpenters adapt historic methods, allowing them to shape the timber without a perfectly square face and edge.

It is an important part of the traditional concept that the structure is subdivided into its constituent plane frames, each being prefabricated in its entirety, and then broken down again for the next lay-up. The process entails setting out the frame floors, walls and roof components over marks that are chalked according to their actual size, on a level and true framing floor. Using the plumb bob, the carpenter accurately places the beams over the marks, a process termed "laying-up," or sometimes "piling." As the members are stacked over one another, the ends are propped to bring them all into level. Once pegged together, the upper faces will thus form a true plane.

To achieve this, after initial laying up, the joints are "scribed," again using the plumb bob or spirit level. Thus the carpenter accurately marks the joint faces, despite any irregularities of the reference surfaces. As a consequence, despite the great size and weight of many of the members, truly accurate joints are achieved, with no visible gaps. To ensure the exact 90-degree rotation of the members that usually occurs in the two lay-ups, plumb and level marks are cut into the member faces. In this way, all adjoining frames of the building joint to one other at right angles, or at another desired angle. As each lay-up is completed, the carpenter also cuts assembly marks. Often, as in the past, these are indicated by Roman numerals. During the final site assembly, such marks allow the accurate re-instatement of every component within the entire building. During restoration work, similar assembly marks, plumb and level marks, and cut lines are clearly found in numerous ancient structures, indicating that the techniques in use in today's framing yards have an ancient pedigree.

Figure 6.2 The Great Oak Hall, built in 2000 at Westonbirt Arboretum. The traditional design includes two cruck frames
Photo: C Mettem

Figure 6.3 Eyeing up the sweep of a tree against a shape template in the forest for selection for Pilton Barn, see Figure 2.11
Photo: Wood Awards / McCurdy & Co

Figure 6.4 Hundegger numerically controlled CAD - CAM system in use for green oak framing manufacture
Photo: T J Crump Oakwrights

Figure 6.5 After main preparation using Hundegger equipment, green oak framing work is completed using traditional hand tools
Photo: T J Crump Oakwrights

6.2 Automation

In parts of Continental Europe and in North America, framers in both softwood and oak have for some time employed purpose-developed CAD-CAM technology. This involves using, for example, the Hundegger K2 System (*Figure 6.4*). Several installations of this type are now supporting heavy framing in green oak in the UK.

Steps in typical CAD-CAM assisted heavy framing:

- Develop the Computer Aided Design (CAD) model for the desired building type and form. This requires an understanding of the practical and geometrical intricacies of framing. An experienced carpenter guides and checks the work.

- Verify how each member is to be used within the completed frame - double check schedules before cutting - again an experienced job. Prior to machining, each timber is rotated or reversed if necessary, to enhance appearance and to reduce the influence of defects.

- The last point is now reached at which selection and grading can take place, before experiencing considerable loss of output and waste. After automatic machining, hand-cutting and tidying operations are performed, using powered hand tools.

Automation places more precise demands on the purchase and selection of the timber. It not only speeds up good work, but also reproduces errors very fast, and sometimes irreversibly - resulting in waste that may eliminate the profits of a job. The usual start-point for this type of production is timber that has been planed true and square on all four sides. As with hand-building, jointing is usually entirely by carpentry, with no metallic fasteners or connectors involved. However, rather than hand-made pegs, turned dowels are often preferred for jointing, sometimes from kiln-dried furniture-grade white oak from North America. Alongside this, draw-boring may be eliminated, although this is controversial, and practices vary. Some of the mortice profiles may be left with a semi-circular rather than a squared-off shape.

If well designed and executed, this type of work achieves beneficially close tolerances between the fitted elements, along with strong joints. It is generally regarded as better suited to relatively standard box framing carpentry and to simpler post-and-beam types of project, rather than the more complex traditional frames that are the speciality of the modern hand-builders. The trend towards automation is only a matter of degree. Parts that cannot be automatically machined are still incorporated in many of these buildings – items such as curved arch braces, and jowl posts are cut by hand. Furthermore, to finish details, and to adjust rectifiable errors, hand skills are also required (*Figure 6.5*).

6.3 Selecting the timber

Selection of timber for particular purposes can be undertaken on the basis of its strength and/or its appearance. It is important to understand the distinction between the two approaches.

Appearance grading systems, such as laid down in BS EN 975-1 (Ref: 18) and proposed in 'Making the grade' (Ref: 23 and Section 8.2) are primarily intended for non structural applications such as cladding and furniture. They assess the visual impact of defects such as knots, fissures, grain irregularities etc.

Formal strength grading is an assessment of the strength of a piece of timber. For hardwoods this is undertaken by a visual assessment and measurement of strength-reducing defects, such as knots, splits and slope of grain. Strength grading allows design values to be assigned to each piece of timber to enable engineering calculations to be undertaken. (See Sections 6.3.3 and 6.3.4).

Quality is normally a matter of close collaboration between the framer and the supplier. However, occasionally defects arising from the log may remain in the sawn members, for example tension wood, spiral grain, ring shakes, and fungal degrade. The selection or grading process should ensure the rejection of such material. Ring shakes occur in a small proportion of European oak logs. Specialist sawmillers who deal in carpentry oak are aware of the need to avoid members that include this defect, so pieces showing it should rarely arrive at the workshop, but would in any case be rejected there, if missed at an earlier stage.

Selecting or grading green oak is mainly concerned with controlling knots and sloping grain, because splits and checks are generally the consequence of drying, and when the oak is still green, these effects have not yet occurred. However, irrespective of its species or commercial quality, any structural timber is bound to contain a certain number of strength-reducing features, against which the selection must be made.

In Chapter 5, two categories of green oak project are defined. Category A relies on skilled carpenters in the framing yard selecting the timber to limit or avoid growth characteristics that might interfere with the strength or stiffness of the member or upset the cutting of the joints. The Category B approach requires formal strength grading to enable engineering calculations to be undertaken for the frame design.

There is also a possibility that within the complete cutting schedule for a particular building, only certain members will require the formal strength grading level of inspection and selection. An example of a specification and cutting list for a traditional frame building, Rowses Farm, is included in Appendix I.2.2. In many frames, even where there is some adventurous engineering, there are less critical elements, for which the carpenter's selection will suffice. Sole plates, for example, need only to be generally straight and free from excessive wane. The design and build team always needs to retain such discretion, since a green oak project is conceived and executed in an entirely different manner to one involving industrially produced, high-volume softwood light framing.

6.3.1 Carpentry workshop selection for traditional framing

Guidance on the selection of oak for traditional (Category A) frames is given in Appendix I. Natural characteristics, including knots and some irregular grain are believed to bring character to projects, but potentially strength-reducing features are sensibly limited in size and position. Features regarded as “defects” in formal grading, are controlled through a process of judgement, during timber selection, based upon an awareness of whether the timber will act as a beam or column, and its location within the final building. For example, joists are selected bearing in mind that these often work quite hard, so knots or short grain would cause excessive spring or even failure. Defects close to traditional pegged joints are also avoided, so as not to impede the work of the carpenter, as well as for the benefit of assembly and appearance. Aesthetic considerations are always important, and care over potential distortion needs particular attention, such as in members near glazing or in decking. Certain frames may need to be more highly specified than the minimum suggested here.

6.3.2 Strength grading and design codes

Strength grading applies a scientifically-derived selection system to limit strength-reducing characteristics to a level reflected in the prescribed mechanical properties for the grade of timber concerned.

For most structural timber, the design codes, BS 5268-2 (Ref: 7) and Eurocode 5 (Ref: 20), refer to timber strength graded in accordance with defined strength grading standards, such as BS 4978 (Ref: 6) for softwoods and BS 5756 (Ref: 12) for hardwoods.

The visual strength grading rules for European oak included in BS 5756 are intended to cover all structural applications, but for green oak framing they have been little used. On the one hand, for framers applying the practical guidelines of the type outlined in Appendix I, they seem too inflexible, with the grade designations pitched at inappropriate levels. For special project engineers, wishing to extend oak into new applications, there is also too little scope, with only two grade levels, and correspondingly limited design properties. For this reason, revised rules have been developed specifically for heavy framing applications.

6.3.3 Green oak strength grading rules

The Green Oak Strength Grading Rules (GOSGR) given in Appendix II have been devised specifically for heavy framing timbers in green oak. They are based on the principles laid down in ASTM D245 (Ref: 2) and have been prepared in consultation with timber engineering experts and specialist producers and framers.

The rules are to be applied during the frame building process when the end-application of each member is known. This has been taken into account in devising the rules, making the method more efficient compared with general grading procedures, such as BS 5756, where the end-use in unknown.

Three strength grades are provided, since it has been found in practice that for efficiency, this is the optimal number. They are designated simply as:

- Grade A - the highest, normally only to be specified for exceptional structural duties; indicative bending strength ratio 71%.

- Grade B - a good average grade selection, corresponding quite closely to the carpenters' selection criteria, given in Appendix I; indicative bending strength ratio 62%.

- Grade C - to be used where economy is required, and where the structural duty of the piece is low; indicative bending strength ratio 48%.

The strength ratios mentioned above are conceptually the ratio of the maximum strength in bending of the actual graded piece, compared with that of a perfect piece. However this should be regarded as background information, rather than being used for interpolating or extrapolating calculations, or for trying to compare the grades with those in other rules. This is because the theory behind visual strength grading contains a number of practical adjustments and simplifications, some of which are mentioned below.

6.3.4 Application of the strength grading rules

Allowing for the strength reductions caused by knots and other strength reducing features (mainly sloping grain), enables engineering design properties for each of the three strength grades to be provided in Appendix III. The principles by which the strength and stiffness assignments were made are cited in Appendix II.1. Whilst Appendix II.4 gives instructions on the measurement of features, and is principally addressed to the frame maker, it is also commended to the engineer who intends specialising in green oak, since a good understanding between parties in the design is essential.

The strength grades built into a job will also reflect the general visual quality (appearance) and what is displayed in finished, open parts of the frame may be critical. This is also true where the green oak is closely associated with glazing or other brittle materials, when material prone to distortion needs to be omitted. Hence strength grading should be linked with the carpenters' quality selection methods, outlined in Appendix I.

Guidelines for the specifier:

- Don't stipulate Grade A for every part of the frame – this is inefficient, expensive, a poor use of the resource, and it may in fact make the specification impossible to fulfil.

- Most members in a normal job should conform to Grade B. Members for the less onerous duties, eg the bottom plates, may be of Grade C, provided they are of generally adequate quality (ie reasonably straight and free from wane). This is an aspect of the selection that should be discussed with the frame maker.

- Appreciate the tasks of the frame maker, including the grader, allowing that green oak building entails skills and craftsmanship and is not an exact science.

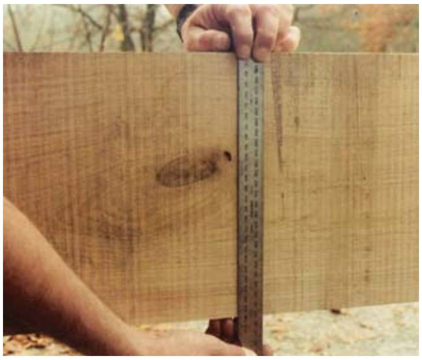


Figure 6.6 Measuring the external surfaces of knots and estimating their internal location and influence is one of the most important tasks in visual strength grading. The oval knot near the centre of the beam is a feature common in oak, and is specifically addressed in the rules

Figure 6.7 A grain scribe is being used to check slope of grain on the upper surface of the beam. The lateral surfaces may need to be checked in a similar way

Guidelines for the grader:

- Visual strength grading is a skill and an art rather than an exact science, particularly for a special material such as green oak.
- There are aspects in the rules where you should expect to apply your skilled judgement – an example being in assessing the significance of a group of pin knots.
- Try to appreciate the engineer's concerns – read the notes below and if uncertain, ask! Quality selection is also often significant – see Sections 6.3.1 and 6.4.

6.3.4.1 General approach

The person undertaking the visual strength grading should be an experienced carpenter or a skilled timber engineering builder, who is aware of the log conversion and the end-application of the member being graded. These points affect the techniques used for knot measurement, and the estimation of their internal influence within the section.

In visual strength grading green oak, the two most important tasks are measuring or estimating the size and influence of the knots (*Figure 6.6*) and assessing the slope of grain (*Figure 6.7)*. For reasons that are explained in Chapter 4, inspection of fissures is not a significant task; they should not yet have occurred. Certain abnormal defects, ring shakes for example, may require elimination, since these may occur in the standing timber. Wane is also a less significant feature than in smaller sections of light framing softwood. Sapwood is generally treated as wane – see Appendix II.4.4.

Knot formation: In visual strength grading generally, knots are approximated as 3D cones (*Figure 6.8)*. These are understood to enlarge towards the exterior of the piece. The heart (usually termed "pith" in softwoods) may be included in the member, as shown in *Figure. 6.8*. In other instances, it may not be present within the sawn section - this is also significant, see Section 6.3.4.3.

Whether or not the heart is present within the piece, the knots estimated by the grader to occur within the section are projected onto a "back plane," where their influence on the strength and stiffness of the total cross section is taken into account in deciding the visual strength grade. For broad-leaved timbers, the conical knot shape assumption is a less precise approximation than for conifers, and this is one of the aspects where the grader of European oak needs to apply more judgement.

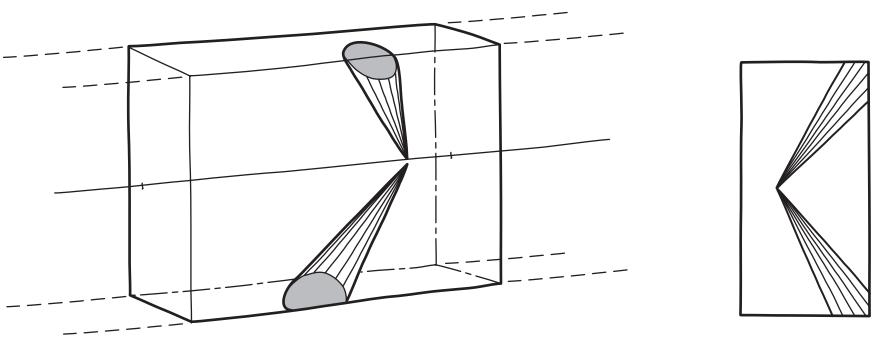


Figure 6.8 Idealised conical knots radiating from the centre of growth and projected onto a "back plane," where the grader estimates their influence on the strength and stiffness of the total cross section

In these particular rules, the grader judges the knot sizes using the methods detailed in Appendix II.2.4.1, and hence derives the "knot fractions" (fraction of knot size compared with the surface width). For this purpose, tables of maximum permissible knot fractions are provided in Appendix II.5.3. Figure 6.8 shows how a typical grade-limiting knot in an oak beam affects the strength. The "knot on a lower surface" shown in *Figure 6.9*, is approaching the maximum permissible fraction of 40%, for Grade B.

Both in oak, and in softwood, the actual knot itself is usually closely surrounded by material whose local grain slope is disturbed - this can be seen in *Figure 6.10*. This "local slope of grain" is not assessed separately from the knot. Appendix II gives more details on distinguishing between the grain slope directly associated with knots, and that occurring alone in an otherwise clear part of the length.

6.3.4.2 Distinguishing knots in different positions and on different members

The grader uses his/her knowledge of the intended end-use of the piece when assessing the knot locations across the cross section. Hence, the limits in the rules differ between beams on the one hand, and posts and columns on the other. For beams, knots near or across the arrises (*Figure 6.10*) are treated more severely than those in the centre of the lateral surfaces, see Section 6.3.4.5. But in posts and columns, the location across the section is not significant. The grader also examines the whereabouts of the knots along the length of the member, since limits are allowed to vary according to this criterion, becoming more lenient towards the ends.

6.3.4.3 Conversion type

It should now be evident that the grader needs to take into account the conversion type used for the green oak members, since particular conversion types tend to be used for certain member types. This is less of a hard and fast rule than in the past, but it is still generally so. Knowledge of the conversion type is also important in estimating the extent of intrusion of the knots beneath the surfaces of the piece.

Ancient conversion techniques involved pit sawing and/or squaring the section by axe or adze. Alternatively, the log would be split or cleft to create paired halves. Sawing has been used for centuries, but before its relatively recent mechanisation, one of the main concerns was to minimise muscle power, and to eliminate unnecessary cuts. Perhaps the main reason for historic beams being placed "the wrong way up" was the use of scantlings (small sections) which were often naturally curved or bent. These were sawn and laid flat as may be seen particularly in the use of rafters and joists (*Figure 6.11)*.

Nowadays, only those wishing to reproduce an historical facsimile will consider employing such laborious hand-tool techniques, although this is still done! Furthermore, since the days of pit or trestle sawing, there are other reasons, such as maximising the yield from the relatively small diameter of typical European oak logs, that mean that broadly speaking, the traditional sawing patterns, as shown in *Figure 6.12*, have remained in use.

Available log diameters are significant in this respect. With structural tropical hardwoods such as ekki, log diameters typically exceed around

Figure 6.9 Part of an oak beam that has fractured at the end of a full-sized bending strength test. The knot on the lower surface (in the foreground - a zone of the beam experiencing large tensile strains) dictated the ultimate bending strength of the piece - a "Grade B" beam, according to the grading rules. The knot emerges from within the section, rather than being a superficial feature, and so it would be assessed carefully by the grader. In general, such knots have a more severe influence on strength than the centreknot type in Figure 6.17

Figure 6.10 This heart-shaped feature on the edge of a beam is termed an arris knot. It has a "root," like that of a molar tooth, penetrating right into the section. Simplified views of two arris knots are also shown in Figure 6.8, but that Figure is more typical of a small softwood member. Because of the deep disturbance to the longitudinal grain, and the emergence of the arris knot amongst the extreme fibres of a beam, it is treated more strictly than the centre knot in Figure 6.17

Figure 6.11 Floor joists, traditionally hand sawn only on what became the upper and lower faces, placed "flatwise," and hence providing a level floor

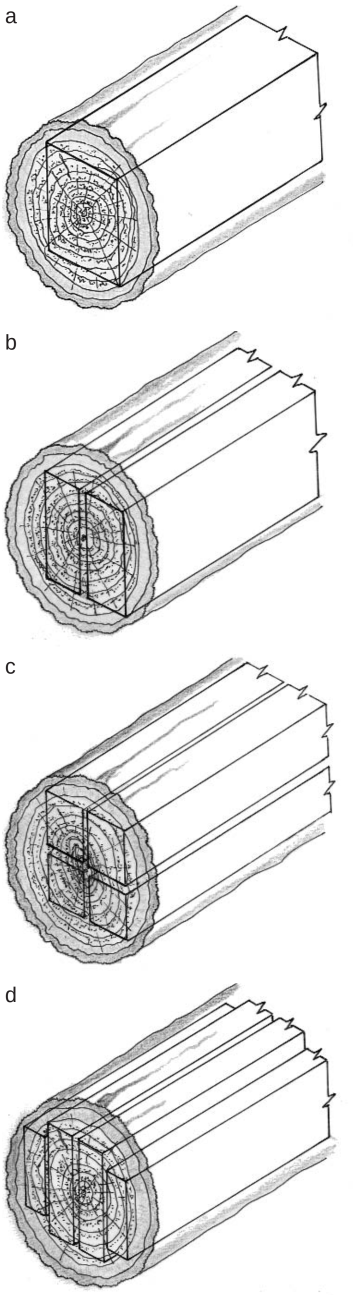


Figure 6.12
a) A boxed heart member
b) A pair of halved members
c) Four quarters
d) Through-and-through cutting - four pieces are shown, but the technique applies to other numbers, dependent upon the log size and the required board thickness

600 – 800 mm, giving the sawmiller a great deal more scope. Mixtures of conversions are employed to maximize productivity and yield. On the other hand, there is rarely such an abundance of large, straight and suitable oak logs. So the squared-off single section from the whole log is still produced. In modern terms, this is the machine-sawn, boxed heart piece taken for a large post or column (*Figure 6.12a)*. The halved pairs (*Figure 6.12b)* are the contemporary equivalent of similar pieces formerly cut with a two-man hand-saw over a pit or trestle. In fact, as discussed below, each of the four conversion methods has its traditional uses, which are still relevant.

Boxed heart members: Figures 6.12 a and 6.13

As indicated in Chapter 4, when the section dries, the appearance of the member will inevitably alter, and fissures will develop. Since the boxed heart piece is little more than a log with squared-off sides, the fissuring may be similar to that of a plain log section (*Figures 4.6* and *6.13)* ie a single main split to the core develops usually from the face closest to the heart. For larger "squareish" sections, boxed heart sawing may be the only feasible conversion. Consequently, hardwood grading rules often contain wording that the "heart shall be well boxed," which is to say that, so far as possible, it should coincide with the geometrically central longitudinal axis of the member. The location of the pith can only be determined in the sawmill. Hence this is a matter of good communication between the framer and the supplier, rather than a matter for end-use grading rules.

Within connection areas, or where a member is required to resist exceptional shear stresses, the large fissure that gradually develops in the boxed heart piece may become problematical. However, assuming the member is graded in the fully green condition, the grader cannot tell where it will occur. Consequently methods such as slotting or boring have been developed to control the position of this type of fissuring, see Chapter 4.

Halved members: Figures 6.12 b and 6.14

Halves are important for the framer, providing many of the tie beams and other large and medium-sized bending members in modern construction. In this situation, they are now normally used "the right way up". For appearance, and for weathering reasons, attention is given to the location of the heart face (or "fair face") (*Figure 6.14)*. In framing, the heart face of the beam often distorts outwards and hence is usually placed up and out in the frame. This orientation also limits the exposure of sapwood to the outer or weathering faces in those frames exposed to the environment. Further, any knots present radiate and expand towards the "inner" (sheltered and hidden) face and fissures will not pass beyond the heart - another significant point for durability.

The term "half timbered buildings" indicates their great significance within the tradition. In good modern sawing, there should be two closely adjacent cuts taken from near the centre of the log, as shown in *Figure 6.12 b*. This creates a small amount of waste, but it eliminates the presence of "pithy" material directly on the lateral surfaces of the halved members. Unless excluded, this juvenile wood is likely to be rather unsightly. The heart, with its small shakes, can just be seen near the right-hand surface of the beam in *Figure 6.14*. The drying distortion is normally as shown, and in a sound halved member, such heart shakes do not extend far in.

Quarters: Figures 6.12c and 6.15

A third general method of cutting not much in use today creates four square or "squareish" pieces.

Not to be confused with quarters is "quarter sawing." This is not appropriate to framing, since it is a much more expensive technique to provide a visually appealing surface. To finish the interior of a frame, or for shelving or other fitments, connoisseurs of quality may still wish to purchase quarter-sawn oak.

Through-and-through: Figure 6.12 d

Slabbed, or through-and-through cutting, was historically used for large boards and planks, rather than for the building frame. Nowadays, joists and smaller beams, whose cross-section is arranged so that the pieces sit "depth wise," are also likely to be obtained from this conversion. A typical contemporary thickness would be in the range of 75 mm to 125 mm. The slabbed board may then be resawn to produce smaller members.

Figure 6.13 A boxed-heart post that has been in service for a long time, and has dried out. The member is sectioned to show the typical single main fissure passing to the heart

Figure 6.14 A sectioned halved beam taken out of service. The method of conversion was clearly as in Figure 6.12 b. The heart can be seen on the right-hand face. This is the "Fair Face," having better appearance - showing few or no knots, and better resistance to exposure. Note the typical distortion of this type of member, similar to Figure 4.5 Sample B

Figure 6.15 A quartered beam taken out of service. The method of conversion, usually for smaller posts, is clearly as shown in Figure 6.12 c. The heart can be seen in the bottom right-hand corner. Note the similarity of the drying distortion to Figure 4.5 Sample A

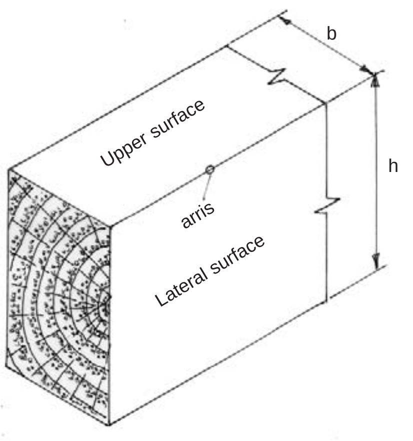


Figure 6.16 A modern green oak beam, sketched with its fair face forward. The upper surface and one lateral surface (as designated in the grading rules) are shown. The arris is also shown, and this term is used in the grading rules, but the confusing term "edge" is avoided

Note also that the symbols "b" and "h," are used in engineers' calculations. Provided the beam is bending in the vertical plane, as shown, they apply in the direction indicated

6.3.4.4 Terms for the lateral surfaces

As illustrated in *Figure 6.11*, beams and joists were formerly orientated in what the engineer would now consider to be "the wrong way," but there were good reasons, as already explained. In traditional carpentry, face and edge are carpenters' terms used to determine the orientation of the beam in its final location. This will of course vary depending on whether the beam is in an external wall, floor or roof layup.

In the Green Oak Strength Grading Rules, potential confusion is avoided by referring to "upper or lower surfaces" and "lateral surfaces" (*Figure 6.16)*. This applies mainly when beams or joists are located "depthwise" ie in the "engineers correct" orientation. Occasionally, members may still be located the "old fashioned" ("wrong") way or they may be arranged vertically, but experiencing their main bending effects laterally (eg from wind loading). These instances are fairly rare, and need to be known by the grader, who works off the frame builder's parts schedule, as well as by the engineer. This is an example of where good communication is required between the designer and the maker.

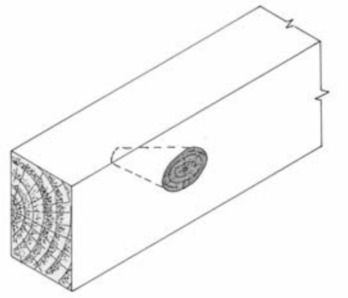
6.3.4.5 Knot types

The strength grading rules refer to five main knot types, as follows:

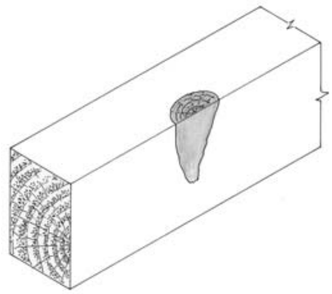
- Centre knots
- Splay knots
- Knots on upper or lower surfaces
- Arris knots
- Margin knots.

Typical examples of each of these are shown in *Figure 6.17a to e*, which indicates their appearance in relation to the wood structure arising from the conversion types discussed above. Also shown at *Figure 6.17f*, is an example of what are colloquially known as "cat's paws." This is a group of pin knots, surrounding a central feature. In this example it would be treated like a centre knot – but there are other cases - see Section 6.3.4.6 for more details.

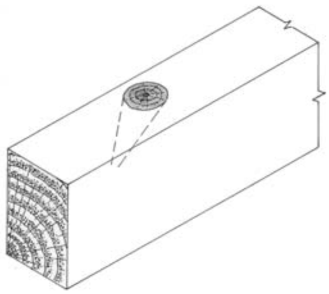
The shape of a knot seen on the surface of a sawn timber depends on the nature of the saw cut in relation to the knot's position, and the location of the heart of the log. Both this position, and the approximation of treating the knot as a true cone (*Figure 6.8*) varies considerably. Hence no precise statement can be made about the surface shape of any type of knot, but it becomes obvious that certain knot types cannot exist immediately adjacent to one another. For example, on the front surfaces in the sketches (*Figure 6.17a to e*) the splay knot, *b*, cannot be next to the arris knot, *d*. For this reason, each sketch shows the heart in a different position. The experienced green oak visual strength grader is able to apply this type of knowledge effectively, and can assess the influence of each of the five knot types in each of the four sawing conversions described above.



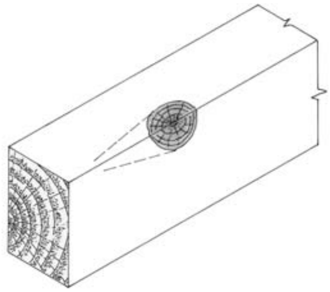
a Centre Knot:
The common round or slightly oval knot on the lateral surface of a beam, close to the centreline of a lateral surface



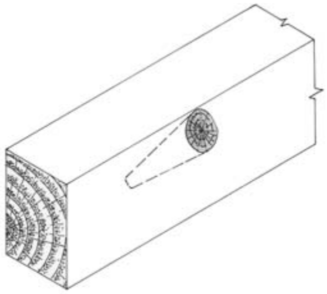
b Splay Knot:
As the slope of the cut knot increases, more of the conic section is revealed. A semicircular or semi-oval shape is normally visible on the adjacent surface. The semicircle is the only part measured



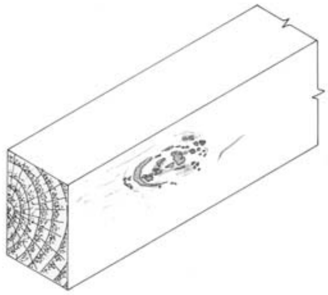
c Knot on Upper or Lower Surfaces:
A round or slightly oval knot. Typically, the “root” of the knot penetrates the section quite considerably, so like the arris and margin knots, it is graded strictly



d Arris Knot:
Formed where the knot is cut so that two approximately semicircular sections show, one on each side of an arris. Both semicircles are measured, and rules are given to combine them



e Margin Knot:
A round or slightly oval knot emerging on the lateral surface, but close to the upper or (in this case) lower arris. See Figure 6.18 for definition of margin zones



f “Cat’s paws”:
A group of pin knots, surrounding a central feature; in this case it would be treated like a centre knot – see text for more details

Figure 6.17 The five main knot types, a to e, showing their typical appearance in relation to the wood structure. Also shown, f, is a feature colloquially termed “cat’s paws,” which is common in European oak

Margin zones:

The arris knot (*Figure 6.17d)* and the margin knot (*Figure 6.17e*) both occupy a zone outside the middle half of the cross-section. Flexural members, generically termed “beams” in strength grading rules, are more sensitive to the influence of knots in such positions (*Figure 6.18)*. Compared with knots that occur around the neutral axis zone (centre knots, *Figure 6.17a*), margin knots are closer to the extreme, highly stressed fibres. For the same reason, knots on the upper or lower surfaces of beams (*Figure 6.17b* and *c*) are also treated more strictly than the centre knots.

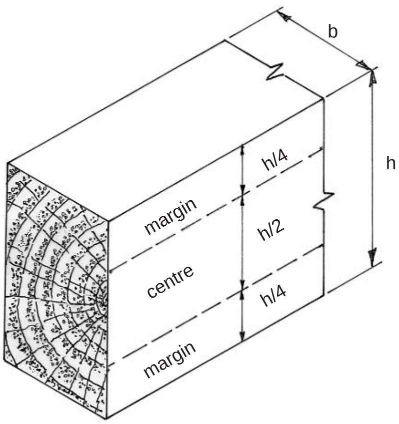


Figure 6.18 The margin and centre zones of the lateral surfaces are defined as indicated above. Knots occupying the margins are treated more strictly

6.3.4.6 Growth features peculiar to European oak

A characteristic of European oak is the frequent occurrence of clusters of pin knots, which are termed "cat's paws" by carpenters. (*Figure 6.17f)* has already shown one example, but a cluster like this may occur in other positions, including the margins. Strictly, this feature is not confined to this particular timber, but certainly it is especially common in European oak, and also in sweet chestnut, another ring porous temperate broad-leaf with strong growth, given suitable soil and climate conditions.

The small knots, often surrounding one or a few larger ones, arise from a biological feature known as "epicormic growth." Under certain conditions, shoots of fresh wood emerge from a mature trunk or limb, and the shoots themselves are called "adventitious growth" (*Figure 4.1*). This is usually associated with physiological stress, ie damage, in the mature wood. The wood from which the adventitious growth starts is slowly grown into the tree, in a similar way to the iron railings that can often be seen engulfed within hedgerow oaks. When the sawmiller opens up the log, the result is the "cat's paws," which are harmless, except in so far that they have to be treated similarly to other knots.

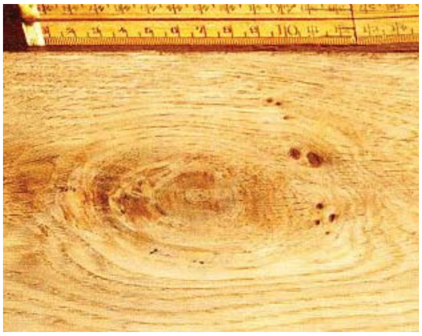


Figure 6.19 A cluster of pin knots around a single main knot, the "cat's paw"- some caution is needed in grading this feature

Figure 6.19 shows a typical "cats paw" with a cluster of pin knots surrounding a larger knot. The grader has two problems – the group of knots does not have a single, clearly defined outline, and it does not necessarily radiate right from the original tree heart, because of the growth process just described. Hence in the grading rules, it is impossible to provide precise instructions on measurement methods. Judgement needs to be applied. The underlying principle is that the grader tries to assess the overall feature in relation to the adjudged grain disturbance. This enables an equivalent knot diameter to be assigned. In doing so, the general location of the feature is compared with the five main knot types (*Figure 6.17a* to *e)*.

Another instance where there is evidence of some peripheral pin knots around the main feature is in the illustration of a fracture on the lower tensile surface of a beam in *Figure 6.9*. This is another case where the grader will make cautious allowance.

6.3.4.7 Slope of grain

It has long been known, both through tests and by experience, that where the direction of the wood fibres is not perfectly parallel to the main axis of the piece, the strength resistance is significantly lowered. This is the reason for the grain slope limits in the rules. Under load, longitudinal strains predominate in most structural members, and straight, along-grain fibres are best able to resist these.

As a general rule, European oak is not especially prone to sloping grain. Amongst the temperate hardwoods, European ash, for example, is more likely to suffer from it and grain slope needs to be guarded against particularly carefully in grading some types of tropical hardwood. Nevertheless, with the general quality of European oak, "short grain" as carpenters aptly term it, may crop up, particularly in lower qualities. Whatever the species, it needs to be controlled carefully where the end use is structural.

As shown in *Figure 6.7*, where its presence is uncertain, the grader uses a simple instrument called a grain scribe to check suspected slope of grain.

Sometimes this is unnecessary, since even small surface fissures will reveal sloping grain to the experienced eye. But superficial wood figure (the appearance to the building user) can be misleading, and is discounted by the grader.

In cases such as that illustrated, both the horizontal and the vertical surfaces of the beam may be checked, and if slope occurs on both, then it is summated – see Appendix II.4.2. This may reveal that in total, grain slope is more severe than cursory inspection suggests. In many cases however, an experienced woodworker has a good eye for deviating grain, and is competent to select, position and if necessary eliminate it, without such formalities. Wild grain is avoided in carpentry joint regions, because it makes cutting and shaping difficult.

General points to note about sloping grain are: -

- There are two conventions for expressing grain slope – by ratio, or by percentage eg 1 in 10 or 10% - this is similar to the way that hills are indicated on traffic signs. Like these signs, the percentage method originated in continental Europe and suppliers of oak from there may use it in their specifications.

- Slope of grain limits for bending members in Appendix II.5.4 range between 1:13 for Grade A and 1:7 for Grade C.

- Slope of grain affects compression strength less severely than it affects bending and tension strength. Hence more lenient limiting rules are given in Appendix II-5.4.

- Sloping grain is also taken into account in the strength properties in Appendix III.

6.4 Appearance considerations

Appearance as well as strength considerations affect the choice of oak quality since the opportunity to enjoy the natural beauty of this material is a major attraction of heavy framing. Exposed roofs are a popular architectural feature (*Figure 2.10*) with a variety of cross-frame options, and there is often the possibility of adding a longitudinal arcade to display decorative bracing. Such highly visible items require care in the selection process.

Where exposed internal galleries are strongly lit by glazing, or in other fully expressed structures, the framer selects the oak through an awareness of likely customer acceptance. *Figure 6.20* shows an example of a building where oak frames needed to be carefully specified and executed with regard to appearance as well as to other criteria. From an appearance point of view the natural features, including the fissures, are fully acceptable. The glazed wall in particular needed careful selection of the timber to avoid potential distortion (see Chapter 7, Example 5). The post bases are well elevated above the splash zone to avoid water staining (see Chapter 8). The connection of the tie beam to the king post is a gib and cotter arrangement (*Figure 5.37*). The tie beam is thus pulled into a very slight camber, locking the truss and eliminating the risk of unsightly sag (see Section 5.2.2). The metalwork is of austenitic stainless steel which is dull in appearance from the sand blasting which was used to clean the frame after assembly and covering-in.

Figure 6.20 Private swimming pool. Photo: The Green Oak Carpentry Company

Many factors influence the appearance of an oak frame; some are immediate in their effect, while others have a gradual influence over time. The principal factors are described in more detail below and are illustrated in some of the Case Studies, such as 9.1 The Globe Theatre, 9.7 Darwin College Study Centre and 9.9 The National Maritime Museum.

The appearance of all oak structures is affected by:

- the methods of conversion
- the process of drying
- contact with ferrous metals.

For external structures, long-term changes in appearance result from the effects of:

- sunlight
- precipitation
- air-borne pollution, salt spray, sand
- tannin exudation
- and while most frame are left untreated, it is possible to consider a limited range of finishes.

6.4.1 Methods of conversion

These have been extensively discussed in Section 6.3 above. To summarise, historically, beams were hewn or pit sawn, the latter producing a lively texture of irregular lines at a steep angle to the edges. However, economics and shear practicality mean that these techniques can only be used in a specially organised project. Today, the timber for most projects is band-sawn, which produces regular lines at right angles to the edges. All traces of the cutting method can, if required, be eliminated by final planing, which will show up the surface figure in greatest detail. Adzing or hewing the surface is a lot of work, but both leave distinct surface marks which can be very attractive if well done. An experienced carpenter will easily recognise which tool has been used, although there is a scudding plane with a concave blade which leaves an undulating surface as a adzed effect. The architect and building owner should agree on the choice of surface in consultation with the framer.

6.4.2 The process of drying

The movements of oak as it dries out are described in Section 4.3 and their effects on the built structure are illustrated in Section 5.4. The effects on oak members themselves are seen as the gradual occurrence of surface fissures, more particularly in members which contain boxed heart. If there is a "fair face" to, for example a post, the fissures may be minimised by pre-cutting the back face. For critical members where drying shrinkage might produce undesirable slip, as in a stub tie (see Appendix I.2.2, Rouses Farm), the framer can eliminate the problem by specifying dry timber for this particular member, although this is obviously only possible for members 50 mm thick, or less. The spurs of cruck frames are another small, but important member for which the use of dried timber is common.

6.4.3 Contact with ferrous metals

As oak is highly acidic, even brief contact with a ferrous metal will produce a blue-black mark which is unsightly and not easy to remove. The presence of water is required for the stain to occur, but green oak has plenty of that, and even brief contact with a hand plane bed or the forks of a fork lift truck can leave irregular stains on the surface.

6.4.4 The appearance of internal frames

For a brief period, even frames which are finally enclosed will be exposed to the weather while they are being erected, as well as collecting dirt and scuff marks from the process of erection. After completion of the external envelope, the recommended method of cleaning the frame (including the removal of stain) is by sandblasting. Green oak carpentry specialists are familiar with the procedures, which should be undertaken by a contractor experienced in cleaning timber (as opposed to concrete), using a relatively fine grain of sand. This method gives the timber a more uniform pale-straw colour and an appealing texture. It will pick out the softer summer growth, and lessen the severity of a band-sawn surface. Oxalic acid is a further option to clean the face of a beam, but may not be suitable on large structures and it should be remembered that high concentrations are required to be effective in bleaching out iron staining. Methods such as disk or belt abrasion are not recommended.

Most internal frames are then left as constructed. Finishes which actually build up a coating thickness are not recommended, as they will simply break up over the developing surface fissures. The use of wax or oil finishes often make the surface sticky, with a tendency to retain dust and dirt - the reverse of what was intended. Areas subject to frequent hand contact might be given a single coat of sealer, or simply allowed to develop their own patina.

6.4.5 The appearance of external frames

For external frames, cladding and free-standing structures, the major change in appearance of the surfaces over time is due to the effects of the weather. A gradual change to varying shades of grey is due to the action of daylight (or more strictly its ultra-violet component) on the surface of the oak, while direct sunlight will effect a change in a few years. The affected layer is a fraction of a millimetre thick, and, as any owner of a wooden boat will know, it can be scraped off to restore the original colour. Such efforts, however, would become an unending maintenance cycle for structures, which is really not practical. The change in colour should simply be accepted, unless finishes are applied (see Section 6.4.6). Air-borne pollutants, mainly dust and dirt, will accumulate on horizontal surfaces and to some degree of vertical surfaces, with a darkening effect, whilst driving rain has a cleaning action.

Figure 6.21 The River and Rowing Museum at Henley on Thames, built in 1996 was one of the first projects in the UK to use green oak cladding. It illustrates how small changes in exposure can produce large variations in colour
Photo: P Ross

Thus the final appearance of a particular elevation will depend upon the net effect of these three factors (*Figure 6.21*). South-facing cladding exposed to rain will relatively quickly become silver-grey while an area protected from sun and rain by an overhang will gradually darken. Timber very close to the ground, eg a door threshold, will be further affected by being in the splash zone. The surface will gradually darken where it is subject to frequent hand contact. These factors are further discussed in the Case Studies, particularly 9.1 The Globe Theatre and 9.9 The National Maritime Museum.

The external appearance can also be affected by the appearance of tannin, an extractive contained with the oak (see Section 4.8) which can be washed to the surface by the action of water, appearing as a dark stain. By the same token, it will eventually be washed away, but this may take several years. During this time, other materials placed below the oak may also be stained and may need protection.

The occurrence of tannin staining is variable, and, unfortunately, unpredictable. Seasoned oak, used, for example for window joinery, is just as vulnerable. Proof that it will eventually be eliminated can be found in decking where it is generally less of a problem. Here it accumulates mainly on the underside, and if the deck is elevated, the washout may temporarily stain any hard surfaces below.

The caution regarding contact with ferrous metal must be repeated for external applications, where rain will continue the corrosive action, on for example, door furniture (see Case Study 9.1 The Globe Theatre). For this reason, stainless steel, or the equivalent, is generally used for fittings.

This section has attempted to spell out objectively the consequences of exposing oak to the weather. It should be said that they are seen by many as a virtue rather than a fault, giving texture to the building or structure – the idea of a 'living' material, in contrast to brick and steel. For clients who are undecided, the best approach is to visit existing examples, such as those included in the Case Studies.

6.4.6 The use of external finishes

Most frames exposed to the weather are left with no applied finish. This is hardly surprising, since the messages of this book are that oak heartwood is adequately durable in this situation and the maintenance requirement needed for any form of finish is eliminated.

Figure 6.22 A mill cap finished with linseed oil paint
Photo: C Mettem

Any surface coating used on green oak must be both flexible, to accommodate movement in the timber with changes in moisture content, and vapour permeable to allow moisture to escape. Unless pigmented, the finish will require frequent maintenance as it will deteriorate due to ultra-violet light.

For external surfaces, there is a definite recommendation not to use any finish which builds up a coating thickness, such as a varnish, or oil-based paints, as this will quickly be broken up by the fine fissures created by constant wetting and drying.

The acidic nature of oak can cause difficulties with the adhesion of surface coatings. However, various types of protective finish can be used successfully, including traditional lime washes and distempers, traditional Scandinavian red ochre finishes as well as modern microporous exterior wood stains.

If it is necessary to plug or fill gaps in a green oak structure before applying a surface coating, then a flexible material, such as haired lime mortar should be used.

Figure 6.23 Building finished with a red ochre limewash at the Weald and Downland Museum
Photo: C J Mettem

7 Enclosing green oak structures

A wide range of roof and wall constructions can be employed to enclose green oak frames. The solutions discussed in this chapter are not exhaustive, neither do they include full construction details, since these can be found elsewhere (see References and further reading). The aim is to illustrate the relationship between the various forms of enclosure and the frame and to highlight the effects of drying movement on performance.

7.1 Design criteria and construction forms

The usual design criteria for the building envelope (walls and roofs) are:

- Strength – to withstand wind, snow and access loads

- Weathertightness – to prevent air and rain leaks

- Thermal performance – the requirements are defined in relevant building regulations with guidance available in separate documents

- The term thermal performance does not simply cover the thermal resistance (U-value) of the structure, but also includes the vital considerations of condensation control, both on surfaces and interstitially (within the construction), and of air tighness

- Fire performance - the requirements are defined in the relevant building regulations with guidance available in separate documents

  External walls are required to have appropriate fire resistance (from within the structure) and internal reaction to fire (surface spread of flame) characteristics. The periods of fire resistance vary with the building's purpose group and height and whether the element is loadbearing. If the building is within one metre of the boundary, there are also requirements for external fire resistance and reaction to fire

- Durability – dependent upon expected service life, the choice of materials and the degree of maintenance that they may require.

7.2 Construction detailing

7.2.1 Frame shrinkage

The shrinkage and possible distortion which will inevitably occur in green oak members as they dry is a significant factor that must be taken into account in the design of the enclosing structure. Depending upon the particular construction form, the shrinkage could cause a lowering of performance in the weather and air tightness of the building and its thermal performance. The appearance may also be affected.

As a generality, only elements in the plane of the frame are affected by the shrinkage (*Figure 5.41*). Hence a fundamental decision which has to be taken early in the design process is the position of the structural frame in relation to the building envelope and particularly the insulation. In broad terms, there are three possibilities: the insulation can be positioned outside, inside, or between the framing. Although the third option may be viewed as the 'traditional' approach, it is the most difficult and least satisfactory in terms of meeting current requirements for thermal insulation and air tightness.

7.2.2 Thermal performance and condensation control

The overall thermal resistance (U-value) of the building envelope is the major determinant in the thermal performance of the construction as a whole and this is to a large extent governed by the insulation. To achieve current thermal requirements for walls, insulation thicknesses of around 140 mm or more are needed for mineral wool; somewhat less for rigid foam types. For roofs, mineral wool thicknesses of 200 mm or more may be required, less for rigid foams, particularly when placed above the rafters.

Construction detailing plays a vital role in condensation control. General principles to be followed are:

- Controlling the diffusion of internal water vapour into the construction and ensuring that any water vapour that does penetrate can escape to the outside, minimising the risk of water condensing within the construction

- Preventing the transfer of vapour into the construction by air movement by minimising cracks or gaps at joints

- Avoiding cold bridges that cause localised condensation.

Condensation control in walls is achieved by ensuring that the internal, warm face of the construction has more resistance to water vapour transmission than the outer, cold face. A simple 'rule of thumb' is that the vapour resistance of the layers on the warm side should be 5 times greater than those on the cold side. In 'conventional' timber frame walls, a vapour control layer (vcl) is incorporated on the room side of the insulation, behind the wall lining. The vcl is often a separate layer of polyethylene sheet stapled to the studs, but some types of lining board have a vcl incorporated.

To meet thermal requirements without significantly increasing wall thicknesses, various forms of 'hybrid' constructions can be employed. In these walls, rigid insulation is applied on the outer, cavity face of the construction, with insulation also between the studs. A condensation risk analysis of the individual wall make-up must be made in these cases, because the need for a vapour control layer will depend upon the materials used and their relative thicknesses and permeability.

The shrinkage of a green oak frame may allow water vapour into the construction especially when the wall insulation is placed between the framing. Some method of sealing the increasing gap must be introduced.

In so-called 'cold' roofs, interstitial condensation control measures usually involve the provision of adequate ventilation to the cold side of the insulation and a vcl on the warm side. 'Warm' roofs do not require ventilation for condensation control because the design ensures that the timber structure remains above dew point temperature. Warm roofs generally require a high

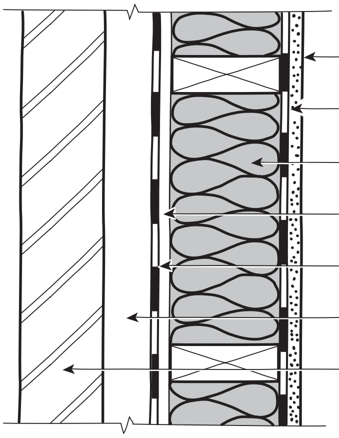


Figure 7.1a 'Conventional' timber frame wall with sheathing, protected by a breather membrane on the outer face of the studs, insulation between the studs, a vapour check layer and lining on the inner face of the studs

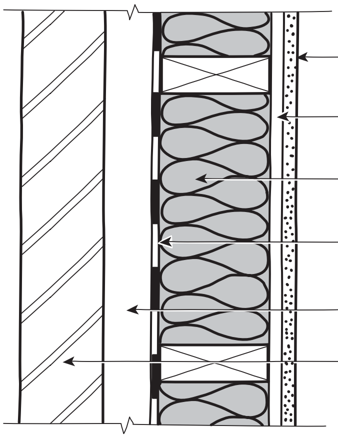


Figure 7.1b The sheathing can be placed on the room side of the insulation, with an internal lining if required: in this case, a vapour control layer may not be required. However, if no sheathing is necessary because the wall is an infill between a structural frame, a vapour control layer will be required on the warm side of the insulation

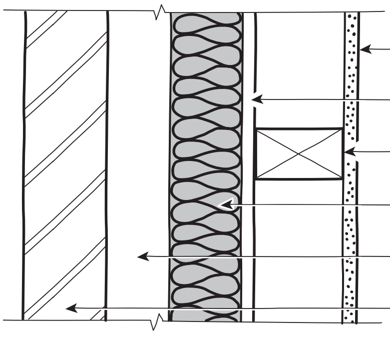


Figure 7.2 'Warm' wall construction where rigid insulation is placed on the outer, cold side of the timber studs and sheathing. A vapour control layer is not normally required in this case. Note: Wall ties must be fixed through the insulation and sheathing into the studs. Claddings which are not normally supported on their own foundations may be fixed through the insulation and sheathing into the studs but may need to be supported at their base since the fixings may not carry the vertical loads of the cladding

performance vcl on the warm side of the insulation, but in some types of warm pitched roof this may not be required. The insulation manufacturer should be consulted.

Timber studs, joists, rafters and lintels normally have sufficient natural thermal resistance to prevent localised condensation but with increasing levels of thermal insulation this may need to be checked and has to be taken into account in calculating the average U-value of the wall.

7.2.3 Weathertightness and durability

7.2.3.1 External cladding - walls

The external cladding to timber structures is typically designed as a rain-screen with a drained and vented cavity behind. The cavity allows water vapour to escape from the construction and any liquid water which penetrates the cladding to be drained away.

Materials for cladding are in two categories: heavyweight types, such as brickwork, blockwork or stone, which are built from their own foundation and simply tied back to the timber structure, and lightweight types, such as timber, tile hanging or render which are fixed to and supported by the timber structure. Differential movement will occur between the timber structure and claddings which are supported on their own foundations due to shrinkage in the oak framing (see Section 4) and this must be taken into account in the detailing.

7.2.3.2 Roof covering

Roof coverings will normally be plain tiles or pantiles on battens, although thatch or various types of timber roofing can also be used. These include timber shingles (typically western red cedar, but can be oak or sweet chestnut) or timber boarded roofs.

7.3 Drying movements and maintenance

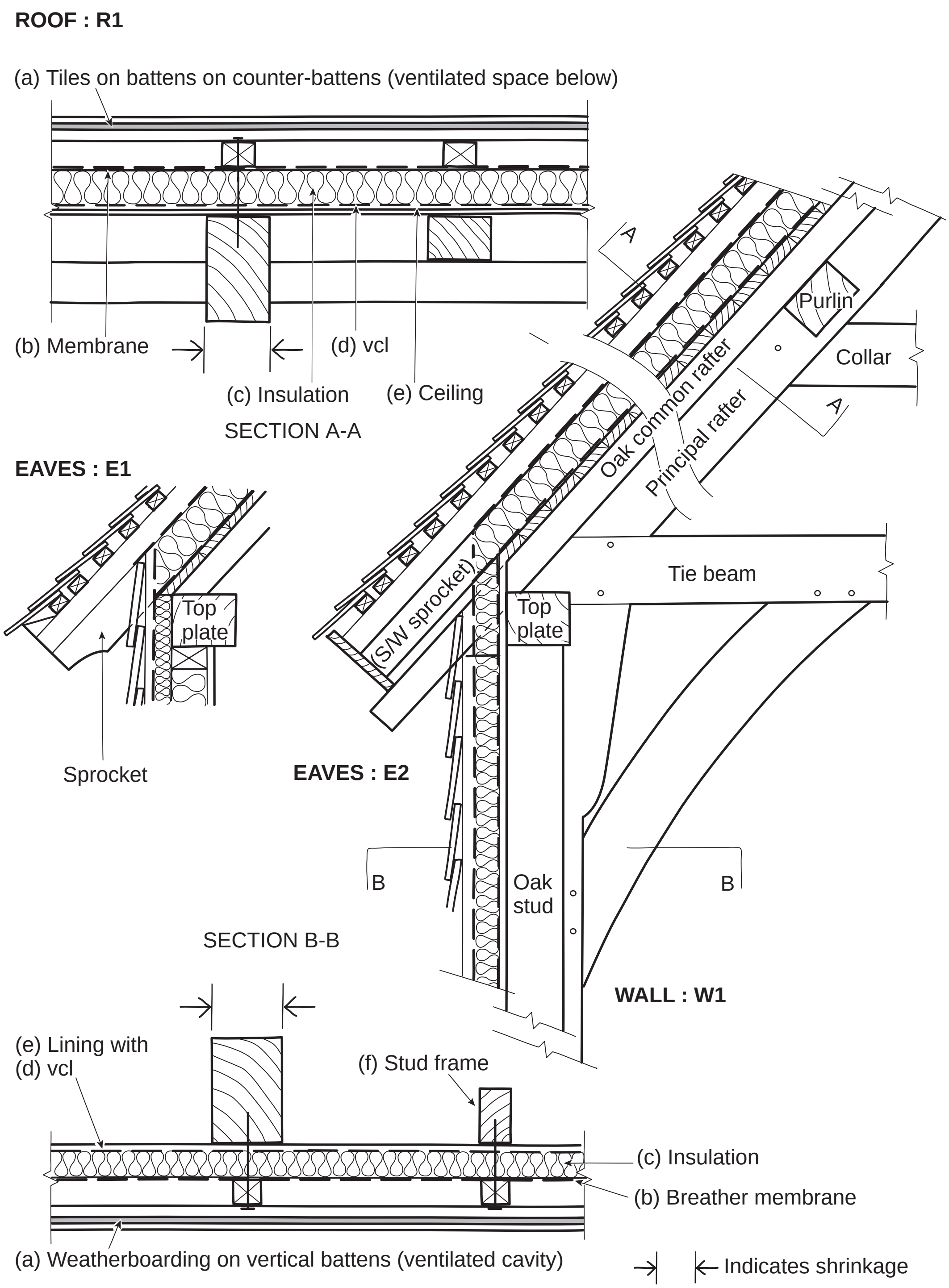
In conventional brick and block house construction, it is usual to allow a year or so as a nominal 'drying out' period, and then to carry out small remedial items of work, such as crack filling, when the fabric has stabilised. The same principle applies to green oak structures, but the stabilisation period will be in the order of 3 – 4 years.

The critical points of shrinkage are highlighted in the example details which follow, and some indication of the amount and timescale of the movement is given in Section 5.4. Clients should be advised to 'sit on their hands' for this period, or accept that any remedial work done will have to be re-done.

7.4 Example details

The construction examples which follow are based on Green Oak Carpentry Company details for buildings they have supplied. Each example represents one approach to closing in a green oak framed structure, though there are often many equally valid solutions which could be used. Accordingly, alongside each example the actual construction is described, whilst a series of Element Design Issues highlights the points which the architect or building designer should address in arriving at a satisfactory solution. Reference is made to documents which provide further information on each point.

Example 1 Warm roof, warm wall construction, with attached cladding



Example 1

Roof R1 Insulation over the rafters

Arrangements R1 and W1 are called warm frame construction as all the structural elements lie within the insulation. The performance of the roof and wall enclosure is basically unaffected by frame shrinkage.

Element (in construction order)		Element Design Issues
e)	ceiling eg boards of oak or softwood	Check surface spread of flame requirements.
d)	vapour control layer	(If needed)
c)	insulation	The insulation should be sufficiently rigid to allow through fixing for the counter-battens without undue compression.
b)	breather membrane	Could be a simple underlay to cover insulation board joints.
a)	roof covering eg tiles on battens or counter-battens	The battens and counter-battens (generally softwood) should be treated with presevative to achieve a durable rating. [See BS 8417, Ref: 13]. Ensure adequate air space over breather membrane. [See Robust Details, Ref: 24]. The fixings for the counterbattens should be of adequate durability and sufficiently rigid to support the weight of the roofing through the insulation.

Eaves E1: Closed eaves with sprockets

Element		Element Design Issues
a)	sprocket (may be tilted)	Timber exposed to rain should be durable, for example sapwood-free oak.
b)	boarding over sprocket	Ensure through ventilation to air space at eaves and ridge.

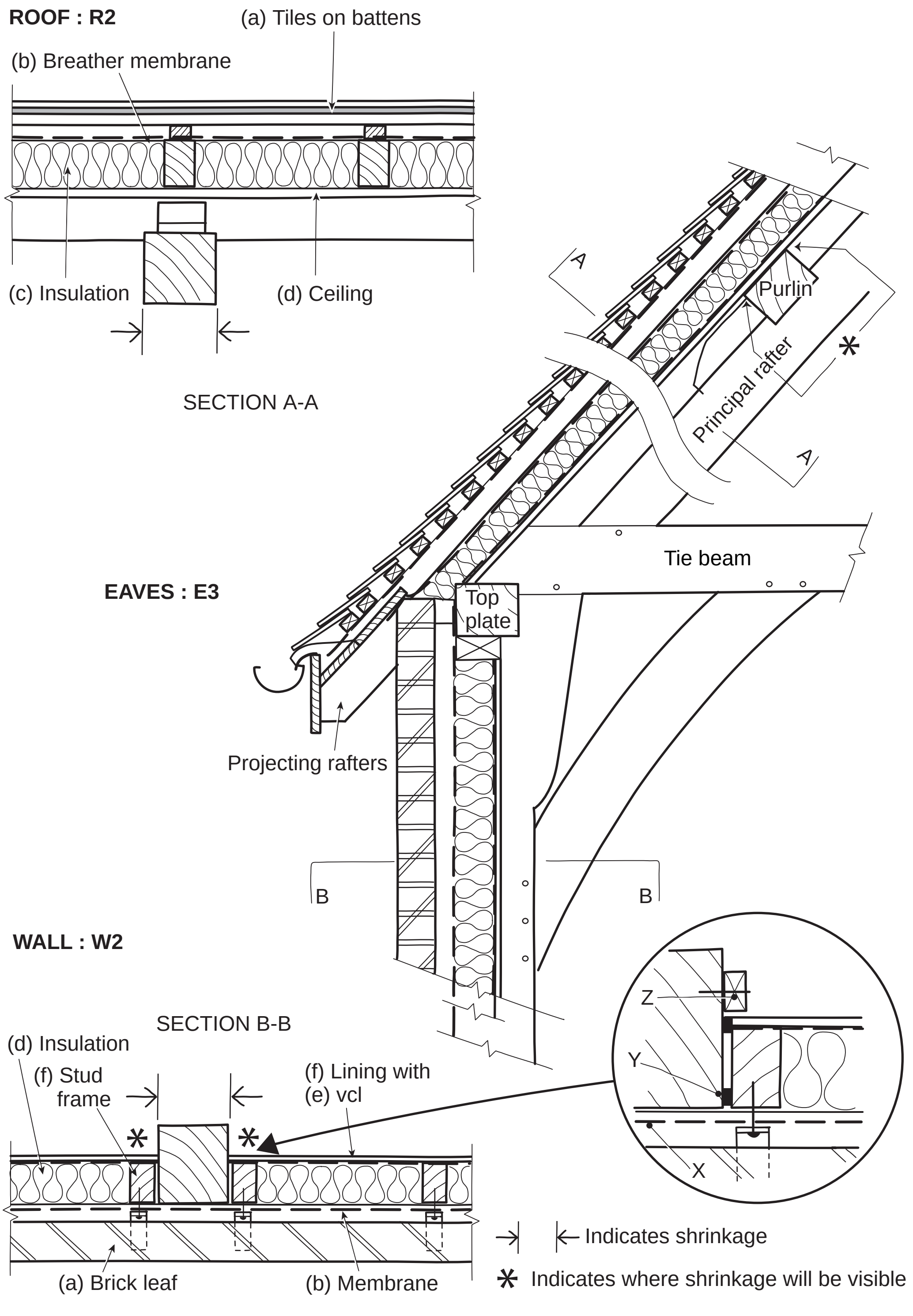
Eaves E2: Open eaves with exposed rafter feet

Element		Element Design Issues
a)	rafter extension	Timber exposed to rain should be durable, eg sapwood-free oak.
b)	boarding under sprocket	Ensure through ventilation to air space at eaves and ridge.

Wall W1 Warm frame: insulation outside the frame

Element (in construction order)		Element Design Issues
e)	stud frame in oak or softwood	Structural framing designed for dead and wind loads. Infill framing may be non-loadbearing.
d)	lining	If the board is to be fixed from the outside to the studs it should be a cellulose reinforced gypsum board (or as a minimum moisture resistant plasterboard).
f)	vapour control layer	May be incorporated in lining.
c)	insulation	The insulation should be sufficiently rigid to allow through fixing for the counter-battens without undue compression.
b)	breather membrane	To protect insulation and to improve the air tightness of the construction
a)	external cladding – weatherboarding on vertical battens: ventilated cavity. Alternatives: tiles, shingles	The battens and counter-battens (generally softwood) should be naturally durable and free from sapwood or treated with preservative to achieve a durable rating. [See BS 8417, Ref: 13]. The fixings for the battens and counterbattens should be of adequate durability and sufficiently rigid to support the weight of the cladding through the insulation or the vertical battens should be supported at the base.

Example 2 Cold roof, stud frame wall between oak frames, brick cladding



Example 2

Roof R2 Cold roof: insulation between rafters

Rafters and insulation hidden by ceiling. Ventilation to the insulation zone is unnecessary. This is a cheaper roof than R1 as the rafters can be softwood and the ceiling could be plasterboard. The roof performance is unaffected by oak frame drying shrinkage.

Element (in construction order)		**Element Design Issues**
b)	breather membrane	Typically draped loose over rafters
a)	roof covering: tiles on battens	Check ventilation below tiles
c)	insulation	No mechanical strength needed but it should be tightly fitted to allow for shrinkage of the rafters
d)	ceiling: vapour check plasterboard	Or separate vapour control layer could be incorporated

Eaves E3

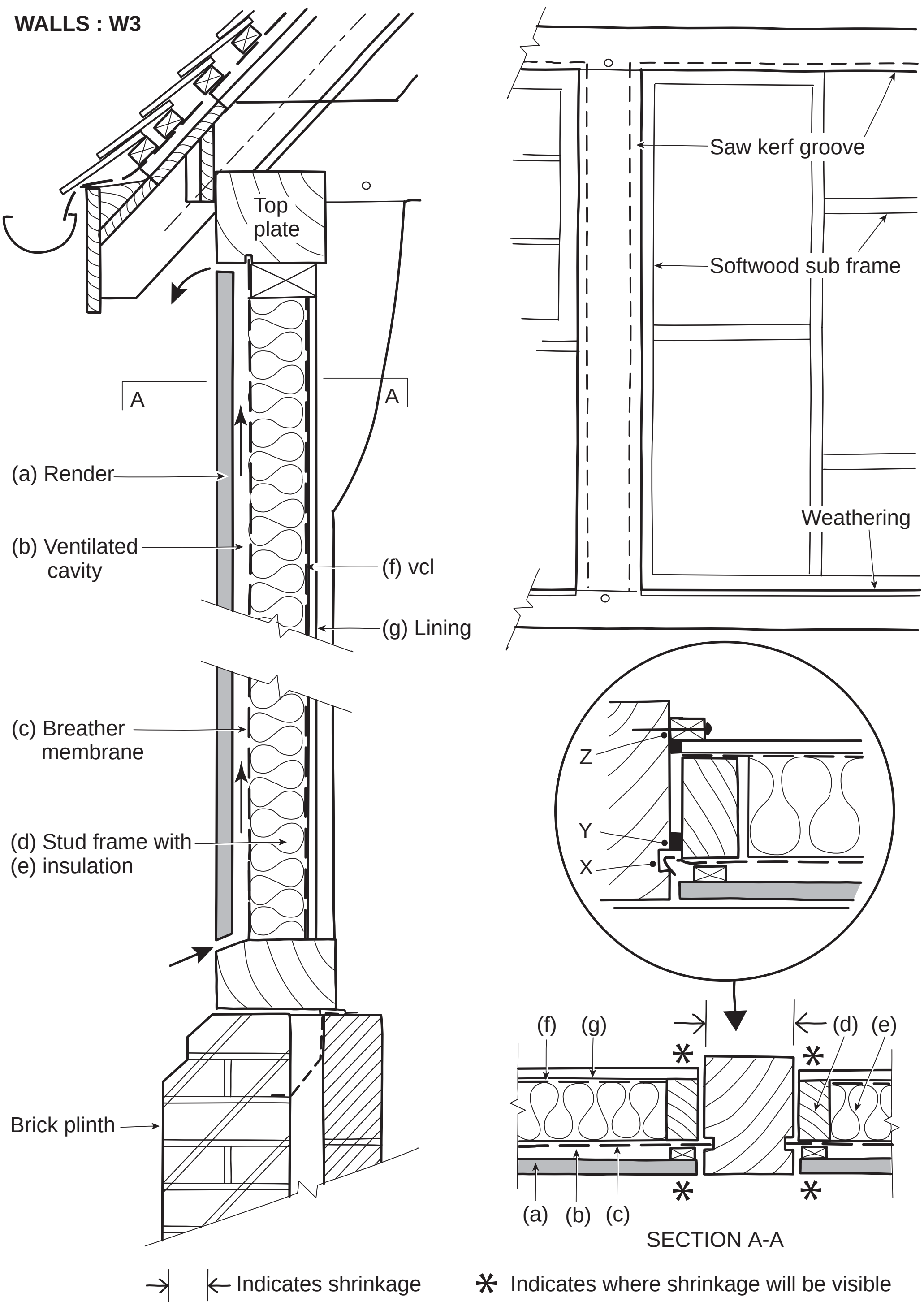
Element		**Element Design Issues**
	Rafter end exposed	Timber exposed externally should be durable eg sapwood-free oak.

Wall W2 Brick cladding

A conventional ‘modern’ domestic timber framed wall (brick outer leaf, stud inner leaf) with the studding set into the plane of the oak frame

Element (in construction order)		**Element Design Issues**
c)	softwood stud frame	Designed to stabilise brickwork and resist wind loading (see below)
b)	breather membrane	Stapled to studs if required to protect insulation
a)	brick external cladding supported on its own foundations with drained and vented cavity. Lightweight stainless steel ties to softwood studs	[See Thermal insulation – avoiding risks, Ref: 42; Thermal performance Robust details, Ref: 24; Timber Frame Construction, Ref: 45]
d)	insulation between studs	Thickness of insulation required to meet thermal requirements may determine stud sizes.
e)	vapour control layer	May be incorporated in lining
f)	Internal lining - plasterboard	
	stud wall/ frame joint	It is important to seal the developing shrinkage gap between the oak frame and the adjacent studs. Approaches include: - continuing the breather membrane across the post (without fixings) (X) - the use of pre-compressed foam strip (Y) - internal beads fixed to the frame (Z)
	wall U-value	Account must be taken of the frame and studs when calculating U-values

Example 3 Wall construction in plane of frame



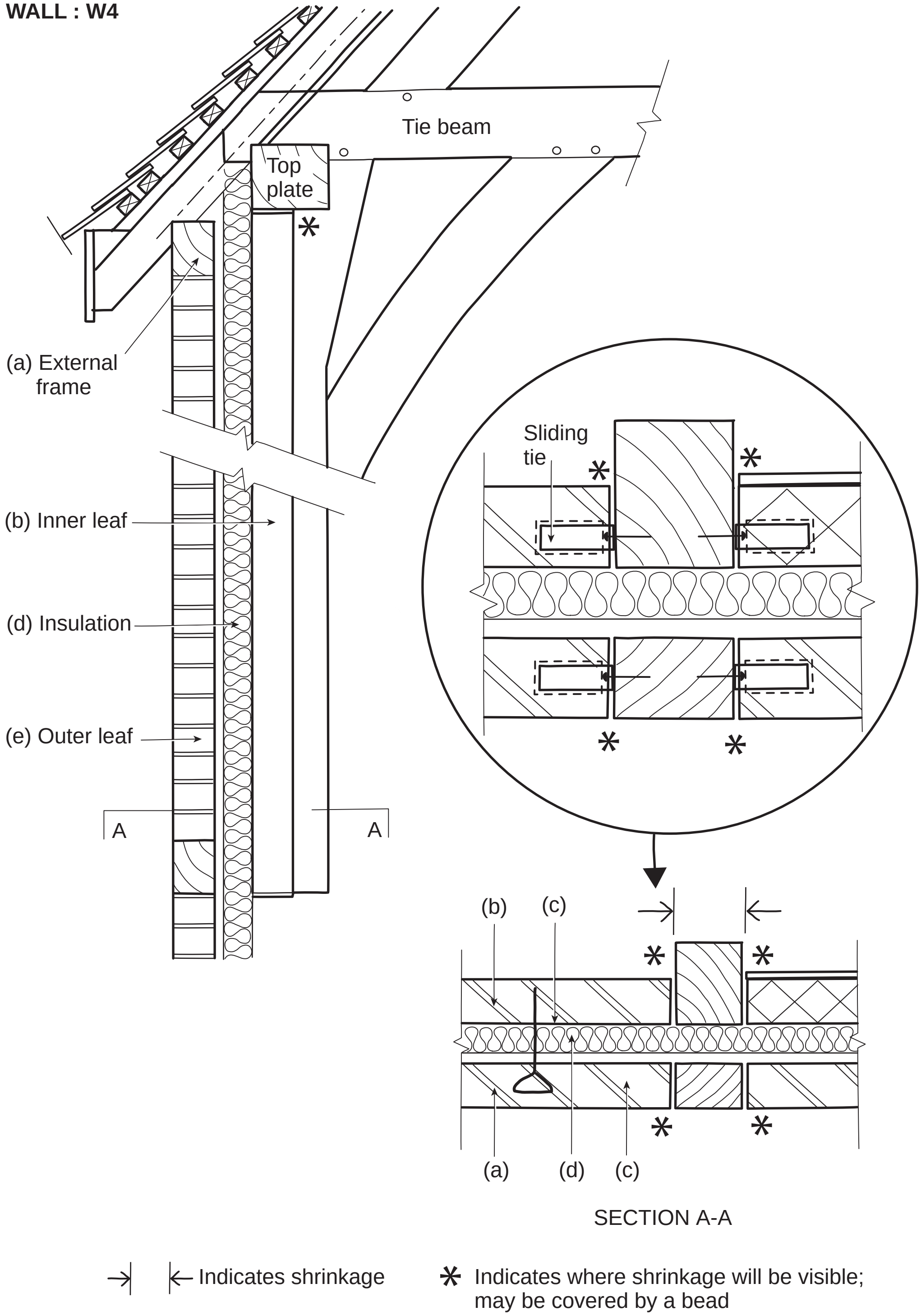
Example 3

Wall W3

Often preferred by clients, as the frame can be seen both inside and out. However, as all the elements of the wall construction lie within the frame zone, frame shrinkage could allow direct air infiltration to the interior.

Element (in construction order)		**Element Design Issues**
d)	softwood stud frame	Designed for wind and cladding loads.
c)	breather membrane	Should be folded into the cavity to allow for frame shrinkage and should be securely fixed
b)	battens framing cavity	
a)	render on eg stainless steel mesh	Lime render should be considered because of its porosity and its ability to act as an insecticide and fungicide.
e)	insulation	
f)	vapour control layer	
g)	internal lining - plasterboard	
	stud wall/ frame joint	Sealing the developing shrinkage gap beside the frame and avoiding cold bridging is the most important design issue of this construction form. Approaches include: - tucking the breather membrane into a groove (X) - the use of an expanding foam strip (Y) - fixing internal beads to the frame (Z).
	wall U-value	Account should be taken of the frame and studs when calculating the wall U-value. The insulation thickness required may determine the stud depth.
	brick plinth detail	The setting of the sill plate flush with the brick below, with no dpc is an acceptable detail if only lime mortar is used for the brickwork.

Example 4 Framed cavity walls



Example 4

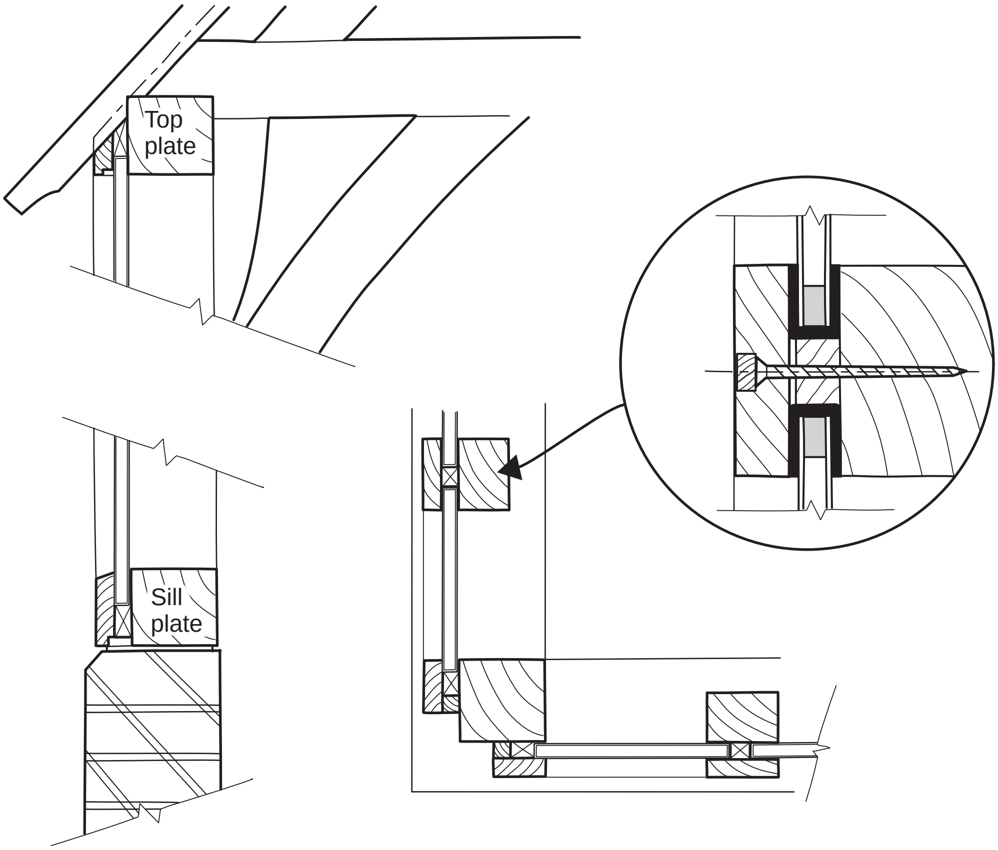
Wall W4 Framed cavity walls

A possible alternative to W3, giving a framed appearance externally. The two separate leaves ensure maintenance of wind resistance and insulation value.

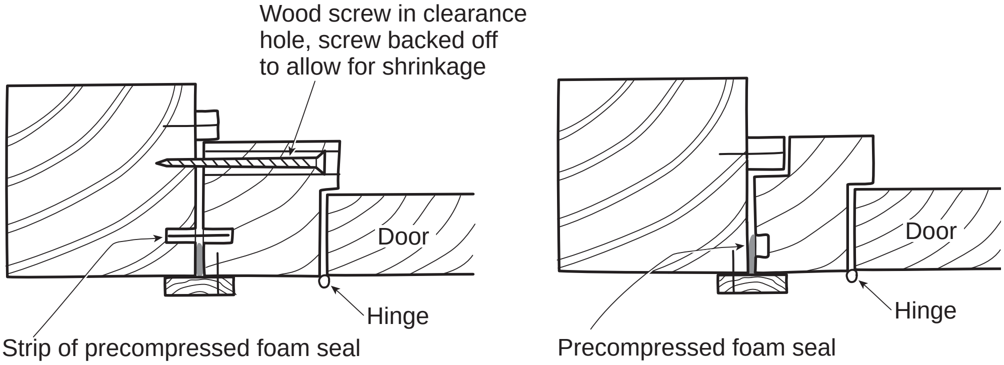
Element (in construction order)		**Element Design Issues**
a)	External frame	Non-loadbearing outer frame is stabilised from the main frame, generally by metal connectors.
b)	Inner leaf of brick/block (generally leads outer leaf)	Designed to resist wind loads, which are transmitted through ties to main frame – see below.
c)	Membrane	May not be necessary if the insulation forms impervious layer
d)	Insulation	Requires mechanical support from the inner leaf, generally provided by fixing with proprietary cavity ties.
e)	Outer leaf of facing brick	Lime mortar is recommended with no dpcs. The joint against post will open as the post dries. The post should be allowed to dry before filling the gap. The outer leaf is stabilised by cavity tie connection to the inner leaf.
f)	(Fair-faced brickwork) Lining (plaster)	A plaster strip bead can be incorporated against the post, to generate a clean line as the post shrinks.
	Brick ties to green oak	Sliding ties (metal 'L' shape) screwed to the post, with plastic sleeves over horizontal leg allow movement as the post shrinks.

Example 5 Direct frame glazing

WALL W5: Direct frame glazing



Example 6 Insertion of door into an exposed oak frame



Example 5

Wall W5 Direct frame glazing

This is obviously not a medieval form, but is often used to increase the rather limited transparency of a traditional façade.

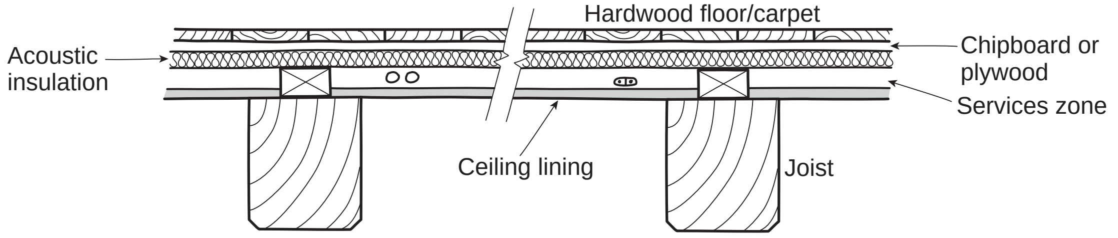
Element		**Element Design Issues**
	A glazing ‘groove’ is formed by screw fixing a kiln dried spacer batten with a cover plate of dried oak to the faces of the posts, top plate and sill plate	The green oak members should be designed and specified to minimise drying distortion in the length, by limiting the length/depth ratio to around 15, and specifying SF or better (see Appendix I).
		The principal design issue is the method of bedding the double-glazed units. In part, this will depend upon the manufacturer’s view in relation to any extended warranty. The detail is drawn illustrating a fully-bedded system, which can only perform satisfactorily given a high standard of workmanship which eliminates any significant cavities in where water might accumulate and, over time, break down the unit seals. Problems can arise if the beads swell, compressing the bedding, and then shrink, leaving a gap for water to enter. The alternative is to employ a ‘drained and vented system’ which provides an exit path for any water which bypasses the seal. The system is described in the TRADA Technology publication ‘High performance wood windows’ (Ref: 31). Experienced framers will generally have their preferred system.

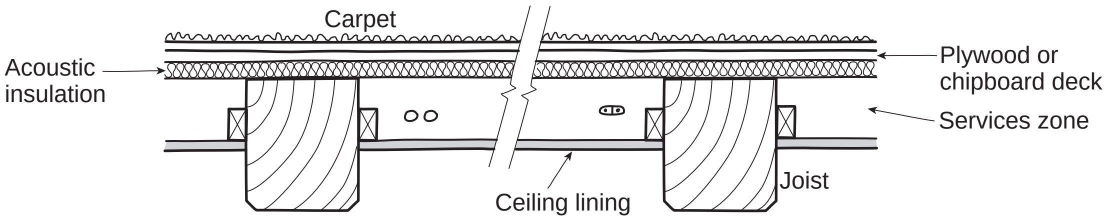
Example 6

J1 and J2 Two possible solutions are shown:

Element		**Element Design Issues**
J1	The stile requires support at intervals, achieved in the usual way by screws into the oak.	The screws, in clearance holes, should be backed off a couple of turns to allow for the shrinkage of the post. To prevent air leakage through the joint, a strip membrane is let into grooves in the post and frame or a precompressed foam seal can be used. The movement is concealed externally by a cover plate, and internally by another bead.
J2		If the stile of the joinery item is adequately strong to span from head to sill, then a cover plate and internal bead, backed up with sealant with a precompressed foam seal between the frame and post outside will suffice.

Example 7 Exposed joist intermediate floors





Example 7

Exposed joist intermediate floors (not separating or compartment floors)

As noted in Chapter 5, the performance of the traditional open floor comprising boards laid directly on joists may not be satisfactory in terms of sound transmission or fire resistance. The two options F1 and F2 address these issues.

Element (in construction order)		**Element Design Issues**
	Joist	
	Batten fixed to joist to support flooring and provide service zone	Should be sized to transfer floor loads to joists.
	Lining – plasterboard or fire-resisting board	Thickness determined by fire performance requirements
	Acoustic insulation	Should be sufficiently robust to support flooring above.
	Chipboard or plywood deck	
	Flooring material – carpet or decorative timber	

Element (in construction order)		**Element Design Issues**
	Joist	
	Acoustic insulation	Should be sufficiently robust to support flooring above.
	Chipboard or plywood deck	
	Batten fixed to joist to support ceiling and provide service zone	Contributes to fire and acoustic performance of the floor as the oak joist shrinks
	Ceiling lining – plasterboard or fire resisting board	Thickness determined by fire performance requirements
	Flooring material – carpet or decorative timber	

8 Exterior uses of green oak

As a strong timber whose heartwood has a good natural durability, European oak continues to be favoured for use in bridges and other exposed structures such as walkways and towers. Throughout its geographic region, it has a millennia-long record in these types of application. Green oak is also being used for external timber cladding on modern buildings, such as the National Maritime Museum, Falmouth (see Case Study 9.9).

8.1 General approach to durability in design

In addition to verifying the strength and checking the mechanical serviceability of any proposed design, an important task is to address the issue of durability. This should be treated as an integrated aspect, rather than an afterthought. Under-specification will result in premature degradation, with direct implications for serviceability and quality of performance. Furthermore, if deterioration is allowed to progress, the strength and stability of the structure could be at risk. Conversely, over-specification for durability will invoke unnecessary costs - both financial and environmental.

A good general principle, and not only for structural members, is that given by BS EN 1990: 2002 Eurocode 0 (Ref: 19) which states that ‘the environmental conditions shall be identified at the design stage, so that their significance can be assessed in relation to durability, and adequate provisions can be made in relation to the materials that are chosen’.

Checklist for the durability aspects of timber design:

1 Consider the natural durability of the timber species and the need to exclude vulnerable sapwood from the specification or to specify preservative treatment
2 Avoid ground contact or contact with wet materials
3 Ensure end grain protection
4 Avoid moisture traps
5 Provide ventilation
6 Consider the implications of member size and shape
7 See whether it is possible to protect key elements from precipitation and solar radiation
8 Consider whether to specify a protective coating
9 Consider risks specific to the building or other structure in question.

All of these aspects are embodied in formalised decision-making processes. For instance, BS EN 335-2 (Ref: 14) includes guidance on the selection of appropriate timbers and the identification of hazard classes.

Key aspects of each of the checklist items are outlined below:

8.1.1 Natural durability

The heartwood of European oak has a natural durability rating of Class 2, durable (see Section 4.4). It can therefore be used for an external structure which is required to achieve a design life of fifty years or so, provided that it is well detailed, following the recommendations given below. Oak sapwood is rated as Class 5 (not durable) and should therefore be excluded from timber for exterior use.

8.1.2. Avoiding ground contact

Although European oak survives for centuries under completely anaerobic conditions, ie permanently immersed and buried in silt or peat, its performance in ground contact where oxygen supports the wood decay organisms is measured in decades rather than centuries. The precise lifetime will depend to some extent upon the size of the cross-section. There is no doubt about this, since the ground sills of historic oak frames have always had to be repaired and have in fact usually been replaced with more durable materials such as stone or brick. For a modern green oak structure designed for an external application, a prolonged life is normally anticipated through the use of a framework that is isolated from the ground (*Figures 8.1 - 8.3*).

Timber should not be placed in direct contact with moisture retaining or permeable materials. Impermeable damp proof courses and damp proof membranes, washers and packers (see Section 8.1.4) or a sufficient gap to prevent water absorption and allow ventilation should be used to isolate the timber from the risk of long-term wetting. Lime mortars or grouts should always be used in preference to cementitious mortars for bedding oak members on masonry. The porosity of lime mortar helps to wick away water from the timber surface as it dries rapidly and also, being strongly alkaline, it is a natural fungicide and insecticide.

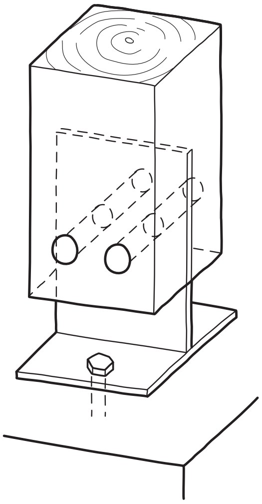


Figure 8.1 Example of an external post base out of ground contact, designed to avoid water entrapment and splashing

Figure 8.2 The technique of building oak frames using sill beams mounted on stone or brick was developed quite early, because earth-fast posts rotted quickly. A horizontal sill beam resting on a low stone wall resists ground water because moisture absorption across the grain is much more limited than through the end grain. In conjunction with modern damp proof courses and flashings, this is still best practice (Weobley, Hereford and Worcester)
Photo: C J Mettem

Figure 8.3 A small modern green oak frame having sill beams mounted on a low brick and flint wall. The detailing also avoids the commonly-found problem with older buildings of decay at the base of the door posts, another position at which there used to be water uptake through end grain
Photo: The Green Oak Carpentry Company

Figure 8.4 Green oak bridge for the Grand Union Canal, in Ealing, by The Green Oak Carpentry Company
Photo: Green Oak Carpentry Company

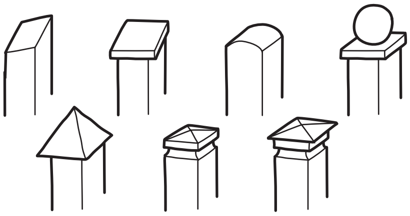


Figure 8.5 A range of post caps giving scope for choice, according to taste and the overall nature of the design
after Nordic Timber Council (Ref: 26)

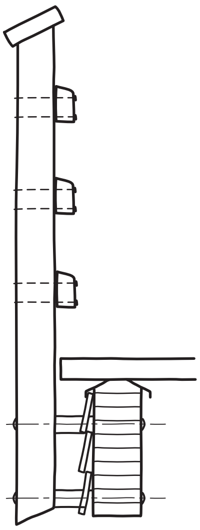


Figure 8.6 Cross-section of a beam and the parapet of a pedestrian bridge. The top surface of the beam is sloped and protected with a corrosion-resistant sheet metal. The outer face of the beam is protected with replaceable cover boards. The contact surface for the deck is as small as possible and well ventilated. The handrail is sloped and includes drip mouldings on the underside. The parapet rails are lifted off the post by means of galvanised round washers. The upper edges of the rails are sloped
after Nordic Timber Council (Ref: 26)

In bridge design, isolation from the ground is achieved through various details, but generally the oak-work commences above sill walls with protective coursing; piers with appropriate supports; bank seats with requisite elevation and ventilation, and so forth. Between the oak structure and the foundations will be reinforced concrete, stone or brickwork.

Quite often, a replacement bridge is requested, to be built on existing civil engineering works. This was the case for instance with a green oak carpentered bridge that was recently supplied for the Grand Union Canal in Ealing (*Figure 8.4* and Case Study 9.10). In such instances, it is simply a matter of assessing and if necessary repairing or extending the present abutments or piers, and ensuring that the protective design features required for timber bridges can be incorporated when the new structure is erected and anchored in place.

Above the levels described, the timber structure is supported with stainless steel or galvanised steel shoes or plates. Timber design codes, such as Eurocode 5 (Ref: 20) give details of the recommended levels of protection for such metalwork and for the associated fasteners.

8.1.3. End grain protection

The end grain of all species of timber permits access to moisture. The open pores of oak are particularly vulnerable. Capillary action through the wood structure adds to the tendency for the end grain surface texture to draw in moisture. Therefore, as far as possible, members should be located so that the ends are not directly exposed to rain or standing water. Often this can be achieved by simple measures such as standing the piece on a support, perhaps raised off a surface that naturally drains because of its shape. Where members have to be positioned so that their tops are potentially at risk (*Figure 8.5*), caps or flashings should be applied. These may be of timber, possibly of oak, using air-dried or kiln-dried stock. Alternatively, various types of durable or protectively-coated metal covers can be used.

8.1.4. Avoiding moisture traps

A major cause of timber decay is the formation of pockets in which water, dirt and dust become trapped. This generally occurs at poorly designed junctions between members and at connections between members and lower supports. As well as measures similar to those described to avoid ground contact, the careful shaping of timbers, and sometimes their actual orientation in relation to the cross-section, can improve matters considerably. Slots and bored ventilation holes may be possible. In traditional carpentry jointing generally, open-bottomed or vented mortices should be applied for exterior structures. Their use is exemplified in the bridge at Ealing (see Case study 9.10).

Simple but effective protective design measures can be incorporated at an early stage in the design of a bridge or external timber deck (*Figure 8.6*).

8.1.5. Provide ventilation

Where there is any risk of moisture build-up or condensation in inaccessible locations, ensure that ventilation is provided and that this is in the form of free air movement. Examples include drained and vented cavities behind cladding (*Figure 8.7*), ventilation below timber ground floors and ventilation in cold roof spaces and voids.

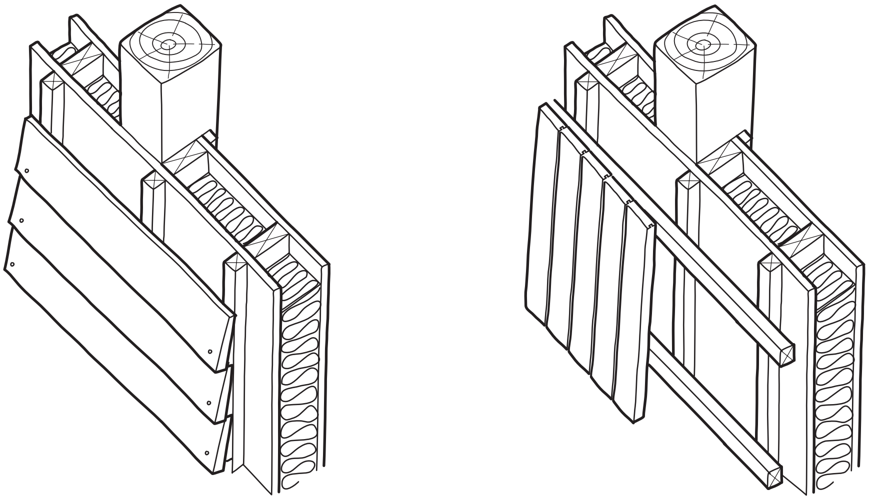


Figure 8.7 Drained and vented cavities. Left Horizontal lapped timber boarding supported on vertical battens,
Right To provide a clear ventilation and drainage path vertical boarding requires horizontal support battens on vertical counter-battens

8.1.6. Member size and shape

The sizes and sawing methods used for European oak members have significant implications for durability. The larger cross-sections cannot usually be fully dried before installation, and indeed it is the fundamental premise of green oak construction that this is not attempted. Consequently, shrinkage, changes in sectional shape, and fissuring are inevitable. There are historically proven methods of minimising water penetration into the heart of the cross-section. These include taking care of the orientation of the piece in relation to the location of its annual rings and other natural features. For structural components such techniques are discussed and illustrated in Section 6.3.4.3. Thinner boards follow the 'rule of thumb' that the growth rings try to flatten as they dry (*Figure 8.8)*.

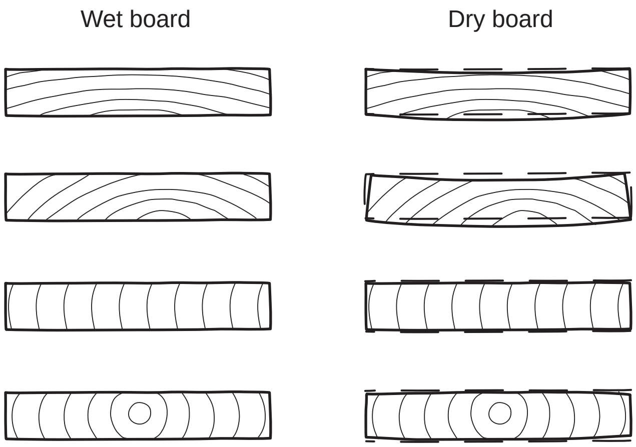


Figure 8.8 Changes in shape of sawn boards as they dry out

8.1.7. Protecting key elements from precipitation

In buildings where the oak is exposed externally, and in roofed bridges, eaves overhangs can be used to minimise the direct wetting and splash-back caused by precipitation, reducing the flow of water over wall elements and hence reducing the risks of decay (*Figures 8.9, 8.10*). However, this can result in distinct colour differences due to differential weathering, described in 6.4.5 and in the Case studies, Chapter 9.

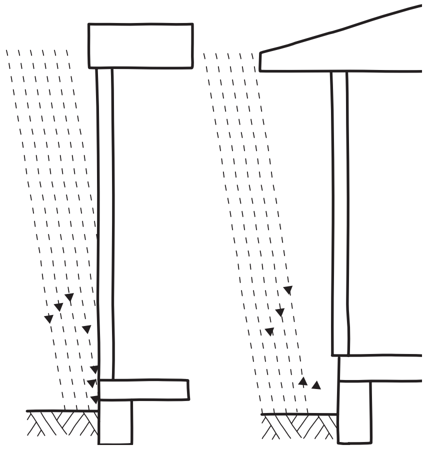


Figure 8.9 Protection afforded by roof overhangs; avoid extending timber cladding into splash zones

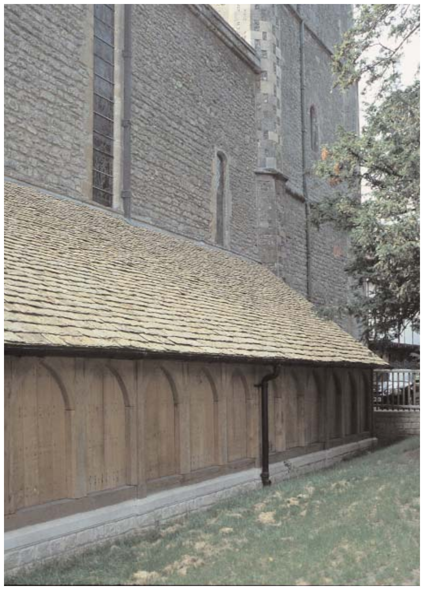


Figure 8.10 Protecting key elements. The Cloister Pentice, Dorchester Abbey. A new-build in green oak, exposed externally and well designed with regards to protection. There is an eaves overhang; the timber is elevated on a masonry sill well above the splash zone, and there is an effective rainwater drainage system
Photo: P Ross

8.1.8 Protective coatings

Although green oak exposed externally is often left to 'weather' naturally, this can produce a dirty, patchy appearance which may not be the desired result. A surface coating will provide protection against greying caused by the loss of natural colouring materials from the wood, accumulation of dirt from atmospheric pollution and possibly mould growth on the timber surface. It may also reduce splitting and checking of the timber surface, although some timber movement will still inevitably occur. The use of external finishes is discussed in Section 6.4.6.

8.1.9. Risks specific to the building or structure

In many instances, the historically proven methods mentioned above have been developed and adapted for especially hazardous building uses and situations. For instance, barn and granary frames are supported on raised stone plinths, not only for protection of the post bases from vehicular impact, but also to prevent moisture uptake from wet farm waste such as straw and dung, lying on the floor. Timber is often preferred for modern buildings in which wet and/or corrosive materials are stored. Similar principles can be applied to the detailing of fully external structures.

8.2 Appearance grading

For non-structural or 'semi-structural' uses, such as cladding, appearance can be defined according to a grading system based on BS EN 975-1 (Ref: 18). A national commentary entitled 'Making the Grade – a guide to appearance grading UK grown hardwood timber' (Ref: 23) gives guidance to both producers and specifiers and end users to enable them to obtain material to suit their needs. This system of appearance grading is quite different from strength grading discussed in Chapter 6 and Appendix II.

Three appearance grades are defined to describe the main features of a plank or board, although these may be further divided into sub-grades.

- Grade 1 describes planks or boards having a uniform appearance with few if any knots, splits or other features that would limit their use in applications where little variation in appearance is permitted. Equivalent to what is often called a 'clear' or 'prime' grade.

- Grade 2 has some knots, splits or other features that limit use where uniformity of appearance is important. Nevertheless the piece will yield areas clear of unacceptable features along with timber suitable for applications where some variation is acceptable.

- Grade 3 timber will include all manner of knots, splits colour variation and other features.

Note: Grade 1 material attracts a premium price and is appropriate for high class joinery and furniture. For external uses, particularly cladding, Grade 2 is likely to be the most appropriate.

8.3 External cladding

The use of external timber cladding is governed by building regulations which limit the area of 'unprotected cladding' ie combustible materials, such as wood, permitted in proximity to boundaries.

European oak is available from air-dried stock in the thinner sections required for cladding. However, the use of green oak cladding, which avoids the drying premium, is popular with some designers and building owners. The guidance given here relates solely to the use of green oak; more general information on cladding design and specification is given in 'External Timber Cladding' (Ref: 30).

In addition to the exclusion of sapwood discussed in Section 8.1.1, factors of particular relevance to the use of green oak for cladding include shrinkage and movement, fixings and tannin exudation.

Fixings must allow for initial shrinkage as the timber dries from the green condition as well as the subsequent movement which will occur from season to season. This natural tendency can be exploited to advantage by careful selection during preparation and installation, see *Figure 8.11*. Board on board or open jointed designs are particularly appropriate for green oak cladding as movement can be accommodated.

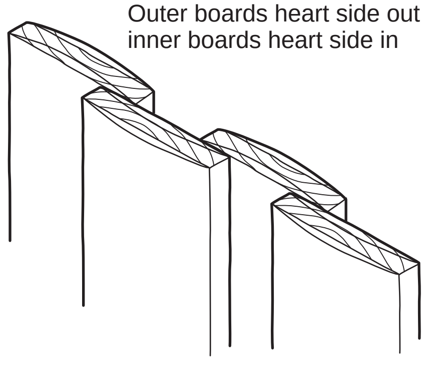


Figure 8.11 The natural tendency of boards to cup as they dry can be exploited in the installation of board-on-board cladding

Figure 8.12 Mitred corner in green oak cladding at the Earth Centre employs a gap between the ends of the boards to disguise movement between the faces and to conceal the exposed end grain of the boards

Figure 8.13 Use of oversize washers to allow movement in green oak cladding Photo: P Ross

It is advisable to predrill boards to provide a 4 - 6 mm clearance between the shank of the fixing screw and the hole. A washer must be provided under the screw heads to provide sufficient cover. The washers can be slotted to allow them to move with the wood, although care must be taken in aligning the slots. Alternatively oversized washers can be set into recesses in the boards to allow movement between the washers and the wood (*Figure 8.13*).

All fixings; screws, washers or clips should be of austenitic stainless steel. Tannin run-off can also be a problem in the early months after installation of green oak cladding (see Section 6.4.5).

Exposure to ultra-violet light will bleach all woods to a grey colour if the surface is unprotected. If the appearance of the weathered timber without a surface finish is acceptable, then no further maintenance is required. This is a major attraction in specifying green oak cladding, which is normally left unfinished. The rate of surface bleaching may be uneven, due to shading from projections such as eaves, balconies and sills. Surface checking (small cracks which open and close depending on the moisture content) of the surface is likely and, in polluted environments, dirt can be picked up by the unfinished wood, eventually leading to blackening of the surface.

The case study of the National Maritime Museum, Falmouth (9.9) shows green oak cladding in a number of configurations.

8.4 Decking

The natural durability of oak heartwood makes it an attractive proposition for deck structures. However, the movement and distortion likely to occur as green oak dries must be accepted as part of the design and accommodated in the design detailing. As for cladding, the use of air dried oak could be considered as board material over a green oak support structure. The guidance included here relates specifically to the use of green oak; more general information is given in 'Timber decking: the professionals' manual' (Ref 32).

A domestic ground level deck, terrace, pool surround etc would not normally need to be submitted to building control for approval under building regulations. However, a raised deck should be designed by an engineer in accordance with a structural code.

The principles of design for durability outlined in Section 8.1 are all of vital importance in designing timber decks. Other considerations of particular relevance include board layout, stability, resistance to wear and slip resistance. The possibility of tannin run-off (see Section 6.4.5) may also be a consideration in the choice and design of decking.

Oak is rated as having "high" movement and green oak is likely to split and distort as it dries. This can be alleviated to some extent in decking boards by making two or three approximately 3 mm deep sawcuts on the underside of each board, reducing the tendency for the board to cup or bow by reducing tension stresses. Small surface cracks or checks will still occur on the surface due to drying out when exposed to hot sun.

Spaced deck boards do not spread loads in the same way as tongued and

Figure 8.14 Green oak decking and cladding is a feature of this office building
Photo: Brocklehurst Architects

grooved floorboards so whilst a joist size, spacing and board thickness may be adequate according to strength calculations, the deck may 'feel flexible'. The solution is for the engineer to adopt a cautious design load and to apply the principles of serviceability design given in Section 5.2.2.

Using green oak boards it is essential to fix frequently along the length of the board. Joists or bearers should preferably be at 400 mm centres to ensure that the boards are held flat as they dry. This will also enhance the robustness of the structure. To reduce the effects of shrinkage across the board it is advisable to use relatively narrow boards, certainly no wider than 150 mm and preferably less. For boards 75 mm wide or less, only a single fixing is required in the centre of the board. This single fixing has the advantage that shrinkage will not result in stresses developing between fixings which may cause splitting, although there is a higher risk of distortion of the boards sideways. For wider boards, two fixings are necessary and allowance must

Figure 8.15
Top: Light galvanised mesh overlay (Tattershall Castle footbridge). Note: the cheap alternative of fixing chicken wire over boards is easily damaged and is not recommended
Above: Battens nailed to the deck
Photos: P Ross

Figure 8.16 In Crest, Drôme, France, a modern bridge superstructure made exclusively from locally-grown timbers. Capable of pedestrian, equestrian and light vehicular traffic, of 33 m main span (total length 92 m). A timber bridge was created, following the demands of the town residents and others employed locally, who called for a sustainable solution, which supports their local economy
Photo: C J Mettem

be made for the shrinkage of the board between the two fixings. Oversize holes must be drilled for the screws and it will be necessary to use screws with sufficiently large heads or add washers to ensure adequate retention of the boards (see *Figure 8.13* where a similar detail has been used for cladding).

Metal fixings for green oak should always be austenitic stainless steel or non-ferrous material of equivalent durability.

Efficient drainage of decking will depend on the width of the gap between the boards. The gap should exceed 6 mm to avoid water droplets being held by capillary attraction, and should be at least 8 mm wide to avoid dirt accumulating. A maximum of 10 mm is suggested to avoid problems with narrow shoe heels, bicycle or pram wheels, roller blades etc. Note that drying shrinkage will contribute 4 - 6 mm to the gap width and should be taken into account when the deck is laid.

Fixing boards 'heart side up' (ie convex side up) to exploit their natural tendency to cup (*Figure 8.11*) will encourage water to drain off the boards, whereas boards fixed 'heart side down' will retain water within the 'cup'.

Practical steps to reduce slipperiness are covered in 'Timber decking: the professionals' manual (Ref: 32). *Figure 8.15* illustrates some options.

8.5 Bridges and other external structures

The detailing principles for timber bridges can also be applied to other modern timber structures, including towers, jetties and marina structures, as well as timber walkways. The recommendations of this Chapter also apply in many respects to the design of other external civil engineering works, which although not discussed in any detail, usually need to provide safety alongside durability. Examples of these include road separation and acoustic barriers, revetments, cribs, and timber culverts. The long and successful record of European oak as a mining timber attests to its suitability in such applications.

Recently, timber bridges have experienced a significant revival with some spectacular timber structures (*Figure 8.16*). However the fulfilment of such large spans from simple sawn-section green oak would not be technically feasible.

Nevertheless, there is a continual demand for very short span, and often in reality quite lightly loaded structures (*Figure 8.17*), for which sawn oak is an excellent choice. The popularity of properties such as those in the care of the National Trust and English Heritage (*Figure 8.18*), annually brings millions of people across small and maybe even unnoticed timber crossings.

There are also opportunities to employ individual oak elements within the larger timber engineered structures whose major elements are glulam or other structural timber composites. However, the properties of oak commend it for situations such as decks, step treads, and as elements for the parapet or handrails.

Combining timber compositely with other materials, including steel and concrete, is also now a well-established procedure in heavy-duty structures such as bridges. However, due to its acidity and high tannin content, the use of completely green oak in such situations may be problematic. Although parts of completed bridges may be fully exposed, and hence designed for Service Class 3 (see Chapter 5), a degree of air-drying before manufacture is normally recommended for most sawn members. Indeed generally, for exposed structures discussed in this Chapter, partially dried oak in relatively thin sections (thicknesses up to about 63 mm) is more usual than the very heavy, green cross-sections associated with traditional carpentry framing.

Figure 8.17 A typical oak footbridge of modest scale on the Thames towpath, at Marlow, Buckinghamshire. The parapet design reflects a famous nineteenth century suspension bridge crossing the river nearby
Photo: C J Mettem

8.5.1 Structural forms

Not all of the structural bridge forms that are possible in timber may be resolved by using sawn green oak for the principal elements. However, for relatively small spans, and particularly for beam and bowed bridges, solutions using true heavy-framed green oak carpentry may be competitive and attractive, see for example Polesden Lacey bridge (Case study 9.11). As indicated above, there are often also positions within the structure where sawn air-dried European oak may be a suitable choice.

Figure 8.19 indicates four of the main types employed for short and medium spans in timber. Detailing is extremely important - protective design features as outlined earlier should be fully incorporated at an early design stage rather than being added as an afterthought.

Figure 8.18 The Moat Bridge, Tattershall Castle, Lincolnshire. An English oak structure recently repaired, typical of the many small bridges crossed by large numbers of visitors to properties in care
Photo: Wood Awards

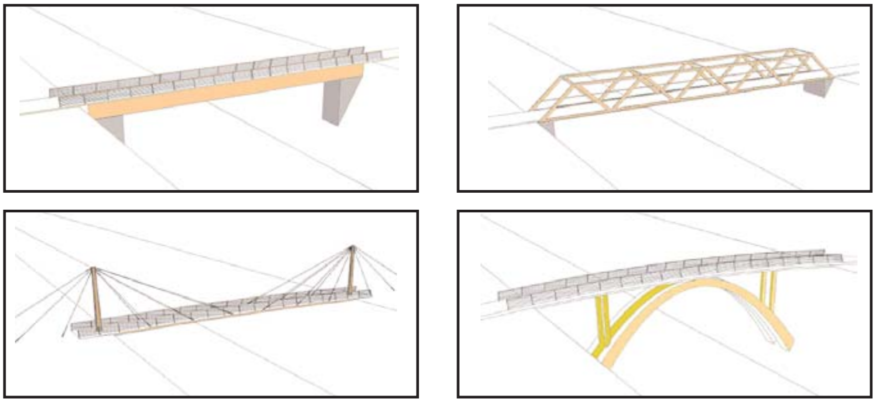


Figure 8.19 The four main bridge types commonly employed for short and medium spans in timber. Clockwise from top left: beam, truss, arch and cable stayed
Images: C J Mettem

8.5.1.1 Beam bridges

Single and multiple span beam-based designs are common, although multiple span bridges are usually calculated and built as a series of simply supported spans rather than as continuous beams. The normal structural arrangement for a simple beam bridge is with longitudinal stringers and lateral transoms, to which are added a deck and diagonal, lateral bracing. Outrigger parapet braces are a common provision, *Figures 8.20* and *8.21*. These may be strutted up from longer-than-normal deck boards. More sophisticated timber beam bridges may include stressed laminated decks, and for ambitious structures, glulam (using dried laminates) is normal for the principals, in which case the inclusion of continuous spans is more likely. Larger bridges and those having more demanding performance specifications, although they may be timber, are unlikely to include green oak.

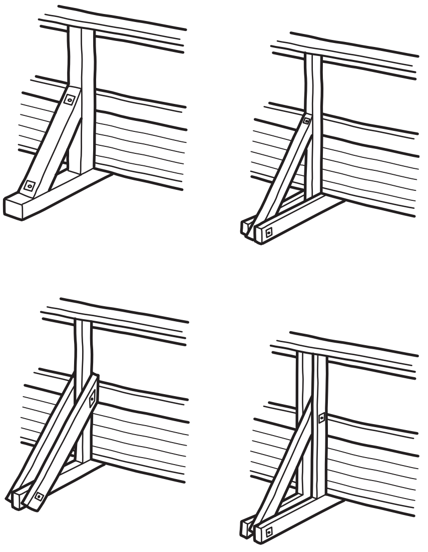


Figure 8.20 The posts of a parapet need to resist horizontal loads from lateral forces on the rails that are stipulated in design documents. In small beam bridges for pedestrian use, there are a number of alternative arrangements for the inclined struts that are often included to triangulate this effect
after Nordic Timber Council – Railings for Timber Bridges (Ref: 26)

Available material lengths have always limited the simple spanning capability of a beam bridge constructed from individual sawn timbers. Other than when using pole-beams or exceptional-sized timbers such as greenheart, this either means that splicing or finger jointing must be undertaken, or that each span is limited to about 8 m at the most. Historically, this limitation has driven bridge engineers towards many of the alternatives still in use today, such as laminating or beam-girder bridges (trusses).

Lightly bowed forms of beam bridge are achieved by bending individual timbers or laminates during fabrication. As well as the technology of glulam (Ref: 43), mechanical lamination is an option (Ref: 3) which could be applied to oak. This is an older system, but still extensively used. It requires hydraulic equipment and specialist know-how to apply the correct pressure and to make allowance for the estimated spring-back. Tightly fitting steel doweled systems are employed, both for joining the individual laminations, and also to make the node connections. A finger-joint system has been developed that also depends on mechanical fasteners rather than adhesives, making the methodology attractive for heavy-sectioned timbers that are not fully dry at the core. Stainless steel options are regularly included in these bridges, making them ideal for the inclusion of corrosive timbers such as oak.

Figure 8.21 Green oak bridge at Whitchurch, Hampshire with triangulated parapet supports
Photo: The Green Oak Carpentry Company Ltd

8.5.1.2 Trussed bridges

Straight members connected to one another by pinned nodes lead to the classic types of trussed bridge that have been described since at least the time of Palladio, if not earlier (Ref: 28). Of these, many variations were introduced from alpine Europe into North America and there transformed into systems capable of rapid mass production. Most of the traditional covered bridges both in Switzerland (Ref: 33) and in Canada and the USA were based on trusses or hybrid truss-arch constructions .

Figure 8.22 illustrates another modern light vehicular bridge type that has been widely used in several world regions. System-built and prefabricated, it has the advantages of being formed from short straight pieces of relatively thin section, as well as containing very standardised fasteners and connecting plates. The system provides spans of up to 30 m, with the capability of being launched into place using just man-power and hand-operated winches. This bridge type has been built in Chile using a durable southern hemisphere temperate hardwood known as rauli – a type of southern beech (*Nothofagus procera*). It has also been employed as a forestry bridge in Austria, where larch was the principal species involved, together with some members in oak. The standard design is a good example of the type that could be progressed more extensively in rural situations in the British Isles, using indigenous resources, including air-dried European oak.

Figure 8.22 Modern system-built light vehicular bridge, widely used in several world regions. Suitable for incorporation of strength graded air-dried European oak
Photos: C J Mettem

8.5.2 Protective design features in bridges and similar external structures

The inclusion of relatively simple protective design features increases the service-life of a timber bridge considerably. The most complete protection is from a roof, which may cover the entire bridge or only parts of the structure.

The principles shown in Section 8.1 should be followed, such as ventilated metal covers over key structural elements. Well-ventilated cladding and decking generally are essentials for good durability. There should be well-designed drip features, water shedding through sloping topped surfaces and upper edges, and the provision of positive drainage systems at kerbs and deck ends.

9 Case studies

The case studies have been selected from a very wide range of green oak structures built over recent years in the UK to demonstrate the concepts initially set out in Chapter 2 and which are then followed and expanded through the rest of the book.

In terms of structural framing, Chapter 5 (*Figure 5.5*) identified three categories of structural framing. For the case studies additional categories of historic reconstruction and exterior applications have been added.

9.1 - 9.2 Historic reconstructions

Whilst these have not been covered extensively in this book, they are a significant, but highly specialist area of green oak construction, often requiring extensive research, firstly to establish and then to mirror the original framing. They are exemplified here by the Globe Theatre in London and the roof of Stirling Castle.

9.3 - 9.4 Traditional models

These form the basis of much of the work undertaken by the green oak framing companies today, particularly for housing and for domestic-scale structures. Chapter 5 illustrates some of the forms which could provide the inspiration for such buildings and the case studies illustrate the range of possibilities in this area, ranging from a relatively modest scale house at the Mill O'Braco to the large-scale frame forming the boathouse at Abingdon School. Typically these structures use interlocking and pegged joints.

9.5 - 9.7 Modern green oak frames

Modern structures can be designed to extend the green oak framing tradition by taking advantage of developments in grading and connection techniques to create stylish and attractive buildings for a wide range of uses. Buildings in this category are designed with reference to structural engineering codes; often incorporating metal connections. The case studies selected show York Minster roof, where a modern solution was selected for reconstruction after a fire, Bedales School Theatre and a study centre for Darwin College, Cambridge.

9.8 Innovative or unusual forms

These are essentially 'one-off' structures requiring individual research and complex analytical engineering design; hence they have not been covered in detail in this book. Nevertheless, they represent a further step in the long history of development and use of green oak in construction and are exemplified by the gridshell roof at the Weald and Downland Museum.

9.9 - 9.11 Exterior uses

Finally, the use of green oak in external applications as discussed in Chapter 8, is demonstrated with case studies of the cladding at the National Maritime Museum, Falmouth, and bridges at Ealing and Polesden Lacey.

Historic reconstructions:

9.1 The Globe Theatre

Photo not available in PDF edition

9.2 Stirling Castle roof

Traditional models:

9.3 Mill O'Braco house

9.4 Abingdon School boathouse

Modern frames:

Photo not available in PDF edition

9.5 York Minster roof

9.6 Bedales School theatre

9.7 Darwin College study centre

Innovative constructions:

9.8 Weald and Downland gridshell

Exterior uses:

9.9 National Maritime Museum

9.10 Ealing bridge

9.11 Polesden Lacey bridge

Historic reconstructions:
9.1 The Globe Theatre

The story of the modern Globe began in 1949, when Sam Wannamaker, an actor newly arrived from America, visited the South Bank in London to see what remained of the original Globe Theatre – Shakespeare's wooden "O". He was dismayed to find only a plaque on a brewery wall, and as a result, set about the realisation of a seemingly impossible dream – the recreation of the Globe as a working theatre, presenting performances of Shakespeare as they would originally have been seen. The rest of his life was devoted to this cause, and although he died in 1993, he lived long enough to see the impossible made possible – two bays of the structure built, and the knowledge that the project would indeed be completed.

Figure 9.1.1 The audience gathers for a matinee performance
Photo: P Ross

In 1970, the Shakespeare Globe Trust was formed, and a professional team assembled. Initially this was made up of Pentagram Design, architects, and Buro Happold, engineers, who were later joined by Peter McCurdy as the Master Carpenter. The first Globe Theatre dated from 1599, using timber from the earlier theatre in Shoreditch. The first Globe burnt down in 1613, and was rebuilt, only to be closed down by the Puritans in 1642, and demolished soon after. Thus direct evidence of the construction was almost non-existent, and the team spent much time, aided by historians, researching various fields of information (Ref: 35).

In brief summary the investigations uncovered:

- a tantalisingly small area of the original footings (the remainder being covered by existing buildings). Nevertheless, it included an external angle and stair tower (*Figure 9.1.2*).
- an engraving by Hollar, including the second Globe, made from the tower of St Mary Overy (now Southwark Cathedral).
- the Fortune contract, a detailed description of a theatre similar to the Globe, and built by Peter Street, the carpenter of the Globe, a year later.
- surviving buildings of the period, particularly those with a polygonal plan, such as market crosses, chapter houses and dovecotes.

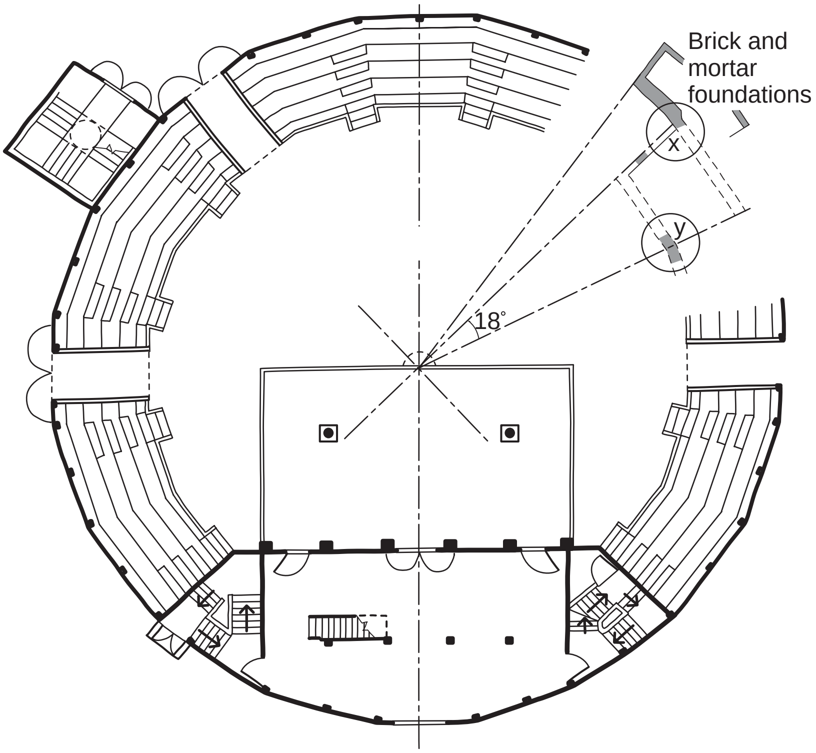


Figure 9.1.2 Plan of the Globe, with archaeological excavations superimposed. Although the exposed area was small, the changes in footing alignment at X and Y allowed the determination of the overall building diameter and gallery width, and confirmed the plan form as a twenty-sided polygon. A stair tower footing was also found, which was enlarged in the rebuild to meet current regulations
After Mulryne and Shewring (Ref: 35)

After a considerable period of research and discussion, a consensus was achieved on the reconstruction form which would best fit the available evidence. This was a twenty-sided polygon, of overall dimension 100 feet (30 m), and three storeys high (*Figure 9.1.2*). The structure is essentially a series of radial cross frames, joined by concentric floor and roof members. At the back of each frame is a single full-height post, giving robustness to the structure, while storey height posts at the front stand on jettied summer beams. There was no definitive information on bracing, but conventional bracing at high level in each storey could easily be fitted to the cross frames and rear wall. Braces fitted across the front posts would obviously interfere with sight lines, but the engineers were satisfied that the stiffness of the back wall, together with the diaphragm stiffness of the floor, would allow them to be omitted.

Polygonal buildings present jointing problems. In conventional rectangular buildings, the longitudinal members, such as the wall plate, are jointed away from the frame (*Figure 5.33*), because life is easier that way. This option does not exist for the polygonal building, and so the lap dovetail joint was abandoned, and the tie beam was run over the top of the post, with the wall plate tenoned in from either side (*Figure 9.1.3*). It was still possible to tenon the principal rafter into the tie beam, but there was no way of pegging it. Fortunately, an analysis showed that wind uplift would never exceed the dead weight, and so in this case a peg was not necessary.

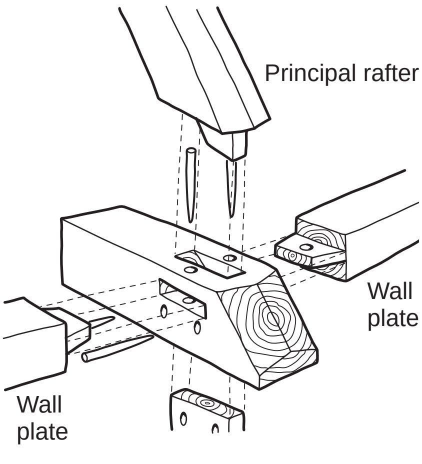


Figure 9.1.3 The jointing of the wall plates into the tie beam at roof level. It was not possible to peg the principal rafter. Note that much of the timber at the heart of the joint in the tie beam has been cut away to form the mortices
After Mulryne and Shewring (Ref: 35)

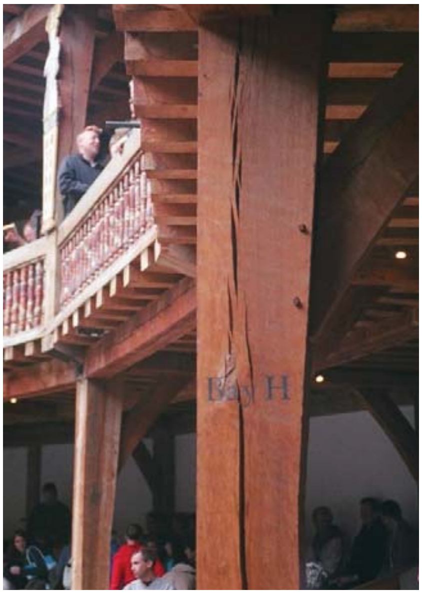


Figure 9.1.4 The major fissure in one of the ground floor posts
Photo: P Ross

Figure 9.1.5 A newel post with boxed heart showing radial fissures. The handrails, being quarter-sawn and excluding the heart, have few fissures. The polish on the top of the post is entirely due to hand contact
Photo: P Ross

The Globe, completed in 1996, stands as one of the largest green oak frames built in recent years (and, incidentally, the first in the capital since the great fire of 1666), but it is also a very public 'worked example' of the behaviour and appearance of green oak over time. The size of the frame means that most members contain boxed heart and so the front posts (exposed on all faces) can be seen to have one major fissure, and often a few subsidiary fissures (*Figure 9.1.4*). Fissures, by their nature, demonstrate grain slope and it is clear that the timber was supplied to a high specification. The ends of the newel posts show similar fissures (*Figure 9.1.5*) and sometimes an end split.

There is occasional evidence of twisting - the base of one of the posts in the north east tower has rotated slightly (*Figure 9.1.6*), but the width of the end tenon on the post will prevent further movement. Typical wedge-shaped gaps can be seen at the ends of the wind braces (*Figure 9.1.7*), caused by shrinkage in the brace width. On a small contract this would also have opened up a gap between the brace and the infill render, but the Globe, due to its size and funding requirements, was built on a relatively long timescale. This meant that many of the framing members had undergone most of their shrinkage before the panels were rendered. Nevertheless, a small amount of making good and repainting was necessary.

Figure 9.1.6 Slight twist at the base of one of the posts in the north-east tower
Photo: P Ross

Figure 9.1.7 The typical wedge-shaped drying movement at the ends of the wind braces
Photo: P Ross

While the occurrence of fissures in the frame members could be regarded as the character of green oak construction, it was felt that they would be less acceptable in the stage columns - two of the largest pieces in the assembly, with elaborate surface decoration (*Figure 9.1.8*). In order to minimise the tendency to fissure, McCurdy and Co drilled a hole down the centre of each column (on the principle shown in *Figure 4.6 C-E*). To date, this has effectively maintained the integrity of the 'marbled' surfaces.

Figure 9.1.8 One of the two stage columns, looking up at the 'heavens'. They are painted to resemble marble and topped with elaborate Corinthian capitals. The stage as a whole, literally the focus of the theatre, is a riot of 'early Renaissance' decoration
Photo: P Ross

The natural weathering of the exposed oak surfaces has produced a range of colour changes. The external frame faces, most exposed to sun and rain, have changed to a silver-grey (*Figures 9.1.6 and 9.1.7*), while the interior timbers, afforded varying degrees of weather protection, have been affected in proportion to their exposure: the posts at the courtyard level and the floors retain virtually their original colour (*Figures 9.1.1 and 9.1.4*). However, the timber close to the ground in the splash zone rapidly darkened (*Figure 9.1.9*). Contact with iron (and rain) also produces marked staining (*Figure 9.1.10*).

It is also not surprising that the capacity audiences leave their mark; the newel posts (*Figure 9.5*) carry a polish which is solely due to hand contact, and the temptation for the 'groundlings' (members of the audience who stand in the open area in the yard) to squat on the sill beam of the courtyard is also recorded on the planking above. (*Figure 9.1.11*).

Thus the oak responds, and will continue to respond, to the effects of the weather and the audiences which fill the theatre over the summer months. Any potential client for a green oak structure who wishes to judge the appearance of an oak frame as it matures could do no better than to visit this simultaneously ancient and modern building, which received a Carpenters' Award in 1997.

Figure 9.1.9 Timber in the splash zone darkened rapidly
Photo: P Ross

Figure 9.1.10 Staining from the iron nails in the door
Photo: P Ross

Figure 9.1.11 The sill beam, showing water marking and darkening on the planking above where 'groundlings' squat on the beam
Photo: P Ross

Credits:

Client: The Globe Theatre Trust
Architects: Pentagram
Engineers: Buro Happold
Framer: McCurdy and Co.

Historic reconstructions:
9.2 Stirling Castle Roof

Stirling Castle, dating mainly from the fourteenth century, is set in a commanding position overlooking the River Forth, 37 miles from Edinburgh. The Great Hall was completed around 1502, with sandstone walls supporting an oak roof of 11 m span and 42 m long (*Figure 9.2.1*). Towards the end of the 1700s the Great Hall was turned into a military barracks, the roof was replaced and the space subdivided with intermediate floors. The army finally departed in 1964, following which the Historic Building and Monument Directorate, subsequently Historic Scotland, gradually restored it as a scheduled Ancient Monument and opened it to the public (*Figure 9.2.2*).

Photos not available in PDF edition

Figure 9.2.2 The south east face of the Great Hall in the 1960s (top) and in 1999 (bottom)

Figure 9.2.1 Stirling Castle replacement roof

In 1996, Carpenter Oak and Woodland Co Ltd was appointed to re-build the roof as a replica of the original. For large projects such as this, the procurement process needs to be understood, with the possibility of long lead-in times built in to the programme. For the Great Hall, Historic Scotland wanted to source local Scottish oak and this required a two-year lead-in period with Forest Enterprise being commissioned to source suitable oaks in spring 1995. Setting aside agreed samples early in the selection and grading process proved invaluable in providing an objective guide to what was and was not acceptable.

Although no physical trace of the original timbers remained, corbel positions and wall head levels could be identified. Designs for the hammerbeams were not entirely speculative; contemporary drawings (1719) by the Board of Ordinance survive, and it was known that the jointing arrangement was similar to a surviving roof at Edinburgh Castle Great Hall (Figure 2.7), also constructed around 1500, although of smaller span and lower pitch. From this information, a roof design was prepared which is unusual in its form. Every fourth truss is a principal (*Figure 9.2.3* bottom) with hammerheads supporting an upper collar on doubled principal rafters. The collar in turn supports a top central purlin set on a crown post. The three intermediate trusses (*Figure 9.2.3* top) between each pair of principals consist of two long rafters with scarf joints, braced by a top collar and intermediate strutting from the lower purlins. In all, there are 57 trusses and a total of 1328 members.

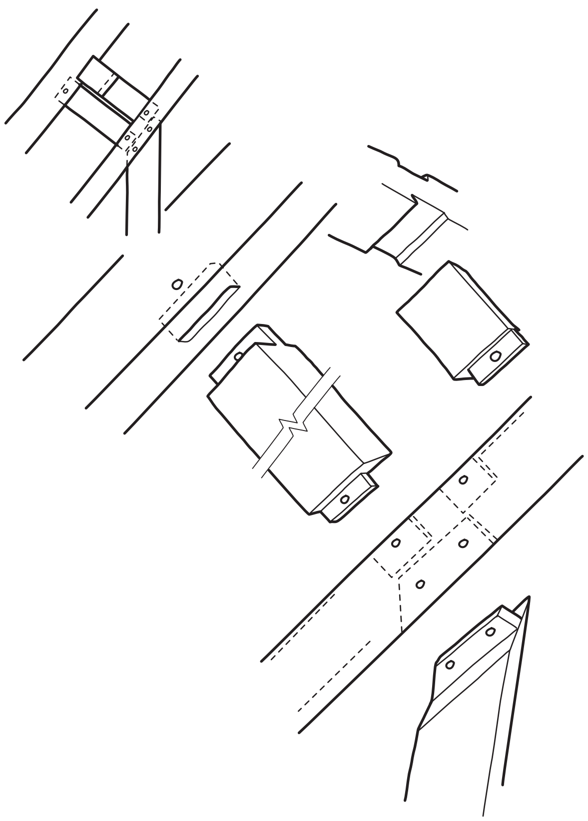
Photos not available in PDF edition

Figure 9.2.3 Principal hammerbeam (bottom) and intermediate trusses (top)

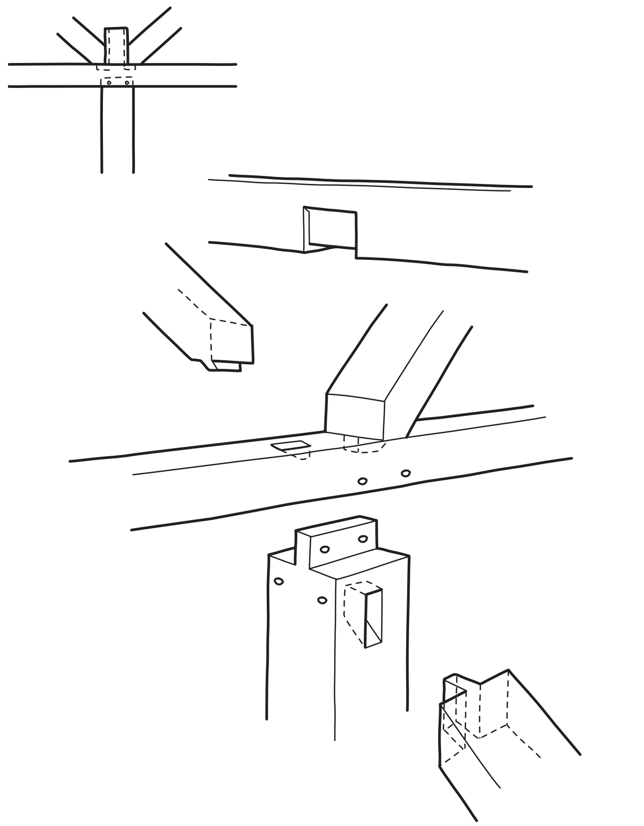
Major complications in the design arose from the results of the site survey. The west wall head formed a shallow curve, giving a variation in span of 450 mm. To consolidate the masonry, 400 mm square reinforced concrete beams were cast on top of the walls, following the existing shape. As the aim of the frame setting-out was to achieve a straight ridge, the east face was set at a constant pitch, while the west face varied to follow the line of the wall head. Since the profile of each truss would therefore be slightly different, it was decided (as at York Minster, Case study 9.5) to cut the whole frame over full-size layouts marked on the floor.

In addition, the survey of the corbel block positions revealed that the original trusses were not set square across the span, but skewed, first one way and then the other, in progression down the hall. There was no obvious explanation, but the positions would clearly have to be accepted. This made it particularly difficult to determine the lengths and mortice positions for the six flights of purlins, and so a computer model was set up, taking all the site variations into account and generating points in space for the purlin/truss connections. Only then could any sort of plan be made for actually laying out the trusses. Given the size of the trusses, the work had to be split into manageable sections – the principal truss dividing into the upper section above the collar, and the two side assemblies. The intermediate trusses were split into two sides, plus a collar which could be separately framed into each side. Precision in the setting-out was essential, as no truss would be assembled as a whole before the final erection on site.

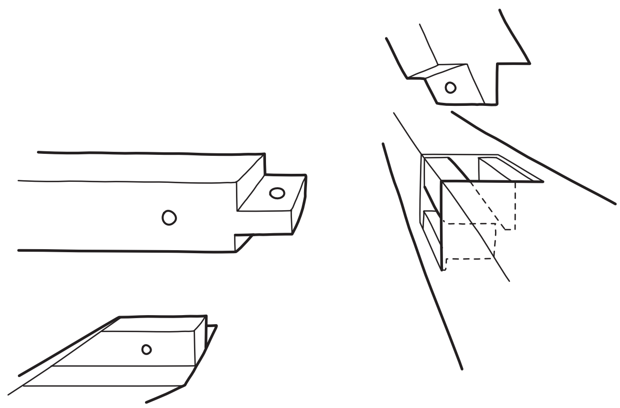
The fabrication of the components took about five months, during which time the building was given a temporary roof, which, because of the very exposed location, over-spanned the two wall heads, allowing the roof and subsequent finishes to be erected under cover.



Junction of rafters / lower purlin / hammer post



Principal truss: Junction of topmost purlin/upper collar



Intermediate truss / purlin connection

Figure 9.2.4 Stirling Castle joint details
Drawings after G McMorran

Access to the site presented special problems. There was no position for a tower crane, so no prefabricated assemblies could be lifted into place. Indeed, the medieval confines of the castle were such that the timber had to be palletted to fit on to a purpose-built truck only 1.8 metres wide.

The final lifting and erection of the roof was an entirely manual operation. The temporary roof had been fitted with five hoisting beams running the full length of the building; each beam was fitted with a trolley, which ran on the bottom flange, carrying a chain block. Naturally, the chains were very long, but it was a simple and safe method of lifting the material. After a while, a rhythm of assembly was established, and the roof was completed in twelve weeks.

The assembly acts as an arch, rather than a truss, and so the weight of the roof as a whole exerts an out-thrust on the wall heads. Thus, as an additional precaution, six 17 mm stainless steel tie rods were added at this stage, linking the concrete edge beams. With these in place, the 25 mm oak sarking boards were laid, and the whole assembly covered with slates.

Photo not available in PDF edition

Figure 9.2.5 The completed interior in 1999

Credits:

Client: Historic Scotland
Green oak roof framing: Carpenter Oak and Woodland Co Ltd

Traditional models:
9.3 Mill O Braco House

The house at Mill O Braco, Aberdeenshire, was designed for his parents by Andrew McAvoy of Bl@st Architects. The starting point was an existing long barn with massive stone walls and small windows which faced onto a courtyard. The interior was cleared out to leave a basic shell, which was then extended to the west by a new timber framed wing at right angles to the barn, following the fall of the land, and capitalising on the views in this direction of the distant Benachie hill.

Figure 9.3 1 External view showing the original barn and new wing
Photo: Bl@st Architects

The new wing is based on five oak frames, giving the appearance of crucks, but which are better described as arch-braced collar trusses (*Figures 5.19 and 9.3.2*). The first three frames at the lower level enclose a single full-height principal space, open to the ceiling and furnished at the west end with a hearth and chimney. At the third frame, a higher roof continues to meet the barn, and a slit window between the two roofs allows views out from a gallery at the upper level, set over a dining area below (*Figure 9.3.3*).

Figure 9.3.2 above: The fully glazed south wall, right: View from the gallery, far right: looking west at the lower level
Photos: Bl@st Architects

Figure 9.3.3 The upper gallery with views through the change in roof level
Photo: Bl@st Architects

Both the roof and the walls are set outside the frame and are finished internally with painted plasterboard. The simplicity of the finish allows the form of the frame and the surface texture of the members to be clearly seen. Fenestration is primarily to the west and south, with window joinery in clear Douglas fir.

Figure 9.3.4 Exterior view of the new wing; the oak frame is enclosed within the building
Photo: Bl@st Architects

Credits

Architects and oak frame design: Bl@st Architects
Oak frame manufacturer: Carpenter Oak and Woodland Ltd (Scotland)
Oak frame engineer: Ian Payne

Traditional models:
9.4 Abingdon School Boathouse

Figure 9.4.1. The completed frame
Photo: Marc Nurton, Abingdon School

Figure 9.4.2 Interior, showing the racking for eights
Photo: Abingdon School

Photo not available in PDF edition

Figure 9.4.3 The international framing rendezvous

Space was urgently needed to store top quality racing boats (each eight being nearly 18 m long) (*Figure 9.4.2*), over fifty canoes, plus equipment such as oars and paddles, which were being kept in dilapidated sheds.

The proposal to design and construct a green oak frame arose after parents and Friends of the Abingdon School Boat Club (FASBC) offered to raise the first £50,000 for a new boathouse, and found that the school might be able to provide a further £280,000. However, with an initial cost estimate of £575,000 for a more conventional building, this still left a considerable shortfall. Fortunately, timber frame enthusiast, Norman Guiver, recognised that with contributions in kind from other parents, and the economical methods of green oak framing, the challenge could be met.

The major savings to the design, framing and raising work were realised through the Carpenters' Fellowship and its ambition to emulate the Timber Framers Guild of North America which regularly arranges framing events, in keeping with their national tradition of barn raisings. The requirements of the FASBC were seen as an ideal project, so the idea of an American-style "Rendezvous" was adopted. In the event, with help from the Timber Framers Guild, there were 70 American, Canadian, Danish, English, French, German, Irish, Scottish and Welsh framers engaged, with school pupils, staff and parents working alongside (*Figure 9.4.3*).

It was known at an early stage that the new building would have to be sympathetic to the site, a sensitive environment in the flood plain of the River Thames. Demonstrating a connection with similar existing timber buildings in the area, such as the Tithe Barn at Drayton St Leonard, very close to the school, meant that the aisled oak frame solution was most welcome, both for local residents and for the planning authority.

It was important to have a good-sized covered balcony at first floor level, to view the river and to observe crews in training. Significant design implications arose through the need to support the long boats, and to store the lengthy and valuable oars in an upright position. No internal cross-frame braces could be accepted in the central arcade, so this led to an aisled arrangement which could also accommodate a workshop, toilets and stores. These could be opened to the roof in certain bays, so that oars could be racked. The longitudinal bay spacings, which vary in size to accommodate the boat riggers, worked in well with typical timber barn bay lengths and oak framing sizes. A first floor area houses areas for training, lectures and social events.

The footprint is approximately 58 x 100 feet, since the design was in Imperial units (17.4 m by 30 m), in nine bays. The roof extends over the open gable balcony, accessed by a large oak staircase. The frame draws on simple carpentry techniques found throughout timber frame history, particularly examples within the lowland area of England.

Photo not available in PDF edition

Figure 9.4.4 Part of a principal roof frame being checked during pre-assembly in the framing yard

The main arcade has a curved queen post truss, supported by jowl posts and curved cross-frame braces. These posts are joined to the main jowl posts by an interrupted tie beam and principal rafter. The arcade jowl posts carry the central top plate, and support the floor beams which carry housed oak joists for the arcade first floor. The aisle cross-frames comprise jowl posts, ties and principal rafters, attached to the arcade posts. There are stud wall frames incorporating curved braces to parts of the first floor, the arcade ground floor, and the gable ends. Typical details are shown in *Figures 9.4.4 - 9.4.6*.

Photo not available in PDF edition

Figure 9.4.5 Driving pegs - note also the through-tenon and wedge

Photo not available in PDF edition

Figure 9.4.6 A top plate splice – ideally always located close to, but not within, the post head tying assembly

The ‘English Tying Joint’, which connects the tie beam, plate and jowl post by mortice and tenons, with a half dovetail lap joint between the tie and plate is shown in *Figure 9.4.7*. All the braces are of curved stock, air-dried before use, with the shaping parallel to the grain. The jowl posts are cut from the lower end of a tree butt, with the jowl sawn from the root stock flare in order to maintain an appropriate direction of grain. This is necessary to withstand the forces within this complex joint.

Photo not available in PDF edition

Figure 9.4.7 The ‘English Tying Joint’ is the complex at the head of the jowled post
Photo: Russell Ley © 2003

The main roof (*Figure 9.4.8*) is supported by trenched purlins and curved wind braces above the principal rafters of the arcade trusses. The aisle roofs are also supported by trenched purlins. There is a vertical break between the aisle roof and the main roof, at the arcade wall line. The common rafters are in Douglas fir, and have a nailed birdsmouth joint at the aisle wall top plate connection.

A great deal of the carpentry involves simple mortice and tenons, although half dovetail wedged through-tenons are used where there is tension within the construction. This occurs at the interrupted tie-to-post connections, and at the floor beam to main jowl posts. All of the joints are held with riven oak pegs, whose mating holes are draw-bored between each tenon and mortice.

Figure 9.4.8 The bare frame nearing completion
Photo: Ginette Guiver

The aim of involving teamwork in the frame raising influenced the entire design concept. Approximately 60% of the frame was prepared at The Timber Frame Company’s workshops and erected by the company. The remainder was cut and jointed at the school site, by the international gathering of framers. The “event frame” was raised over a hot weekend in July 2003, with 60 volunteers. A traditional 40-foot gin pole, rope and tackle was employed, rather than a crane. This meant that non-professional volunteers could safely be involved in raising the frame (*Figure 9.4.9*).

Matthew Pinsent CBE formally opened the boathouse, on 23 October 2003; it has been a great success, further stimulating the rowing club and all connected with the school and the Carpenters’ Fellowship.

Photos not available in PDF edition

Figure 9.4.9 Raising the frame

Some facts and figures

- At 100' x 58' x 28' high, this is one of the largest oak timber framed buildings erected in the UK in living memory.
- It contains 1200 individual timbers with 2250 joints, fixed with 2800 pegs.
- The total weight of jointed oak in the building is 59 tons and it took 5200 man-hours to cut the frame.
- The roof comprises 14,000 10 x 20" slates and the building is clad with 460 m^2 of western red cedar.
- The rafters and the 1½ inch thick tongued and grooved floorboards are in Douglas fir.
- The boathouse accommodates 580m of racing boats and 170m of canoes, plus 240 oars & paddles.

Credits

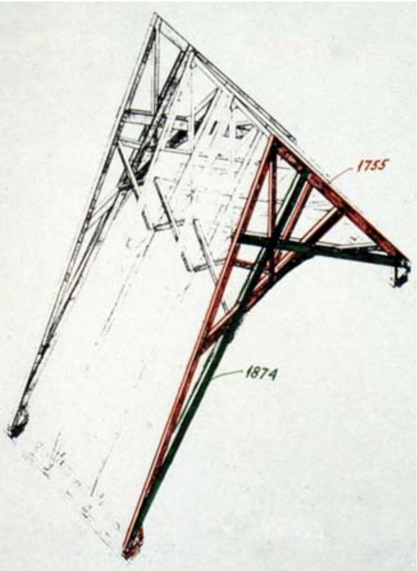
Project manager: Norman Guiver, Carpenters Fellowship Chairman, with architectural input by a parent architect
Frame design and drawings: Jim Blackburn of The Timber Frame Company Ltd
Frame supplier: The Timber Frame Company Ltd
Three dimensional images: Cameron Scott of Timber Design
Structural engineer: Nigel Challis
Raising engineer: Grigg Mullen, Timber Framers Guild
Client: The Abingdon School

Modern frames:

9.5 New roof to the South Transept of York Minster

In July 1984, despite the best efforts of the Fire Brigade, a fire completely destroyed the roof and vaults of York Minster's south transept. The masonry walls of the transept date from the thirteenth century, originally with an open timber roof resting on an aisled arcade with a small clerestory. The vault was not introduced until the fifteenth century, presumably as a 'medieval makeover' to bring the transepts into line with the rest of the Minster, which was vaulted. A stone vault could not be built, as the masonry was not prepared for it, so the carpenters took over and constructed a light-weight timber ribbed vault, much as can still be seen in the north transept opposite.

Following the fire, the Dean and Chapter commissioned Ove Arup and Partners to assist the Surveyor of the Fabric and the Superintendent of the Works in the design and construction of a new roof. The form of the original trusses was recorded: oak kingpost trusses with extended rafters of the eigh-teenth century, repaired in the nineteenth century with overlaid bracing pieces to resist the tendency to spread (*Figure 9.5.1a*). The design team considered that it would be too pedantic to replicate a repaired structure and so oak trusses were proposed, which, while following the original spacing and outline, were in a contemporary form (*Figure 9.5.1b* and *c*). Each truss has two scissor arms, simply lapped and bolted to a top and bottom collar.



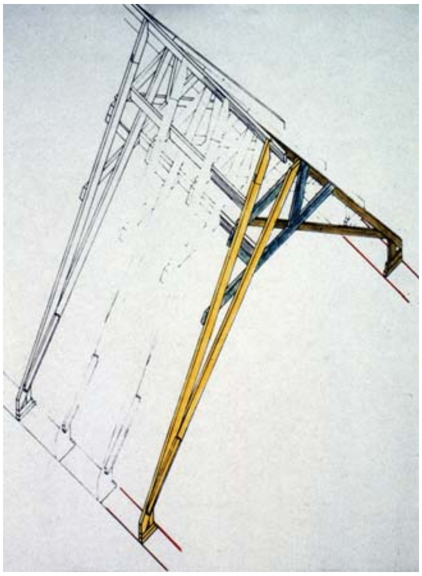


Figure 9.5.1 a and b
a, left: The original roof structure: king post trusses with considerably extended rafters (shown red), dating (as a replacement for the medieval roof) from the eighteenth century. In practice, the trusses acted as arches, and in the nineteenth century it was found that the wall masonry had moved out by around 200 mm due to their thrust. In 1874, crude braces in softwood (shown green) were overlain in an attempt to form scissor trusses
b, right: The new roof truss design, based on lapped timbers throughout: two scissors (shown yellow and brown) each side of a top and bottom collar (shown blue)
Drawings : © ARUP

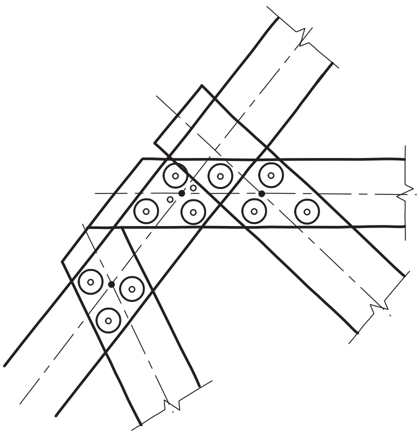


Figure 9.5.1c The top frame joint, with offset intersections. Bolts only have to connect two timbers together

The profile of the truss was determined by the line of the roof above, and the vault below (*Figure 9.5.2*). The replacement roof and vault would both be heavier than the originals, and so it was essential that the new structure was a true truss, rather than an arch, to minimise the out-thrust on the rather slender clerestory mullions below. Thus the connections between the timber members were made with bolts engaging with two shear connectors (*Figure 9.5.3*), for the following reasons:

- bolts, being a shear connection, can transfer either tension or compression in the timber members
- shear connectors almost eliminate the slip experienced with plain bolts
- the shear connectors remain embedded in the timber during drying distortion, whereas split-ring connectors could lose their bite (*Figures 9.5.4 and 9.5.5*)
- the bolts can simply be tightened on a periodic basis to take up any cross-sectional shrinkage of the timber.

Figure 9.5.2 The south face of the central tower immediately after the fire, showing the dripstone which sets the line of the roof, and below it, the line of the vault
Photo: P Ross

The trusses were made at ground floor level under a movable cover (*Figure 9.5.6*), and assembled over a full-scale outline drawn on the floor. Slight variations in the basic profile were needed along the length of the transept to match the line of the stone, which had 'barrelled' outwards by 200 mm under the out-thrust of the former roof.

When four trusses were complete, the workshop cover was rolled back, the trusses raised into the vertical, and then lifted into position by means of a large mobile crane brought to the site for the day (*Figure 9.5.7*). The roof itself was protected from the weather by a cover in three sections, mounted on cantilevered rails, which could also be rolled aside temporarily to allow the trusses to be placed. (When calculating the weight of a green oak assembly, for example for craneage purposes, it should be remembered that green oak is roughly the same density as water (10 kN/m^3) only dropping to 8 kN/m^3 on drying out). With all thirteen trusses in position, the roof deck and lead covering could be laid. The gradual build-up of out-thrust at the frames' feet was dissipated by means of the screw thread release shown in *Figure 9.5.8*.

Photos not available in PDF edition

Figure 9.5.3 A bolt with two back-to-back shear connectors

Figure 9.5.4 Two offcuts of timber, showing how drying distortions could result in gaps between the 'contact' faces of up to 12 mm, which would considerably reduce the capacity of split ring connectors

Figure 9.5.5 The scissor straps before assembly, showing the double shear connectors which will eventually be back-to-back on the same bolt. The connectors move with the timber they are set into, and do not lose strength if the timbers distort while drying
Photo: P Ross

Figure 9.5.6 The temporary covered workshop set up on the north side of the nave. The plywood floor is painted white and the truss profiles drawn on it. In the photograph, two trusses have been fabricated and stacked to one side by lifting with shear legs
Photo: P Ross

Figure 9.5.7 Lifting four complete trusses in one day required a crane with a lifting capacity of four tonnes at a twenty metre radius, but this was an economic alternative to dismantling and re-erection
Photo: P Ross

Figure 9.5.8 The east truss legs rested on a sliding bearing and were restrained by a threaded rod engaging with the upstand arm of a cleat bolted to the masonry. As the load of the roof boards and lead covering were applied, the leg restraint was gradually released by unscrewing the nuts in sequence, a quarter-turn at a time. Most of the out-thrust was dissipated, leaving the scissors acting as true trusses
Photo: P Ross

Figure 9.5.9 left: a section of original oak rib, which, before the fire, was some 350 mm deep. Drawing the trunk outline from the curvature of the growth rings indicates that it was around 1.5 m in diameter.
right: a section of replacement oak rib made up of four laminations, 75 mm thick, grooved for loose tongues. They were kiln dried (which for this thickness took six months) and assembled with a urea formaldehyde adhesive (and the occasional bolt for peace of mind)
Photo: P Ross

The truss bolt heads were recessed and covered with timber pattresses, giving the trusses a one-hour fire survival time. They were removed after a period to tighten the nuts, but in many cases the distortion shown in *Figure 9.5.4* maintained the tension in the bolt.

The ribs of the original vault were of solid oak, curved and up to 6m long, undoubtedly cut green from trees of stupendous proportions (*Figure 9.5.9*). Strict replication of such timbers was obviously not feasible, but the technique of gluing together kiln-dried laminations allowed new ribs to be re-created to the original profiles (*Figure 9.5.10*). The new ribs were cut to length and tenoned into the bosses, which were also made by gluing together oak strips (*Figure 9.5.11*). The arch form of the vault (*Figure 9.5.12*) ensured that it could easily stand by itself, but additional support was also given by ties from the trusses above.

The webs were infilled with plaster on stainless steel mesh, giving the vault a one-hour fire resistance – a considerable improvement on the original 12 mm wooden planks. A final decoration scheme, including much gold leaf on the bosses, produced a 'masonry' vault (*Figure 9.5.13*) matching the high vaults in the nave and choir, which while appearing to be masonry, are in fact, all of timber.

The work was finally complete in 1988 and received the Hardwood Prize in the Carpenters' Awards, 1989.

Figure 9.5.10 Assembled ribs, some six metres long
Photo: P Ross

Figure 9.5.11 The assembly of the vault, with ribs tenoned into bosses (also made from oak strips, brick bonded to keep the grain in one direction out of consideration for the carvers)
Photo: P Ross

Figure 9.5.12 The relationship between the vault and the trusses
Photo: P Ross

Photo not available in PDF edition

Figure 9.5.13 The completed vault, seen from the crossing

Credits:

Client: The Dean and Chapter of York
Surveyor to the Fabric: Charles Brown
Superintendent of Works: Robert Littlewood
Structural Consultant: Ove Arup and Partners

Modern frames:
9.6 Bedales School: Olivier Theatre

Figure 9.6.1 Bedales School Theatre
from top: Exterior
Photo: P Ross
Foyer gallery access
Photo: P Ross

Figure 9.6.3 Balcony support
Photo: P Ross

Bedales School, near Guildford, Surrey, has been known for its academic and artistic achievements since its foundation in the late nineteenth century. In 1993, the governors decided to commission a new theatre for student performances from the Oak Design Group – a partnership between Feilden Clegg Bradley Architects and Carpenter Oak and Woodland – with a brief to respond to environmental concerns, in particular the use of natural ventilation and environmentally 'friendly' materials (*Figure 9.6.1*).

The school already possessed several timber framed structures, including the Grade 1 Listed Library of 1921 in an Arts and Crafts style with traditional pegged joints (*Figure 2.9*).

For the theatre, the design group proposed another green oak frame, but one in a contemporary idiom, using metal-assisted joints. The building form is essentially in three parts – a central auditorium, with an entrance foyer to one side and backstage facilities to the other (*Figure 9.6.2*).

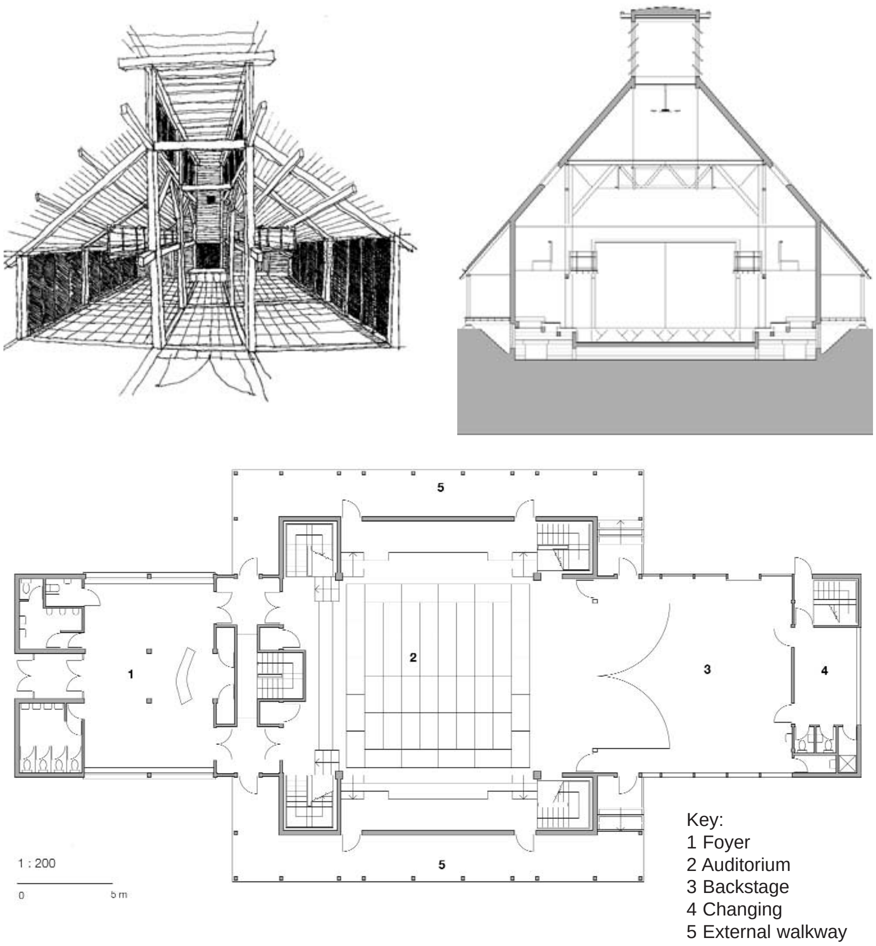


Figure 9.6.2 Bedales School Theatre: perspective, section through auditorium and plan
Drawings: Feilden Clegg Bradley

The auditorium is square in plan, with a total seating capacity of 300, divided between the ground floor level and a gallery on three sides. The superstructure main frame rests on four substantial corner posts linked by Warren trusses, which support the pyramid roof above, and (by means of steel drop rods) the front edges of the balconies below (*Figure 9.6.3*).

The four principal Warren trusses which support the roof over the central area ingeniously combine details from different periods. The truss form generates compression and tension forces in the members, which are nevertheless set in one plane and connected by means of steel flitch plates (*Figure 9.6.4*).

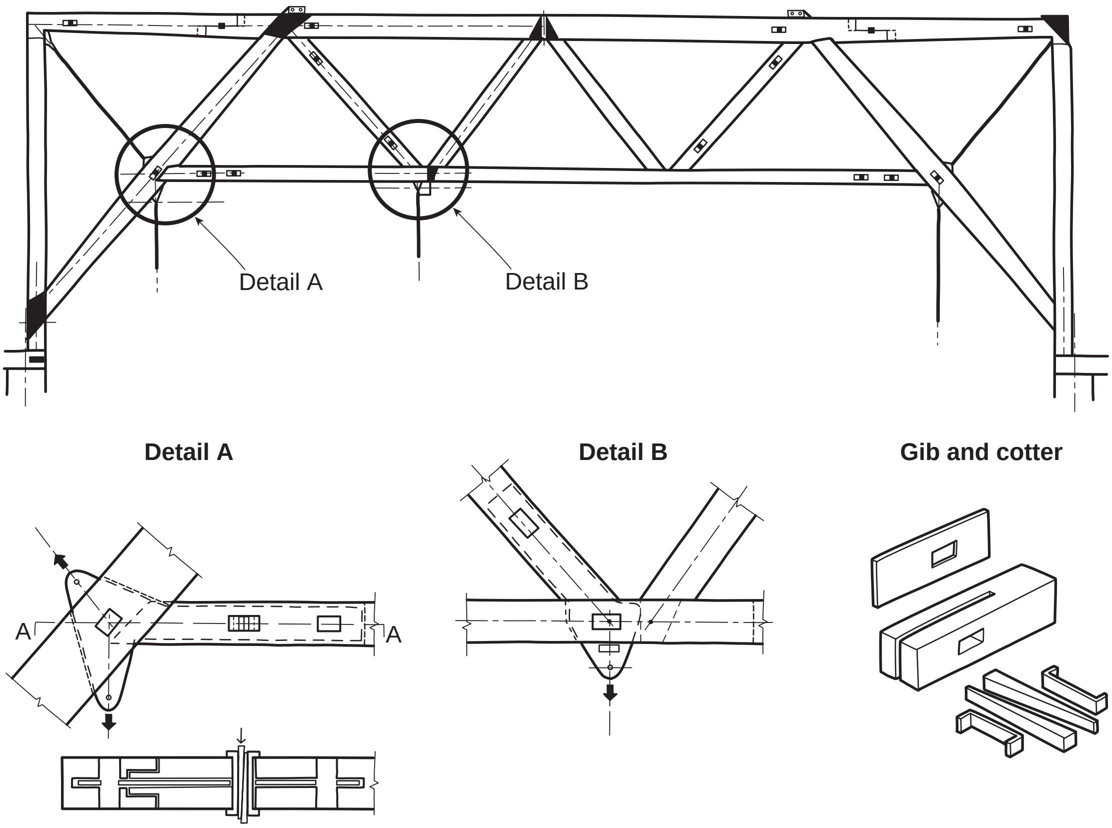


Figure 9.6.4 Warren trusses and joints
Photo: P Ross

Joint A is the most complex; here the centre lines of all the members are arranged to intersect, avoiding secondary bending moments due to eccentricity. The two tension rods connect directly to the flitch plate, while the bottom tie is connected by means of two gib and cotter joints. Although these joints were traditionally applied to splice plates they work equally well on a central flitch, and wedge action allows the joint to be drawn up tight as the compression diagonal dries.

Joint B is internal, with relatively minor loads in the diagonals. For this reason, the intersection points can be moved apart, as is done for most traditional trusses. The compression diagonal is connected by a simple mortice and tenon, while gib and cotters are again used to connect the tension diagonal and the bottom tie to the flitch plate.

Credits:

Architects: Feilden Clegg Bradley Architects LLP
Engineer: Ian Duncan, Structures One
Fabricator: Carpenter Oak and Woodland

Modern frames:
9.7 Darwin College, Cambridge: Study Centre

Darwin College was established in 1965 as the first post-graduate college in Cambridge. It occupies a narrow twisting site between Silver Street and the river (or more correctly, at this point, the Mill Pond), which includes the original family house of Charles Darwin. In 1990, the College held a limited competition for the design of a new Study Centre, on land next to the house. The aim was to create a building which housed a library and computer rooms, but which above all, provided a pleasant working environment for the post-graduates.

Figure 9.7.1 The Silver Street elevation with a wall of reclaimed bricks set in lime mortar. The lantern ventilator can be seen in the distance
Photo: P Ross

The winners, Dixon and Jones, architects, with Ove Arup and Partners as their engineers, proposed a building in traditional materials – roofs of slate and lead, a lower structure in brick, topped with a timber frame, and stone floors. The site presented particular problems; apart from the narrowness (only 6 – 8 metres), it was at the noisiest point in Silver Street, where tourist buses pick up and put down. The design response was to create a low solid wall along this frontage, set to a gentle curve following the back-of-pavement line, with a narrow clerestory of fixed glazing over (*Figure 9.7.1*). A pitched roof rises over the two-storey accommodation on the river side, with computer rooms below and the main study area above, giving views over the river and to the opposite bank. The necessary width for this area is obtained by cantilevering out over the water, with a neat reference to the original Darwin house (*Figure 9.7.2*).

Photo not available in PDF edition

Figure 9.7.2 The river elevation 1994

Since the site was in the heart of Cambridge, the planning application was contentious, and it took over three years for permission finally to be given in 1994. The architect's competition proposal for the timber elements was in softwood, but it was also feasible to consider the use of green oak. The architect was enthusiastic, as this would give a unity to the timber, used both within and without the building. The structural members included the main posts (250 mm square), the principal beams under the river clerestory (250 x 100 mm) and the rafters (250 x 75 mm) (*Figure 9.7.3*), all of which were pre-purchased by the College to give a three-month lead time before they were used on site. As a condition of the purchase, it was agreed that the timber would be kiln dried for that period. The posts were put aside, being far too large for kilning to be of any effect; the engineers' main concern was for the long (up to 7 m) rafters, and the possibility of excessive creep deflection while drying in situ. The beam members, although 100 mm thick, were treated to a 'free ride' in the kiln for that period.

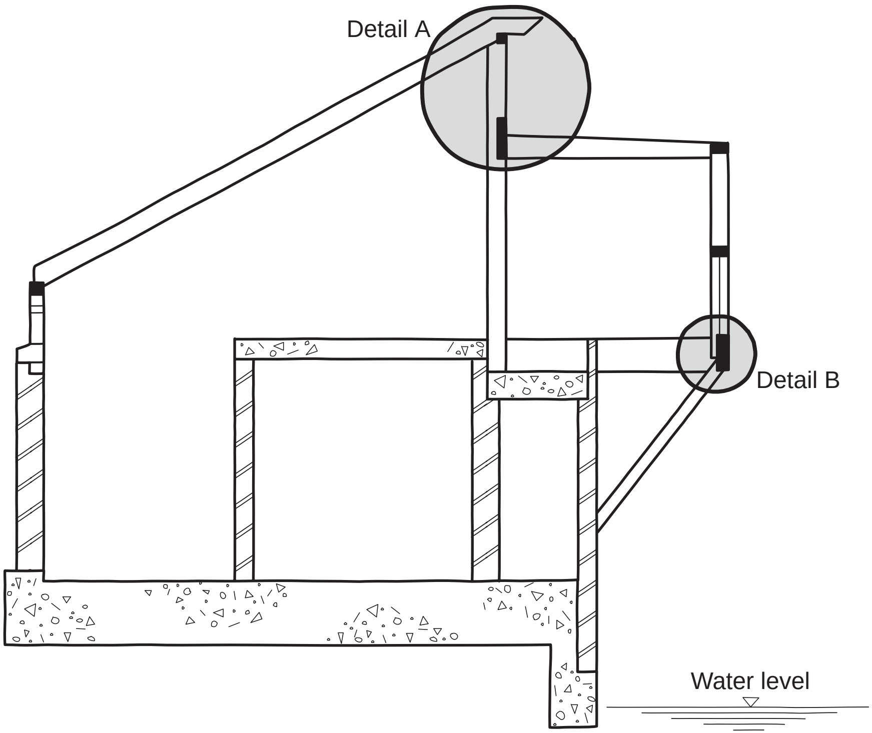


Figure 9.7.3 Section through the building

The kilning significantly reduced the moisture content of the 75 mm material, achieving around 30% at the centre, from readings originally of well over 40%. Little reduction was achieved for the 100 mm material, confirming 75 mm as the upper limit of effectiveness for kiln drying oak. The joinery components, being of much smaller girth, dried down to 15 – 20% within the same period.

The connections between the timber members, all in austenitic stainless steel, were detailed so that they could be tightened as drying took place (*Figure 9.7.4*). The design sought to avoid the conventional appearance of bolt heads, or the false suggestion of a dowel where the head had simply been recessed and plugged. They were based on a countersunk bolt head recessed into a washer, itself recessed flush with the timber; in effect, scaled-up versions of furniture fixings.

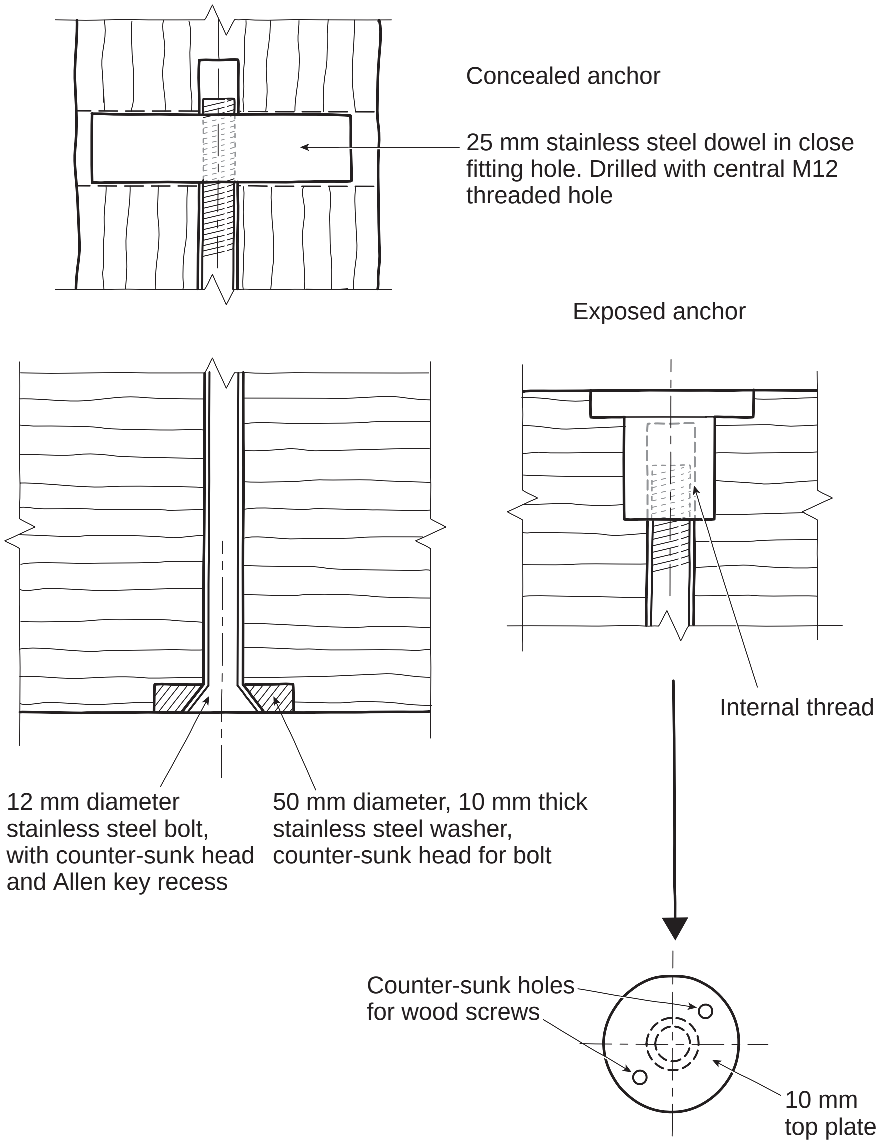


Figure 9.7.4 Connection details

The rafters have a high (25 – 30) span/depth ratio, and to make them work with green material they are designed to act compositely with a two-layer plywood deck, using mechanical fasteners. This detail also reduces deflection, and the extra weight is useful in relation to noise reduction from Silver Street. They have shown very few drying fissures, since they generally do not include heart. The roof fixings have held them effectively to line and there is no undue sag. The posts, which inevitably contain heart, have fissured prodigiously (the College having been informed before the event) (*Figure 9.7.5*). The long principal beam below the river side clerestory has alternate spans of 4.6 m and 1.1 m, and carries the load of the roof (*Figure 9.7.7*). A solution which avoided traditional forms used a double beam of 250 x 100 mm sections, one over the other, with staggered butt joints, and joined together by vertical bolts which could be tightened as the timber dried.

Photo not available in PDF edition

Figure 9.7.5 Interior showing the clerestory windows above the principal beam with the recessed connectors, all supported by fissured posts

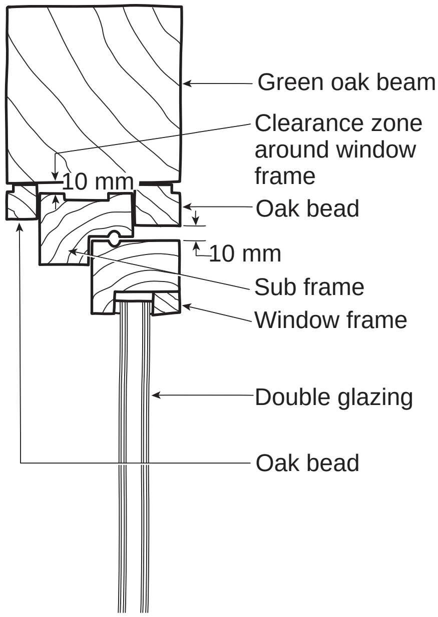


Figure 9.7.6 Detail at clerestory window head. All joinery and fittings made from seasoned oak

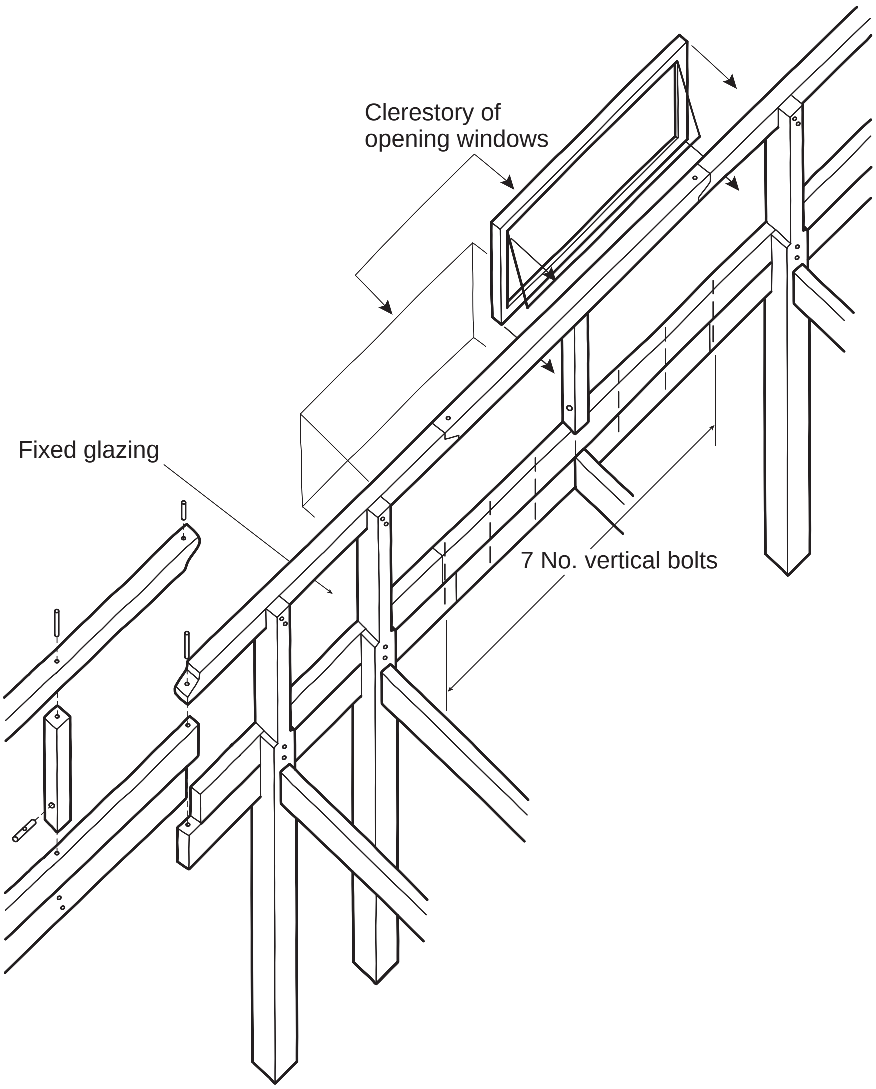


Figure 9.7.7 Arrangement of clerestory frame

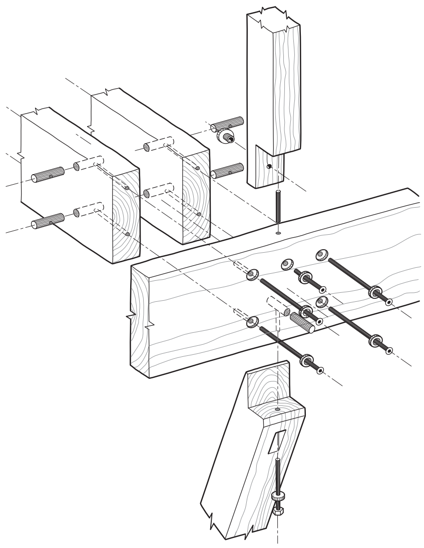


Figure 9.7.8 Jettied frame support

The noise and pollution from Silver Street meant that simple cross-ventilation of the building would not be possible; in fact, the wall, windows and roof on that side of the building were designed specifically for noise reduction. Nevertheless, natural ventilation was a design aim and the engineer made computer studies to validate the proposed solution, which was to draw air into the building through the river side clerestory by the stack effect of a ventilation tower at the east end.

In service, the louvres on the tower and clerestory windows are opened and closed by actuators instructed by the building system control. The windows are surrounded by a green oak frame, and the implications of the drying movements on the performance of the windows required special consideration. Based on advice from the engineer on the scale of the possible movement, the window frames were held in position by double beading, allowing a movement zone around the head and sides. For eight out of the ten windows, the detail was successful, but for two, a slight twist, rather than in-plane distortion, required them to be eased. It is prudent to advise a client that minor 'after-care' works of this kind should be anticipated.

Figure 9.7.9 Details of river elevation, 2006
Photo: P Ross

The use of European oak throughout the building has given the interior both a uniformity of colour and a variety of texture, from the fissured irregularity of the main posts to the refinement of the veneered shelving. Externally the frame has now (2006) been exposed to the weather for some twelve years. The initial light brown brown colour (enhanced by a coat of Danish oil, *Figure 9.7.2*) has changed to reflect the exposure of the various elements. The stair stringer, fully exposed to sun, wind and rain, has now achieved its final sliver-grey colour, while the adjacent frame and infill panels have weathered in response to the degree of sheltering provided by the two roof overhangs (*Figure 9.7.9*).

Credits

Architects: Dixon Jones
Structural engineers: Ove Arup and Partners
Contractors: Rattee and Kent

Innovative forms:
9.8 Weald and Downland Museum Gridshell

In 1991 Edward Cullinan Architects with Buro Happold, engineers, and later the Green Oak Carpentry Company, were appointed to prepare a design for a new building at the Weald and Downland Museum, Singleton, Sussex. The museum contains an outstanding collection of nearly 50 historic buildings dating from the 13th to the 19th century.

The design brief specified two spaces – a climate controlled store for historic artefacts, and a large working area, open to the public, in which building frames could be conserved and reconstructed. The museum's directors actively encouraged an adventurous approach to the design. The preliminary studies, and later the building, were the subject of a grant from the National Lottery Fund, who in all provided two thirds of the budget costs (£1.8 million).

Figure 9.8.1 The Downland Gridshell
Photos: Weald and Downland Museum

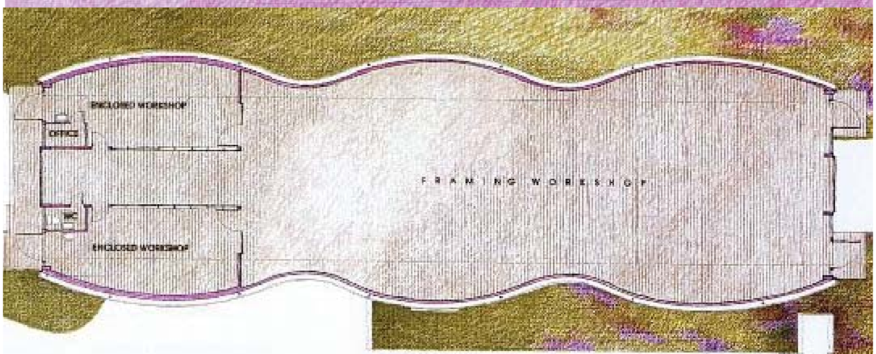
The Downland Gridshell is one of a very small number of gridshells in Britain, and its design and methods of construction are unusual. The gridshell encloses the building conservation workshop and working space and is insulated for year-round comfort. It is constructed over the store, which is located in a basement below. Externally, the shell is clad at lower levels with locally-grown western red cedar.

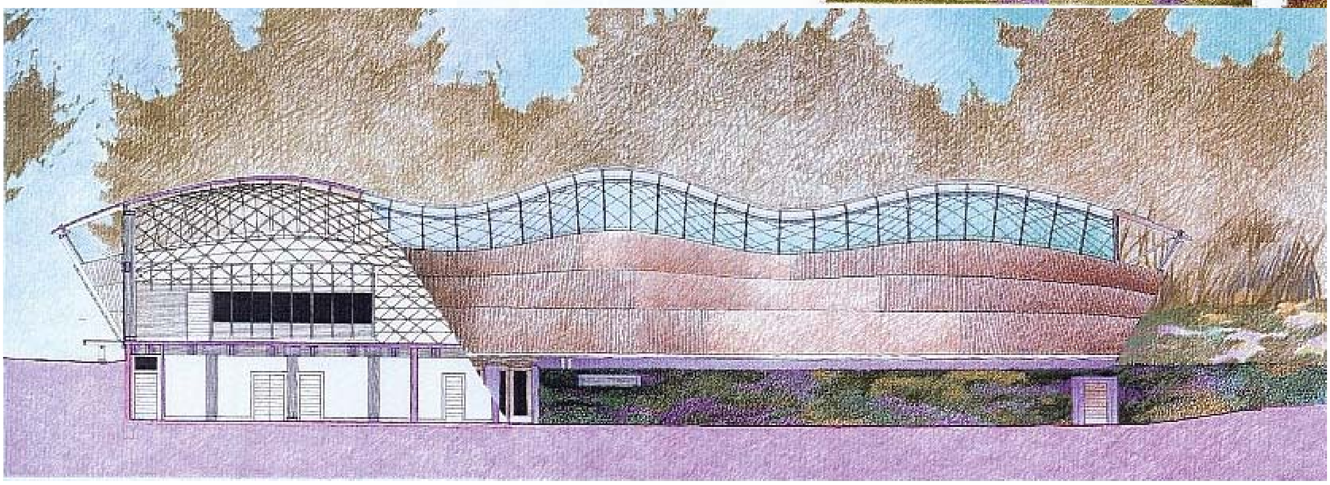
A gridshell gains shape and strength through its double-curvature. Ideally, the static forces within a shell remain within the planes of its defining surface. Shapes should therefore resemble a distorted "soap bubble," or in this case, a "caterpillar" consisting of several connected bubbles. Because there is bending stiffness within some of the timber laths, the practical shapes that can be achieved differ from the ideal, and this needs to be taken carefully into account in design.

The structure is shaped as a triple hourglass (*Figures 9.8.1* and *9.8.2*) with principal dimensions of:

- Width: 12 to 15 m
- Length: 50 m
- Height: 7 to 10 m.

Figure 9.8.2 Plan and sections
top: A cross section
right: Plan of upper floor
below: North elevation showing artefacts store at lower level with gridshell workshop above
Drawings: Edward Cullinan Architects / Weald and Downland Museum





A key feature of the formation and erection of timber gridshells is that during the initial stages of construction the laths need to be pliable. This was achieved through the use of light-section green European oak, which was end-jointed and connected into a mesh or grid and subsequently stiffened through shaping into double curvature, after which the nodes were tightened.

Alternative timbers were considered, including larch, Douglas fir, chestnut and oak. These species were short-listed for the following reasons:

- All naturally durable (when sapwood excluded), eliminating the need for pressure preservative treatment
- Good availability from nearby sustainable sources
- Oak is the most common timber in the museum's building collection.

Initial tests on these timbers were conducted at the University of Bath. The trials showed that the tensile performance of oak was excellent, provided that all of the major defects were removed, particularly sloping grain.

The laths were of 50 mm x 35 mm cross section. Finished lengths of up to 54 m (*Figure 9.8.3*) were required to diagonally span the entire structure, so end jointing was required. After considering several options, it was decided that prefabricated lath units of 6 m length should be produced using structural finger jointing, with a polyurethane-type adhesive chosen for its capability with green timber. The slope of grain was restricted to not exceed 1:10; only small pin knots whose group diameter did not exceed 20% of the width were allowed, and no fissures, nor any sapwood were permitted.

Site-made splices were then required to join the prefabricated 6 m lengths together. These were to be fabricated under a polythene tunnel, hence complex machinery had to be avoided. This requirement led to the adoption of a traditional timber joint in the form of a feather scarf whose faces have a slope of 1:7.

During erection, both the prefabricated finger joints and the field splices performed very satisfactorily. Although provision had been made to repair occasional fractures that were expected to occur, in practice there were only about 145 breakages, out of a total of some 10,000 bonded end joints.

In section, the grid is a double layer, with pairs of laths in each direction (*Figure 9.8.4*). This was necessary to combine the required degree of flexibility with sufficient cross section for strength. In certain regions, there are additional triangulated braces, and areas where the main grid spacing is closer than usual.

The grid was initially formed flat, on a supporting scaffold formed using the "PERI-UP" proprietary system. The edges were then lowered gradually, and the grid bent into shape, until the full shell was formed and secured to the edges of a timber ring beam (*Figure 9.8.5*)

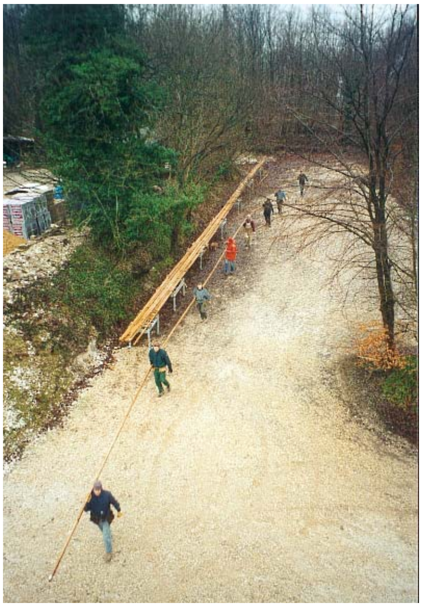


Figure 9.8.3 Carpenters carrying the completed laths on site
Photo: The Green Oak Carpentry Company / Weald and Downland Museum

Figure 9.8.4 The double layer grid partially lowered into place
Photo: Buro Happold / Weald and Downland Museum

Figure 9.8.5 A timber ring beam provides the boundary to the gridshell structure
Photo: Buro Happold / Weald and Downland Museum

Figure 9.8.6 The node connections utilise a patented system of steel plates and bolts. The connector comprises three steel plates, with the central unit having pins to locate grid layers 2 and 3, whilst the outer plates loosely hold layers 1 and 4 until clamping occurs. Two of the four locating bolts also connect the diagonal braces Photo: Buro Happold / Weald and Downland Museum

Figure 9.8.7 At the entrance the shell connects to a European larch glulam arch Photo: Buro Happold / Weald and Downland Museum

Figure 9.8.8 Locally-grown western red cedar cladding. Detail shows grooved boards with slots on the side away from the heart, so that cupping will occur outwards on the lower boards and downwards on the upper boards maintaining a tight weather envelope Photo: Weald and Downland Museum

The node connections involve a patented system of steel plates and bolts (*Figure 9.8.6*). This was designed specifically to provide the required scissors action during formation, whilst clamping up with ease and efficiency at the requisite stage. This is a critical operation, and the special connection is a considerable advance on the standard diaphragm washers and bolts used on earlier gridshells.

At the ends of the structure, a laminated dry European larch frame (*Figure 9.8.7*), arches from the workshop floor to the shell perimeter, resisting wind loads on the gable. Horizontal roof forces are transmitted to the floor by diagonal bracing laths, in the plane of the shell. The vertical and transverse loads at the ends of the shell are carried through the gable frame into the masonry walls of the archive store below.

In the lower region of the shell, diagonal bracing supports the western red cedar weatherboarding. Higher up, there is similar support for a ribbon ridge roof, which apart from its undulating shape, is a relatively straightforward joist and plywood structure. Cantilevered softwood glued laminated beams form the floor of the gridshell workshop and the ceiling of the basement. At the base of the shell proper, the laths are clamped between two 25 mm thick curved structural plywood sheets. These are connected to the workshop floor beams.

The building received the following Awards: RIBA Regional Architecture Award 2002; Runner-up for the RIBA Stirling Prize 2003; British Construction Industry Awards 2002 - Winner of the Small Project category; American Institute of Architects, Excellence in Design Award 2003; Civic Trust Award for outstanding contribution to the quality and appearance of the environment; Sussex Heritage Trust 2003 – Winner, Commercial and Industrial Category; Wood Awards 2003 - Winner, Gold Award and Structural Category; European Wood Facade Contest - Award by the Nordic Timber Council.

Credits

Architects: Edward Cullinan Architects
Structural engineers: Buro Happold
Quantity surveyors: Boxall Sayer
Frame fabricators: The Green Oak Carpentry Company Ltd
Client: The Weald and Downland Museum

Exterior uses:
9.9 The National Maritime Museum, Falmouth

Falmouth is of historic maritime significance, being one of the largest deep-water harbours in the world. The new museum site is an area of reclaimed land, lying on the harbour edge between the town centre, with its small-scale buildings, and the large warehouses of the present commercial area.

Figure 9.9.1 Falmouth Museum seen from the harbour
Photo: P Ross

Two museums came together within the new building, which was completed in 2002. The National Maritime Museum of London donated its small boat collection, and the local Cornwall Maritime Museum needed new accommodation, following expiry of the lease on its original building. The brief called for an area of around 5,000 m^2, some of which had to have at least 12 m headroom, together with smaller display and service areas.

The architect, Rolfe Kentish, based the building form on the vernacular sheds which accommodated the ship builders and timber merchants on the site in the late nineteenth century. A slate roof, tilted slightly as a reference to a sail, sits over walls clad in green oak, all on a granite stone base (*Figure 9.9.1*).

Like most museums, there is relatively little window area in the external walls. To avoid a possible monotony of appearance, three different cladding details are intermixed, giving liveliness to the elevations (*Figure 9.9.2*). All the timber was green oak, with stainless steel fasteners.

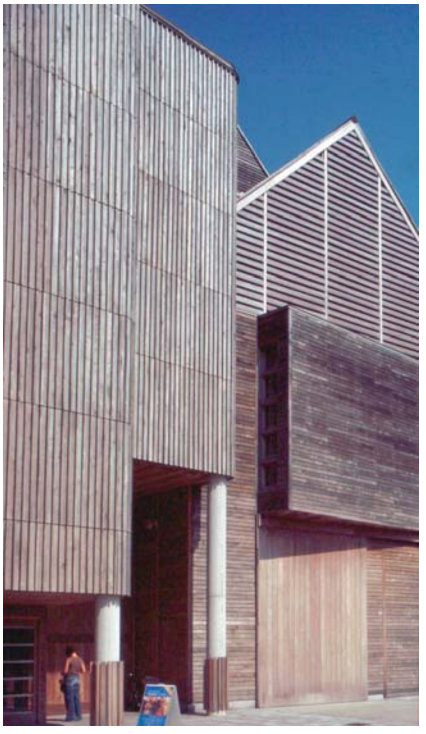
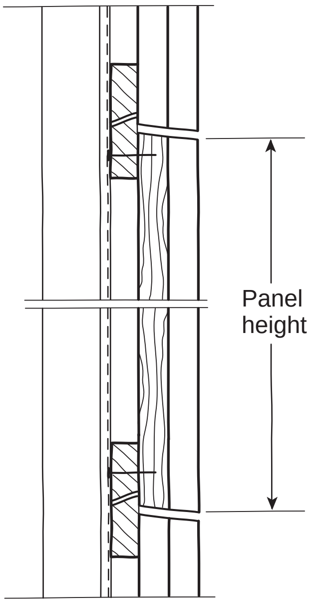


Figure 9.9.2 Intermix of cladding details
Photo: P Ross

Detail A (see *Figure 9.9.3*) is made up of battens set alternately on edge and on the face. The battens are screw-fixed from the rear to horizontal runners to make pre-formed panels, which are then fixed from the front through the gaps between the battens. All fixings are thus concealed, and the use of vertical battens allows them to follow curves on plan, a detail used to effect around the main entrance. (*Figure 9.9.4*). The battens move slightly as they dry out (Figure 9.9.3, photo) which, in this context, adds visual interest.



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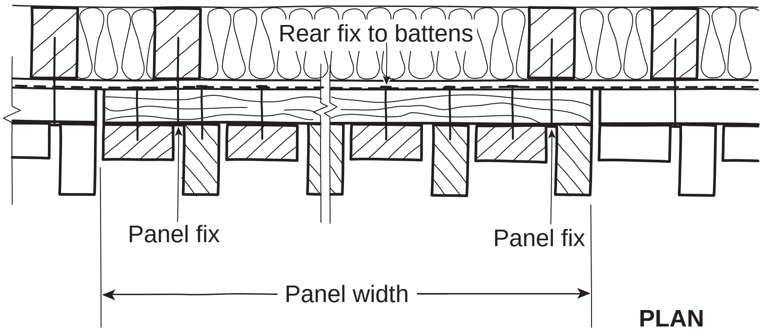


PLAN

Figure 9.9.3 Detail A: Alternate battens
Photo: P Ross

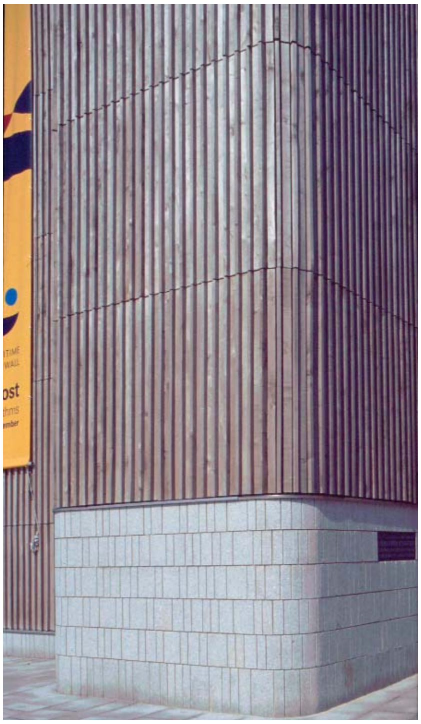
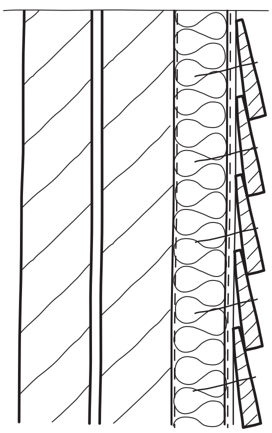


Figure 9.9.4 Alternate batten detail used on the curved wall surrounding the main entrance
Photo: P Ross

Detail B, *Figure 9.9.5* is a familiar form of horizontal weather boarding, using wedge-shaped boards. To avoid a restraint to the drying shrinkage, the boards have one central line of fasteners.



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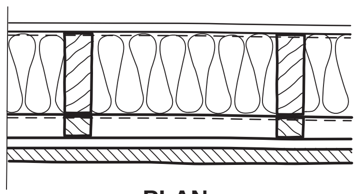
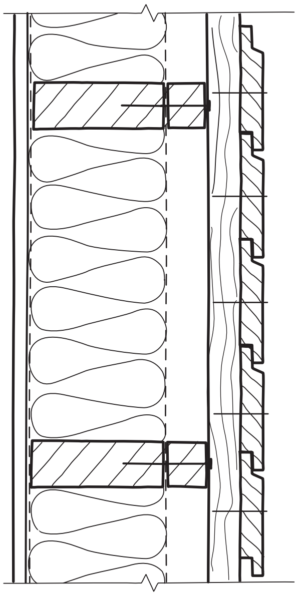


PLAN

Figure 9.9.5 Detail B Lapped boarding. Small in-plane drying movements can be seen, together with a large knot in the third plank down
Photo: P Ross

Detail C, *Figure 9.9.6* is another familiar form, using a moulded section, again with single fasteners.



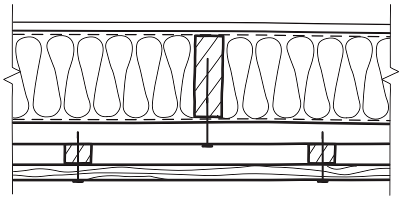


Figure 9.9.6 Detail C Shiplap boarding. Single vertical boards break the area into panels
Photo: P Ross

Figure 9.9.7 Detail - metal drip protecting the masonry below from tannin run-off
Photo: P Ross

The specification of timber grade was deliberately kept low – knots were allowed up to half the board face (*Figure 9.9.5*, photo) - and the board sizes were restricted to those normally used in fencing, which was found to give an economic supply price. To avoid tannin stains on the masonry below, the oak is either set proud or fitted with a metal drip (*Figure 9.9.7*).

On an exposed site, the oak provides an enclosure which is both durable and virtually maintenance-free, while at the same time, presenting a texture which is appropriate to the marine environment.

Credits

Architects: Long and Kentish
Client: National Maritime Museum Cornwall

Exterior uses:
9.10 Ealing Bridge

In 1998, the Green Oak Carpentry Company was commissioned by Ealing Borough Council to rebuild a bridge across the Grand Union Canal at Northolt, re-establishing an access route to a recreational area for local residents. The brief was to provide a robust structure with a long design life, which needed minimum maintenance.

Figure 9.10.1 Ealing bridge

The approach ramps and abutments already existed, setting the basic line and span of the bridge, although the abutments themselves were to be rebuilt. The bridge would have a width of 1.8 m, a clear span of 16.5 m, and an imposed loading of 4 kN/m^2. Simple beams of this span would be beyond economic supply, but the obvious alternative of upstanding trusses would require a large number of joints to be made. There remained the possibility of an arch, if it could be made flat enough to walk over (*Figure 9.10.1*).

The project engineer checked an arch with a rise of only 900 mm, and concluded that two 600 mm deep by 300 mm wide carriage beams would be satisfactory, if the timber quality was reasonably high. The gradient of the deck was set to comply with disabled requirements (generally less than 1 in 12, with a short length less than in 10 at each abutment) by running the walking surface from the top of the beams at the supports to near the bottom at mid-span (*Figure.9.10.2*).

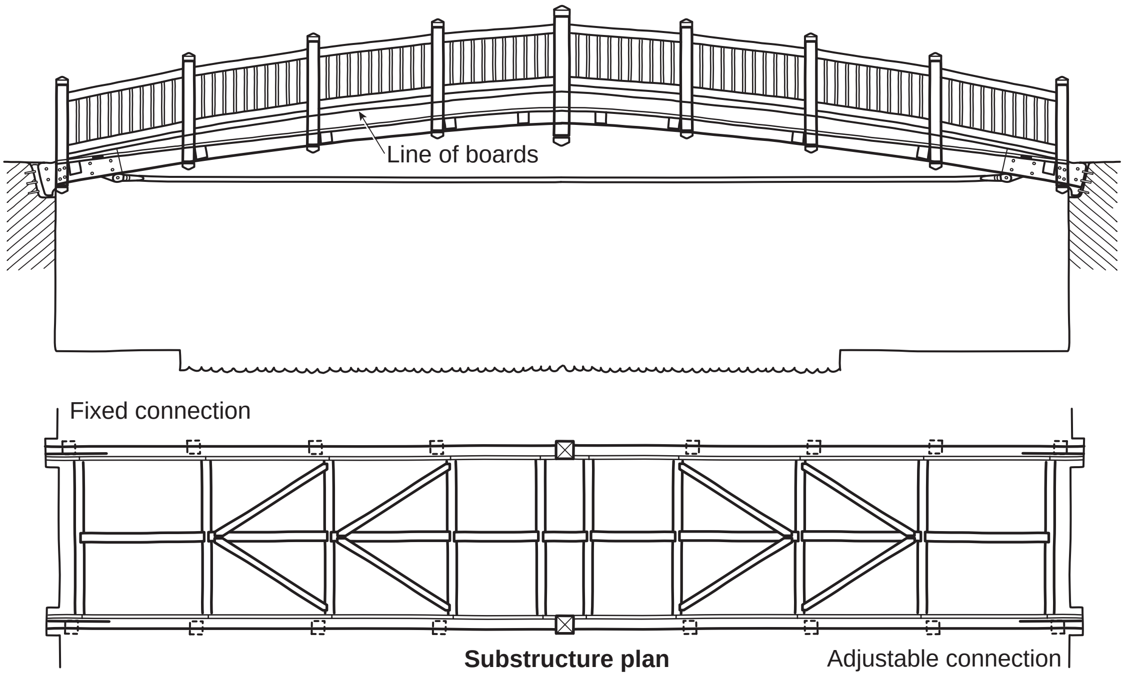


Figure 9.10.2 Elevation and substructure plan

Two butts of oak were required, each of which would need to be some 9 metres long, and contain a 600 mm sapwood-free square section, which, in addition, would be pre-cambered by 100 mm. Such timber required special enquiries to be made with suppliers, and obviously bore a considerable cost premium.

Since the arch was so shallow, it was necessary to check the effects of longitudinal shrinkage in the main beams. A figure of 0.1% was taken for drying shrinkage (since this is an external application), which would mean a 19 mm reduction in length overall. In turn, this would allow the crown of the bridge to drop by 150 mm. The crown was further raised by this amount, to allow for the movement. However, timber is a variable material, and it also seemed possible that slope of grain might allow a component of cross-grain shrinkage into the length, increasing the drop, and hence the abutment forces, which were already large. Hence the introduction of the tie-bars (*Figures 9.10.1* and 9.10.*2*), including a patented coupler, called the 'techno-tensioner' (after the cartoon character Wallace's own trouser invention), which would allow the length to be adjusted under load.

As for all external structures, attention was paid to the weathering details. Water traps were avoided, or vented. Joints were cut in such a way as to allow them to drain freely, and the handrail posts were housed onto the sides of the main beams rather than mortised into the top face. This also meant that the drying movement of the beams (set heart out) tended to tighten the bolts holding the posts in position (*Figure 9.10.3*). As an additional precaution, upward sloping holes were drilled close to the carriage/ spreader beam joists, with boron rods inserted and held in position with plastic plugs. Any moisture would activate the boron, which would then dissipate into the timber. As a maintenance item, the decking boards could be lifted, and new rods inserted.

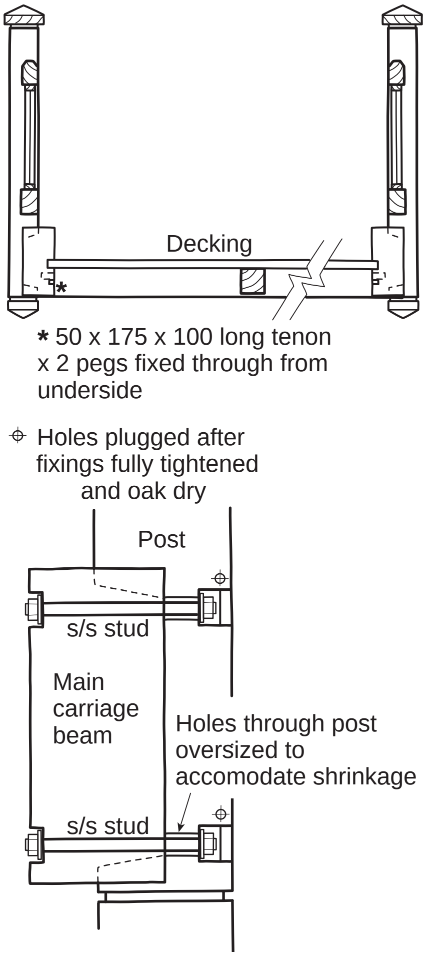


Figure 9.10.3 Parapet connections

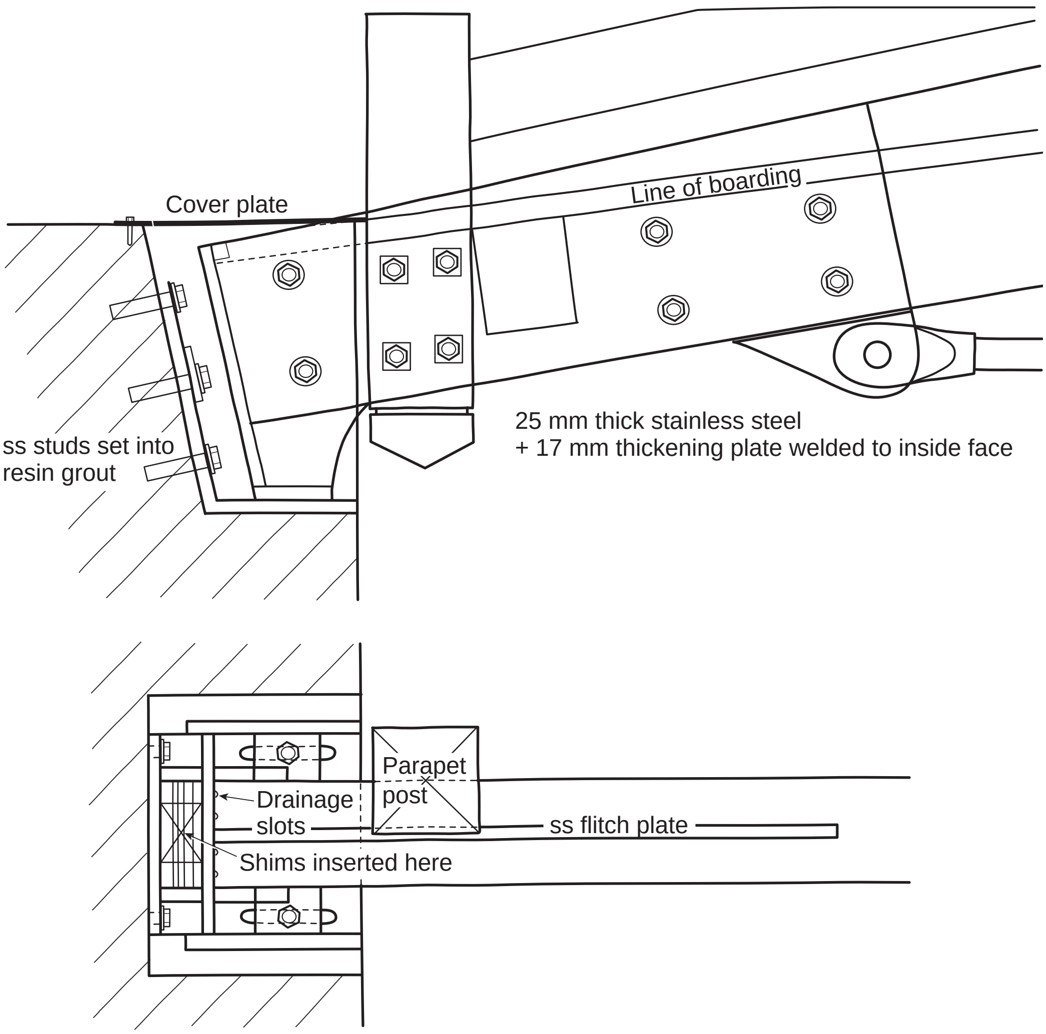


Figure 9.10.4 Adjustable connection details

Credits:

Client: Ealing Borough Council
Carpenter: The Green Oak Carpentry Company
Structural Engineer: Ian Payne

The bridge was installed on its new abutments in March 1999, using a fifty-ton crane, and to everyone's relief, the first canal boat proved the clearance to be satisfactory. Datum levels were marked at the crown and the supports, and monitored on a six-monthly basis. After two years the drop was only 12 mm, and the tie rods became slack. It was assumed that the new abutments had settled slightly towards the canal, and since all was well, the tie-rods were removed.

Exterior uses:
9.11 Polesden Lacey Bridge

Figure 9.11.1 Polesden Lacey bridge

For this Grade II* Listed garden in Surrey, a green oak bridge was recently constructed by means of traditional carpentry and pegged joinery. A famous owner of the original house was Richard Brinsley Sheridan - poet, playwright and Member of Parliament, who purchased it in 1804. The gardens include a "long walk" lined with yews and dating back to his time. Thomas Cubitt designed the present house in 1824. Subsequently in 1906, a famous Edwardian hostess, Mrs. Ronald Greville, commissioned Mewes & Davis, the architects of the Ritz Hotel, substantially to remodel the building. She also added an Arts & Crafts garden by J. Cheal & Sons. Thanks to her generous bequest to the National Trust, the mansion and its beautiful estate remain largely unchanged since Mrs. Greville's ownership.

The new oak bridge was installed in 2001, during work to restore the gardens and improve visitor access. The general format of the design includes deck beams, from which outrigger braces spring, providing stiffness to the parapets. The longitudinal bracing is in swept style, reminiscent of the architecture of local Surrey frames (*Figures 9.11.1* and *9.11.2*). Ventilated mortices are included in the joinery details. A counter-bladed scarf of considerable length is incorporated in each of the carriage beams, and these resist significant bending moments, although sensibly the end joints are not situated right at the centre of the span. Note also that the end grain of the post tops is capped, whilst the vertical support posts are also protected from water penetration (*Figure 9.11.2* Detail).

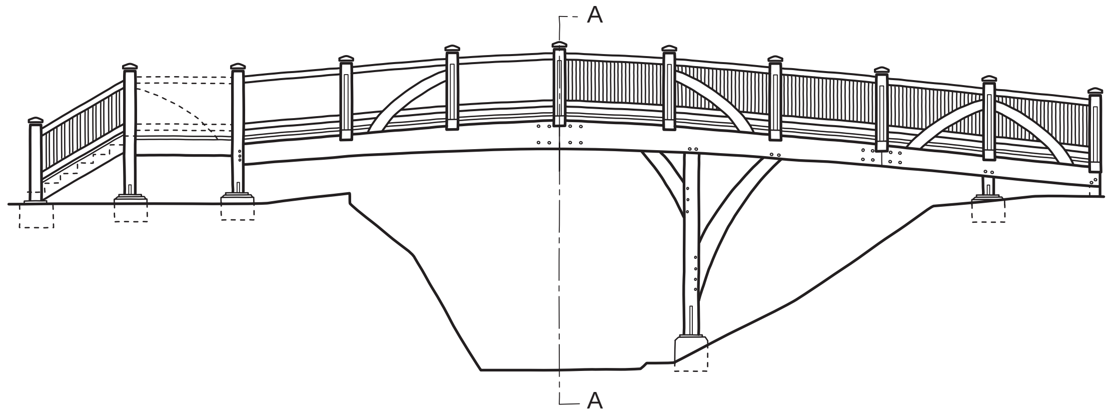


Figure 9.11.2 Bridge elevation

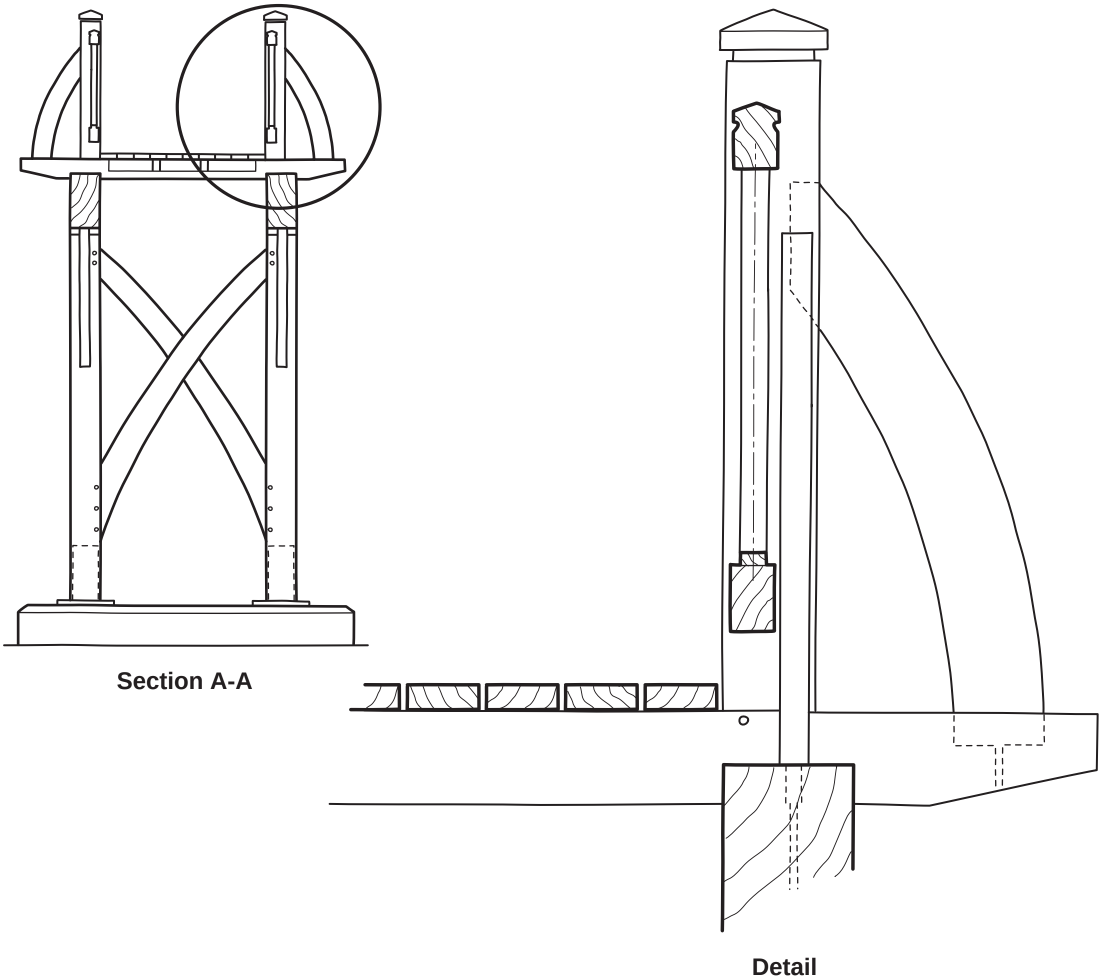


Figure 9.11.3 Section and handrail detail

Credits:

Client: The National Trust
Bridge supplier: The Green Oak Carpentry Company
Structural Engineer: Ian Payne

Appendix I Specifying oak supplies for traditional framing

Oak can be supplied in a range of qualities. Since most framing material is cut to order, rather than drawn from stock, it is necessary to give the supplier some definition of the quality required in order to avoid a debate about acceptability when the material is cut. This usually done by means of a written specification, defining the selection of each piece by setting limits to the various characteristics of growth or conversion, which are generally referred to as 'defects'. It may be helpful to begin by listing the defects usually used to define the selection, and the influence that they have on timber quality.

AI.1 Defects

Assuming that green oak is being specified, common defects are as follows:

- Knots: disturb the line of the grain, and hence reduce the strength of the piece. The larger the knots, the greater the strength reduction. Margin knots are more influential on bending strength than those in the centre of the face (see Figure AI.1a).

- Slope of grain: reduces the strength of a piece progressively, as the slope of grain increases (see Figure AI.1b). If the slope of grain varies significantly along the length, the likelihood of drying distortion increases, although this is less of a problem for a member which is effectively held to line while drying, eg a soleplate.

- Wane: missing timber, usually along an arris or edge resulting from an over-ambitious attempt to cut a rectangle from a circle (see Figure AI.1c), or as a consequence of removing sapwood.

- Sapwood: although sapwood is as strong as heartwood it lacks its durability (see Section 4.4). If the oak is completely within the weather envelope of the building, then rot will be unable to develop, but there is a risk of infestation by beetles. There is of course a cost premium for cutting from heartwood only, and the client should be involved in a decision to allow sapwood for internal framing. For the external framing members, or for external structures, sapwood should be excluded.

- Fungal or insect attack: active signs of either should be excluded (although they will normally only be associated with sapwood). An exception might be made for minor occurrences of small beetle holes, or for the staining (discolouration) associated with minute pieces of metal such as from saws.

- Fissures and splits: are unlikely to be present in green oak, but appear as the piece dries out, as explained in Section 4.3. The client should be made aware of their likely position and extent. Excluding the heart from a piece reduces the fissuring that will occur, but will incur a cost premium for the larger pieces (*Figure AI.1d*).

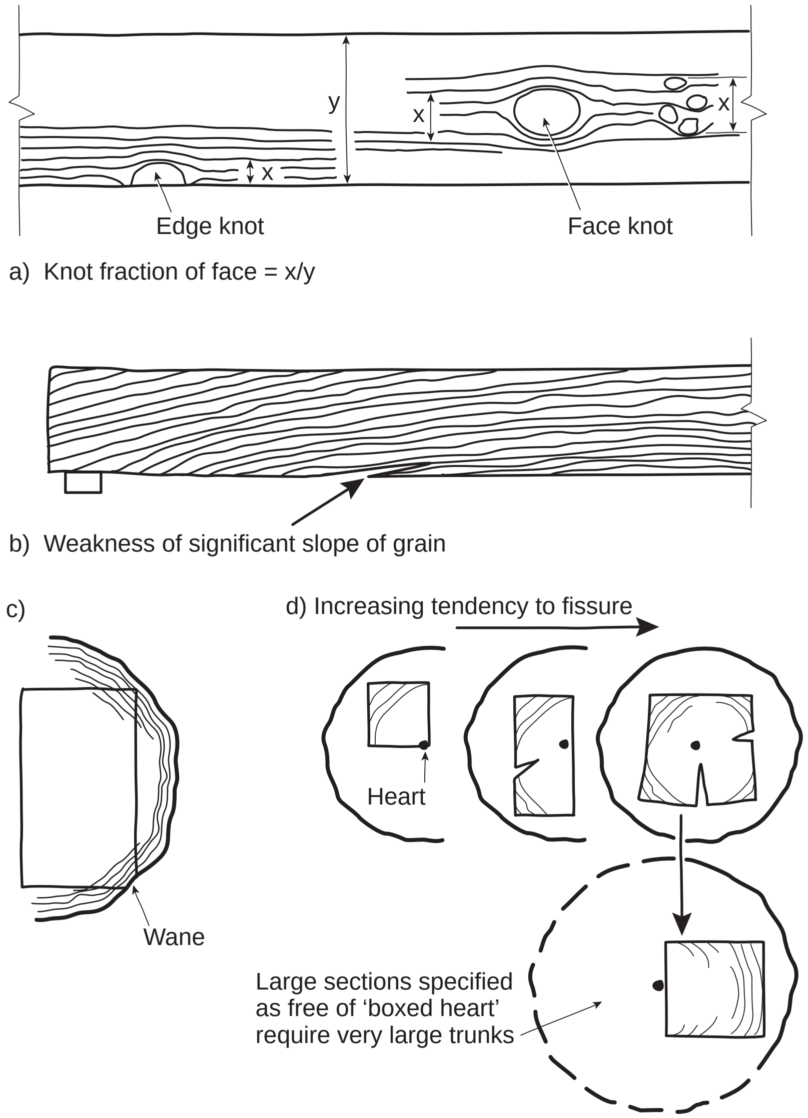


Figure AI.1 Defects assessed in framing member selection

In addition, there are two defect headings which relate to the process of conversion:

- Accuracy of conversion: the primary need for accuracy in conversion is to facilitate the fabrication of the frame. Distortion in the length is sometimes the result of internal stresses within the log being released by conversion, but occurs immediately, and is not to be confused with drying distortion.

- Surface finish: conversion is generally achieved by the use of powered saws. The surfaces are then planed, although some frame members may be hewn or adzed.

AI.2 Specification

The specifier's aims when defining the quality of timber are generally to achieve one or more of the following:

- an assurance of a specified minimum strength or stiffness
- adequate durability in relation to exposure
- control of drying movements and fissuring
- the desired appearance.

A matrix showing the relationship between these aims and the influence of defects is given in *Figure AI.2*. The aim is to set the minimum standard which will satisfy the project requirements. Over-specification will mean that the timber will be more expensive, or of unrealistically high quality.

Defects \ Selection	Strength	Durability	Effect of drying		Appearance
			Stability	Fissures	
Knots	X				x
Slope of grain	X		x		
Wane	X				X
Sapwood		X			
Rot/beetle	x	X			
Position within log (conversion issues)				X	x
Accuracy after conversion	x		(To facilitate frame fabrication)		
Surface finish					X
X major influence x minor influence					

Figure AI.2 Relationship between the specifier's aims and timber defects

On the following pages an example framing specification for green oak is given. The pro forma includes user notes with suggested entries, referring to the grade defects listed in Appendix I-1. The supplier would read the specification together with the cutting list, where the grade of each piece could be entered. A worked example of a specification and cutting list for a traditional frame, Rowses Farm, is given in Appendix 1.2.2.

The specification of member strength can be made in two ways. For members in smaller frames of traditional design (such as most of those illustrated in Section 5.3.1) two basic framing selections are defined: General Framing (GF) and Special Framing (SF). They place limits on knot sizes as a simple proportion of the face and slope of grain, and can be used directly by experienced framers. As the names imply, GF should be appropriate for most elements, such as sill plates, common studs and main posts etc. SF, gives (approximately) a 20% lift in strength for principal members without setting an unrealistically high specification, and might be used for common joists which are often highly stressed and for spanning members such as purlins and top plates. In very broad terms, GF and SF can be compared with C and B strength grades (see below) respectively.

For more ambitious frames, or for critical principal members which have been the subject of formal engineering calculations and for which a quantitative definition of strength is required, the Green Oak Strength Grading Rules (GOSGR) should be used, as set out in Appendix II. The Rules essentially require more detailed measurements of knot sizes, particularly in bending members, but can reliably be used to allocate grade stresses to a particular piece of timber which is within the prescribed grading limits. Three grades are defined: A, B and C. The first grade, A, while allocated high grade stresses, has more stringent limits, and should be used selectively with enquiries as to the availability of the material.

AI.2.1 Framing specification guidance notes

A pro-forma specification for green oak follows, largely in open format, with suggested values [shown in square brackets].

The assumptions are:

- a cutting list of members has been prepared
- the principal function of each member is known (ie beam/post/tie) if the GOSGR strength grades A, B or C can be specified where required.

The aim has been to produce two framing selections (GF and SF) with knot and slope of grain values acceptable to framers for the majority of frames.

A bespoke project specification may be given in the last column.

The cutting list may then be marked up with the grade and (W or S) as appropriate.

Examples:

Framing member, visible, outside face: GF
Purlin, visible, sap allowed: SF/S
Internal rafters, wane/ sapwood allowed GF/ W/ S
Principal, heartwood only, subject to engineering design: Grade A or B.

Figure AI.3 Green oak framing specification pro forma

Grade **Defects**	**General framing GF**	**Special framing SF**	**GOSGR Strength grades: A, B, C**	**Bespoke project specification**
KNOTS: maximum fraction of face	0.45	0.33	As Rules Appendix II	
SLOPE OF GRAIN: maximum	1 in 7	1 in 10	As Rules Appendix II	
WANE: maximum fraction of face: *select entry from:* *not allowed (usual entry)* *[0.1] for members marked W**			As Rules Appendix II	
BOXED HEART: *select entry from :* *not allowed* *allowed for members [20,000]mm*^{2}				
SAPWOOD: *select entry from:* *not allowed* *allowed for members marked S*				
FUNGAL/INSECT ATTACK: *select entry from:* *not allowed* *pinhole borers allowed*				
ACCURACY OF CONVERSION: cross-section <150mm: [*2*] mm >150mm: [*4*] mm bow in length: [*4*] mm/m (max. value): [*12*] mm				
FINISH: *select entry from:* *eg bandsawn/planed*				
User notes in *italics*. A worked example is given in Figure AI.5				

AI.2.2 An example of the use of this specification

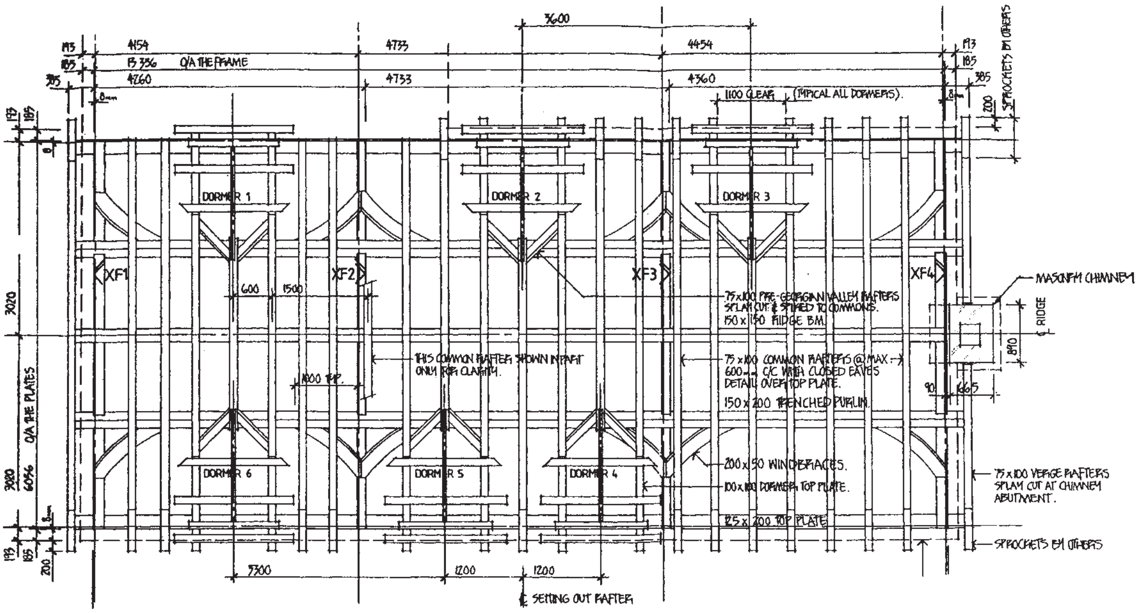
The building 'Rowses Farm' (*Figure A1.4*) is a mainly traditional frame, with one or two pieces which are working hard and which have been sized by an engineer.

The framing specification page has been completed (*Figure AI.5*), and the selection/grade of each piece has been entered on the cutting list (*Figure AI.6*).

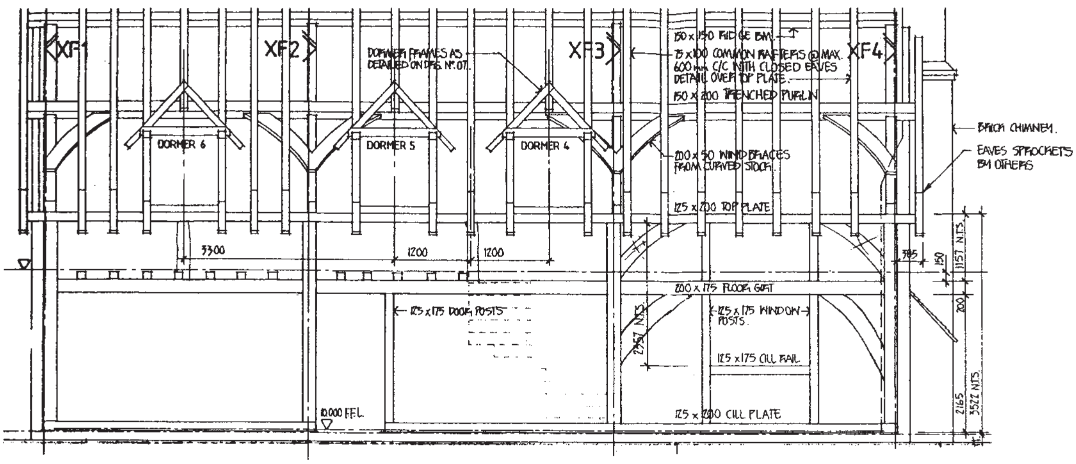
For this example it has been assumed that:

- the frame is exposed externally
- the budget is tight, and the client has agreed to the inclusion of sapwood for internal timber
- the client would like to see waney edges to the floor joists
- the floor is heavily loaded, and the engineer needs GOSGR A grade timber for the principals.

This might be a typical use of green oak, with the majority of members selected from GF/SF, with simple 'proportion-of-face' rules for knots, and a few critical members subject to more rigorous Green Oak Strength Grading Rules.



Top plate / Roof plan



East long wall elevation

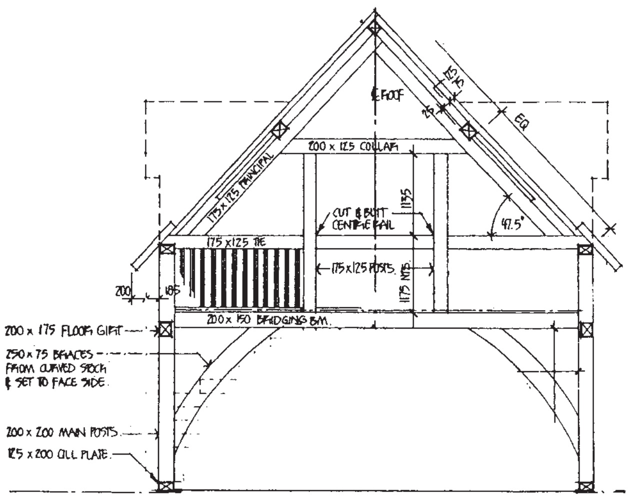


Figure AI.4 Rowses Farm. Example of the use of the framing specification and mark-up on the cutting list

Figure AI.5 Green oak framing specification for Rowses Farm

Defects	General framing GF	Special framing SF	GOSGR Strength grade A
KNOTS: maximum fraction of face	0.45	0.33	As Rules Appendix II
SLOPE OF GRAIN: maximum	1 in 7	1 in 10	1 in 13
WANE: maximum fraction of face:	0.2 for members marked W		Not allowed
BOXED HEART:	Allowed for members > 20,000 mm^2 cross section		
SAPWOOD:	Allowed for members marked S		
FUNGAL/INSECT ATTACK:	Not allowed		
ACCURACY OF CONVERSION: cross-section <150mm: [*2*] mm >150mm: [*4*] mm bow in length: [*4*] mm/m (max. value): [*12*] mm	 2 4 4 12		
FINISH:	Planed		

Figure AI.6 Cutting list for Rowses Farm frame

Job Name: Rowses Farm

F.A.O.

DESCRIPTION	NO	Selection/ Grade	DEPTH MM	WIDTH MM	LENGTH MM	CODE	CUBIC METRES	CUBIC FEET
The following in new sawn oak:								
XF1								
Sill	1	GF	125	200	6,100	S1	0.15	5.39
Post	2	GF	200	200	3,500	P1	0.28	9.89
Post	1	GF	200	175	2,400	P2	0.08	2.97
Post	1	GF	200	175	2,650	P3	0.09	3.28
Bridging Beam	1	SF	200	175	5,900	B1	0.21	7.29
Tie Beam	1	SF	200	175	6,100	T1	0.21	7.54
Collar	1	GF	175	175	3,000	C1	0.09	3.24
Principal Rafter	2	GF	150	175	4,000	PR1	0.21	7.42
XF2								
Post	1	GF	200	200	3,500	P5	0.14	4.94
Post	1	GF	200	200	3,700	P6	0.15	5.23
Post	2	GF/S	200	200	2,600	P7	0.21	7.35
Bridging Beam	1	GF/S	200	200	5,900	B2	0.24	8.33
Truss Post	2	GF/S	200	125	2,650	TR1	0.13	4.68
Stub Tie **Air Dried**	2	GF/S	200	125	2,200	ST1	0.11	3.88
Collar	1	GF/S	200	125	3,100	C2	0.08	2.74
Principal Rafter	2	GF/S	150	175	4,000	PR2	0.21	7.42
							0.00	0.00
XF3							0.00	0.00
Sill	2	GF	125	200	2,150	S2	0.11	3.80
Post	2	GF/S	200	200	3,500	P8	0.28	9.89
Post	2	GF/S	175	150	2,600	P9	0.14	4.82
Truss Posts	2	GF/S	175	125	2,600	TR2	0.11	4.02
Bridging Beam	1	GF/S	200	150	5,900	B3	0.18	6.25
Tie Beam	2	GF/S	175	125	2,300	T2	0.10	3.55
Center Rail	1	GF/S	175	125	1,700	CR1	0.04	1.31
Collar	1	GF/S	200	125	3,000	C3	0.08	2.65
Principal Rafter	2	GF/S	175	125	4,000	PR3	0.18	6.18
XF4								
Sill	2	GF	125	200	2,200	S3	0.11	3.88
Post	2	GF	200	200	3,500	P11	0.28	9.89
Post	2	GF/S	200	150	2,400	P12	0.14	5.09
Post	3	GF/S	125	175	2,500	P13	0.16	5.79
Stud	2	GF/S	125	175	2,400	ST1	0.11	3.71
Stud	2	GF/S	125	175	1,200	ST2	0.05	1.85
Bridging Beam	1	A/S	200	200	5,900	B4	0.24	8.33
Interupted Tie Bear	2	GF/S	200	175	2,600	T3	0.18	6.43
Collar	1	GF/S	200	175	3,000	C4	0.11	3.71
Principal Rafter	2	GF/S	150	175	4,000	PR4	0.21	7.42

DESCRIPTION	NO	Selection/ Grade	DEPTH MM	WIDTH MM	LENGTH MM	CODE	CUBIC METRES	CUBIC FEET
East Long Wall								
Sill Plate	1	GF	125	200	4,400	S4	0.11	3.88
Sill Plate	2	GF	125	200	4,200	S5	0.21	7.42
Floor Girt	1	SF	200	175	4,100	FG1	0.14	5.07
Floor Girt	1	SF	200	125	4,800	FG2	0.12	4.24
Floor Girt	1	SF	200	125	4,400	FG3	0.11	3.88
Top Plate Both Long Walls	2	GF	125	200	5,400	TP1	0.27	9.53
Top Plate Both Long Walls	2	GF	125	200	5,000	TP2	0.25	8.83
Top Plate Both Long Walls	2	GF	125	200	4,700	TP3	0.24	8.30
Window Post	2	GF	125	175	3,500	WP1	0.15	5.41
Window Sill	1	GF	125	175	1,800	WS1	0.04	1.39
Door Post	1	GF	125	175	2,300	DP1	0.05	1.78
Dormers East & West								
Dormer Post	12	GF	100	100	1,300	DP2	0.16	5.51
Dormer Sill	1	GF	100	100	1,200	DS1	0.01	0.42
Tie Beam	6	GF	125	100	1,450	T5	0.11	3.84
Top Plate	12	GF	100	100	1,400	TP3	0.17	5.93
Dormer Principal Rafter	12	GF	100	100	1,000	PR5	0.12	4.24
Dormer Common Rafter	36	GF	75	100	1,100	CR1	0.30	10.49
Dormer Ridge Beam	6	GF	150	32	2,700	R3	0.08	2.75
Hip Rafter	12	GF	75	100	1,200	HR1	0.11	3.81
West Long Wall								
Sill Plate	1	GF	125	200	1,400	S7	0.04	1.24
Sill Plate	1	GF	125	200	5,500	S8	0.14	4.86
Floor Girt	1	SF	200	175	4,400	FG4	0.15	5.44
Floor Girt	1	SF	200	125	4,800	FG5	0.12	4.24
Floor Girt	1	SF	200	125	4,100	FG6	0.10	3.62
Door Post	3	GF	125	175	2,300	DP2	0.15	5.33
Roof								
Purlin	2	SF/S	150	200	5,400	PU1	0.32	11.44
Purlin	2	SF/S	150	200	5,000	PU2	0.30	10.59
Purlin	2	SF/S	150	200	4,700	PU3	0.28	9.96
Ridge Beam	1	SF/S	150	150	5,400	RB1	0.12	4.29
Ridge Beam	1	SF/S	150	150	5,000	RB2	0.11	3.97
Ridge Beam	1	SF/S	150	150	4,700	RB3	0.11	3.73
Common Rafter	50	GF/S	75	100	4,600	CR1	1.73	60.92
Floor								
Spine Beam	1	A	200	225	4,400	SP1	0.20	6.99
Trimming Beam	1	A	200	175	4,800	F2	0.17	5.93
Joist	14	SF/S/W	125	125	3,100	J1	0.68	23.95
Joist	8	SF/S/W	125	150	4,050	J2	0.61	21.45
Joist	4	SF/S/W	125	125	2,150	J3	0.13	4.75
Cut from curved stock								
Brace	4	GF	250	75	2,600	B1	0.20	6.89
Brace	2	GF	200	65	1,300	B2	0.03	1.19
Brace	2	GF	200	75	1,700	B3	0.05	1.80
Wind Brace	12	GF/S	200	50	2,100	WB1	0.25	8.90
Long Wall Brace	4	GF	200	75	1,500	LWB1	0.09	3.18
					GRAND TOTAL		14.20	501.52
					APPROX GROSS TONNE			13.68

Appendix II Green oak strength grading rules

AII.1 Scope

This Appendix contains the Green Oak Strength Grading Rules, as outlined in Chapter 6 - The Green Oak Framing Process. To establish these visual strength grading rules, reference was made to ASTM D245 – 00 (2002), as well as to a number of current BS EN Standards relating to strength grading and to timber test procedures. Full details are given in AII.6 Reference documentation.

These rules are intended for the visual strength grading of green oak that is used for defined engineering purposes. They refer to sawn, rectangular sections, and are applicable only to European oak that is to be graded in the unseasoned state ('green').

Where possible, the strength grading should be applied to material that has been obtained from a supplier who understands the general requirements of oak for use in carpentry. This will ensure that the selection is made from material which is generally of appropriate starting quality for the purpose intended (see Section 6.3.1).

The inspection procedures described, involving the measurement of strength reducing features, are to be carried out close to the time of frame building or structural assembly. They are to be performed by personnel having appropriate skills and experience. This includes knowing the intended end-use of the members being strength graded, with reference to their structural duty and the final location within the structure.

AII.2 The grades

Table AII.1 Green oak strength grades: indicative strength ratios

Grade	Strength ratio %
A	71
B	62
C	48

Table AII.1 shows the strength grades that are provided, together with their indicative strength ratios. The strength ratio is conceptually the ratio of the strength in bending of the actual graded member, compared with that of a perfect timber. However this information should only be regarded as background rather than being used for the purposes of interpolation or extrapolation, because the theory of the grading contains a number of practical adjustments and allowances.

Further information on the basic principles of strength ratios is available in ASTM D 245 Clause 4, and in the other references cited in AII.6.

The green oak members should be graded by assessing the characteristics defined and described in AII.3 and AII.4, and by applying the limits given in AII.5. Each member should be inspected at, or close to, the time of frame making or the time of prefabrication into a timber engineered green oak structure.

The grading should take into account whether the piece is to be used as a bending member, a compression member, a tension member, or one having these effects in combination. In the latter case, guidance is provided in AII.4 on how to make the assessment.

AII.3 Definitions

The definitions in BS EN 844 and BS EN 518 (Refs: AII.6.1) apply, whilst in addition the following precise definitions are given, specifically for these rules.

AII.3.1 Surfaces, arrises and margins

An upper surface, a lateral surface and an arris are shown in *Figure AII.1*. Also shown are the terms for beam cross-sectional dimensions, "b" (width of section) and "h" (depth of section). These are not essential to the grading rules themselves, but are used in structural design codes (see BS 5268-2 (Ref: 7) and BS EN 1995-1-1 (Ref: 20)), and therefore need to be understood by the grader.

The margins and the centre of a lateral surface of a beam are as shown in *Figure AII-2*.

NOTE: In order to know which are the margin areas, the grader needs to know which way a beam is to be subjected to bending effects. Bending in the vertical plane is shown; this is the more usual direction.

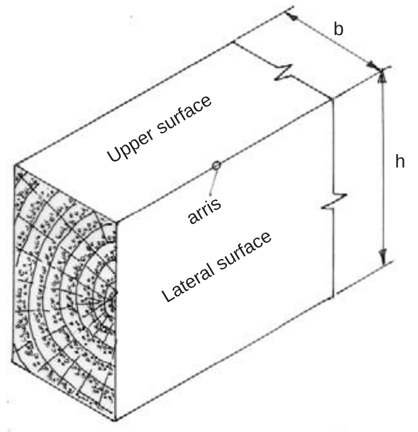


Figure AII.1 Upper surface (lower surface at bottom); lateral surface (another at rear); arris. For engineering calculations, with a beam bending in the vertical plane, the dimension "b" is termed width and "h" is depth

AII.3.2.Knot types

The strength grading rules refer to five main knot types, as follows:

- ♦ Centre knots
- ♦ Splay knots
- ♦ Knots on upper or lower surfaces
- ♦ Arris knots
- ♦ Margin knots.

Typical examples of each of these, together with further figures and notes on conversion and knot definitions, are given in Section 6.3.1.

Also addressed is a common knot cluster feature of European oak known as 'cat's paws'. See Section 6.3.4.6 and *Figures 6.17f* and *6.19* for more details.

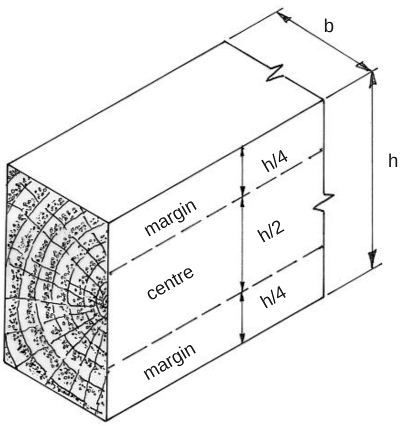


Figure AII.2 Margins and centre of lateral surface

AII.3.3 Equivalent knot size

In AII.4, the term equivalent knot size (d) is required. For an idealised round knot that emerges entirely on one surface, the actual knot diameter is the knot size (d). In other cases, specific measurement rules are given that enable the grader to determine the equivalent knot size (d), see arris knots for example.

AII.3.4 Ring shakes

Ring shakes occasionally occur in green European oak when it is fresh off the saw (*Figure AII.3*). These are indicative of abnormalities, such as tension wood. Pieces containing this feature should be rejected.

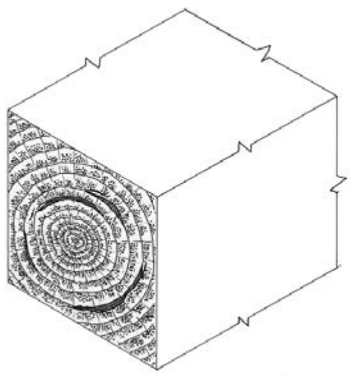


Figure AII.3 Ring shakes

AII.4 Measurement of features

AII.4.1 Measurement of knots

AII.4.1.1 Knots in bending members

General: In general, knots in bending members should be measured between imaginary lines enclosing the knot and parallel to the arrises (*Figures AII.5 to AII.8*). There is an exception for centre knots, as shown in *Figure AII.4*. For oval centre knots, the averaging of the maximum and minimum diameters gives a more lenient rule. The derivation of grade limits and the relevant properties for each strength grade take this relaxation into account. Note also that in bending members generally, the permissible knot fraction tables (see Appendix II.5.3) provide more lenient limits for centre knots, compared with those for knots on the upper or lower surfaces, and compared with those for arris and margin knots.

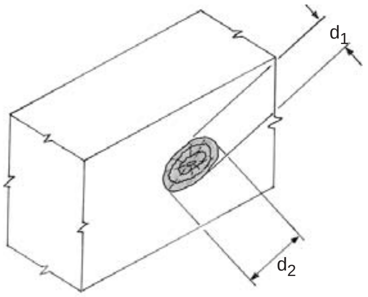


Figure AII.4 Centre knot on lateral surface of a bending member

Centre knots on lateral surfaces of a bending member: The equivalent knot size is the average of the greater and lesser diameter, $(d_1 + d_2)/2$ (*Figure AII.4*).

Note: This type of knot may appear on two opposing surfaces, in which case the measurement should only be taken on the surface displaying the larger knot size.

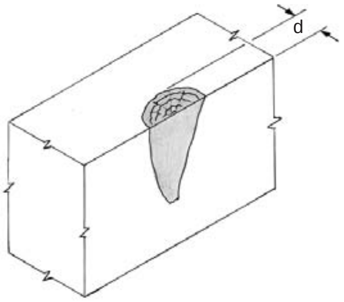


Figure AII.5 Splay knot in a bending member

Splay knots: An imaginary line enclosing the knot and parallel to the arris is used as a datum. The knot size (d) is taken as indicated in *Figure AII.5*.

Note: This type is measured only on the surface upon which the section of the knot is approximately semi-circular or semi-oval – the “tail” of the splay knot is ignored, but care should be taken to differentiate this type from the arris knot – see below and Section 6.3.4.5.

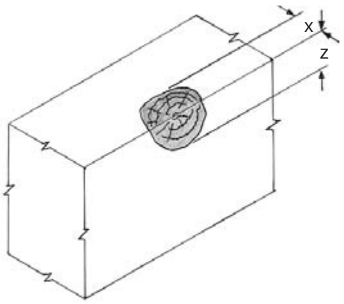


Figure AII.6 Arris knot in a bending member

Arris knots: Imaginary lines enclosing the knot and parallel to the arris are used as a datum. The relevant dimensions X and Z are taken, as indicated in *Figure AII.6*.

The equivalent knot size (d) is the greater of:

$d = (X + Z/2)$

or

$d = (Z + X/2)$

Note: the permissible knot fraction tables contain special limiting rules for margin knots in bending members. An arris knot is a form of margin knot.

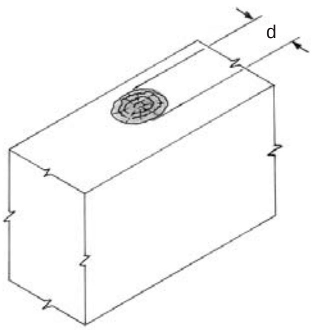


Figure AII.7 Knot on the upper or lower surface of bending member

Knots on the upper or lower surfaces of a bending member: Imaginary lines enclosing the knot and parallel to the arris are used as a datum. The knot size (d) is measured as indicated in *Figure AII.7*.

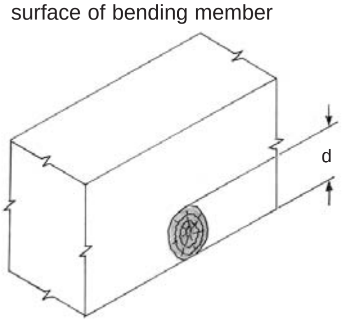


Figure AII.8 Margin knot, on lateral surface of a bending member

Margin knot on lateral surfaces of a bending member: An imaginary line enclosing the knot and parallel to the arris is used as a datum. The knot size (d) is measured as indicated in *Figure AII.8*.

Note: This type of knot may appear on two opposing surfaces, in which case the measurement should only be taken on the surface displaying the larger knot size.

AII.4.1.2 Knots in posts and columns

General: In general, the principles for knot measurement in posts and columns are similar to those for bending members. Knots should normally be measured between lines enclosing the knot and parallel to the arrises of the piece. The exception is centre knots, where, as for those in beams, the "diameter averaging" rule is applied. In posts and columns, margin knots are inapplicable. For arris knots – see Note below. Splay knots are measured in the same way as those in beams, ie ignoring the 'tail'.

Note: The margin zones are generally less significant in compression members, and in members carrying direct compression only, they are have no effect. Hence the concept of "margins" (*Figure AII.2*) is not required. Arris knots may occur in these members, and they are measured using the same method as for bending members.

Hence it only necessary to refer to three knot types:

- Round or oval knots on any surface
- Splay knots
- Arris knots.

Round or oval knots on any lateral surface of a post or column: The equivalent knot size is the average of the greater and lesser diameter, $(d_1 + d_2)/2$ (*Figure AII.9a*).

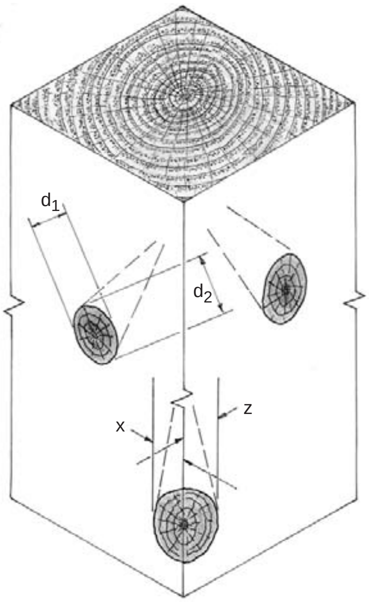


Figure AII.9a Round or oval knots and an arris knot, on a large, boxed heart column

Splay knots in posts and columns: An imaginary line enclosing the knot and parallel to the arris is used as a datum. The knot size (d) is taken as indicated in *Figure AII.9b*.

Note: This type is measured only on the surface upon which the section of the knot is approximately semi-circular or semi-oval – the 'tail' of the splay knot is ignored, but care should be taken to differentiate this type from the arris knot (see below and Section 6.3.4.5).

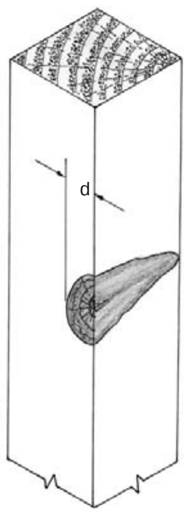


Figure AII.9b A small post, cut as a quarter, with a splay knot

Arris knots in posts and columns: Imaginary lines enclosing the knot and parallel to the arris are used as a datum. The relevant dimensions X and Z are taken, as indicated in *Figure AII.9a*.

The equivalent knot size (d) is the greater of:

$d = (X + Z/2)$

or

$d = (Z + X/2)$

AII.4.1.3 Knots in tension members

General: In green oak carpentry, it is rare that members act purely in tension, without this being combined with other types of action. Hence measurement of knots is given a conservative basis, without significant loss of efficiency.

Measurements: Where tensile forces are combined with a flexural action, then the measurements and applied limits should depend upon whether the action is predominantly tensile, or whether it is predominantly flexural. In the former case – significant tensile action - measurement techniques are generally as for a post or column, but for all positions in such members, the knot fractions (see Appendix II.5.3) are as for margin knots in a bending member. This also applies to the rare case where there is pure tension. In the reverse case - a bending member with only a small degree of tension - the member should simply be graded as a pure beam.

AII.4.1.4 Combining the effect of multiple knots - members of all types

Knot clusters: If two or more significant knots are partially or completely enclosed by the same parallel lines, and are separated from one another by less than 300 mm, then the effective knot size of the group should be estimated. The principle for making this approximation is to apply the measurement rule for the type of knot that dominates the group, and to combine with this the estimated effect of the additional knots. In case of doubt, such a timber should be re-assessed for the next lower grade, or rejected altogether.

Note: Where knots appear to be adjacent, there is a need to check whether the grain reverts towards a straight condition between the individual knots. Also, to check whether the individual knots are separated longitudinally by more than 300 mm. If so, then the knots should not be treated as a cluster, but should simply be measured using the individual knot rules, with the worst knot in the region determining the grade of the piece.

Pin knots: Individual pin knots i.e. those of less than approximately 10 mm diameter, may be disregarded altogether.

Note: When a group of pin knots belongs to an adventitious growth feature ("cat's paws") - see below.

Note: Types of knot cluster may also occur where imaginary parallel measuring lines do not enclose all of the knots within the group. Where the grain does not revert to a tendency to be parallel to the arrises between the individual knots, a cluster of this type is likely to be harmful to strength. In this case, the principle is to estimate the disturbance of the effective strength of the section, using the measuring rules and size limitations for the type of knot that dominates the group, and combining with this the additional effect of the knots elsewhere in the section.

Pin knots from adventitious growth features (cat's paws): (*Figures 6.17f* and *6.19*) It is impossible to give precise instructions on the measurement of pin knot clusters, so judgement must be applied. The above guidelines for general knot clusters should be observed, following the underlying principle that the grader should try to assess disturbance of the general grain of material flowing around the complete feature. Except in small timbers, clusters of pin knots are unlikely to warrant rejection, but in case of doubt, pieces containing them should be assessed for a lower grade.

AII.4.2 Measurement of slope of grain – members of all types

As indicated in *Figure AII 10*, the inclination of the wood fibres (grain) to the longitudinal axis of the piece is measured.

The slope is given by the ratio of distances (a to c) (b to c).

The distances should be measured over a length sufficiently great to determine the general slope, disregarding slight local deviations. All four lateral surfaces of the piece should be inspected for the presence of sloping grain. If it occurs on two adjacent surfaces, the combined slope of grain should be calculated.

Note: Checking is assisted by the use of a swivel-handed scribing tool (*Figure 6.7*).

Note: Combined slope of grain on two adjacent surfaces is calculated as, for example:

$$\sqrt{(\text{slope on b})^2 + (\text{slope on h})^2}$$

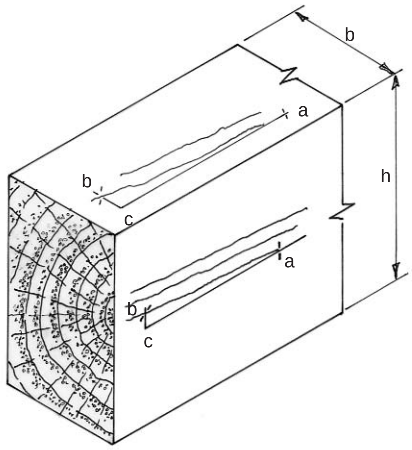


Figure AII.10 Slope of grain. Line a – c is imaginary, and parallel to the arris; line a – b is the general grain direction, with irregularities averaged. If a grain scribe is used, line a – b will be marked, perhaps several times. If grain slope is suspected on more than one surface, each should be checked, ie the upper and lateral surface in this Figure

AII.4.3 Rate of growth – members of all types

There is no requirement to control the rate of growth.

Note: An assessment of rate of growth is normally required when strength grading structural softwoods. However, European oak has a ring porous wood structure, and there are some indications that in timbers of this type, material from faster-grown trees is actually stronger than slow-grown stock.

AII.4.4 Wane – members of all types

Wane is measured as "v," as indicated in *Figure AII.11*. The width of the wane is compared with the full lateral dimension of the surface. The surface showing the worst extent of the feature should be taken in the assessment.

Note: Frequently, requirements for appearance, carpentry assembly, particularly at joints, and other utility considerations, may impose more strict limitations than the structural necessities (see Chapter 6).
For external applications, sapwood is treated as wane.

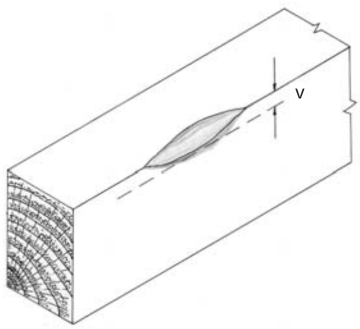


Figure AII.11 Wane - Measured as "v," the width on the worst surface

AII.4.5 Fissures – members of all types

General: During the stage at which green grading occurs, fissures are not formally measured (see Chapter 6). Indicative target control limits are suggested in Appendix II.5.7. These are for cases where some drying, and therefore fissuring, cannot be avoided during member preparation and frame building.

Ring shakes: Occasionally, European oak timbers manifest ring shakes (see Appendix II.3.4) whilst still in the green condition. These are indicative of abnormalities, eg tension wood. As such, pieces containing this feature should be rejected (see Appendix II.4.6).

Note: Green oak is generally stored and worked at a moisture content significantly greater than 20%, during which stage, few if any of the normal fissures will show (see Chapter 4). The pattern of later development of fissures and their ultimate size will depend upon the cutting pattern used in conversion, and the exact arrangements of the parts within the assembly, as well as their final location within the building.

AII.4.6 Distortion – members of all types

General: Undesirable forms of distortion have structural implications, as well as needing to be avoided for appearance and utility reasons. Hence green oak should be selected, stored and prepared under conditions that minimise the onset of drying distortion.

Limits for Bow, Spring and Twist: Recommended limits to assist in restricting initial distortion in the green state are given in Appendix II.5.

Measurement: Based on the measurement methods used in conventional strength grading rules, it is recommended that bow, spring and twist should be measured over a significant length, eg 2 metres (*Figure AII.12*).

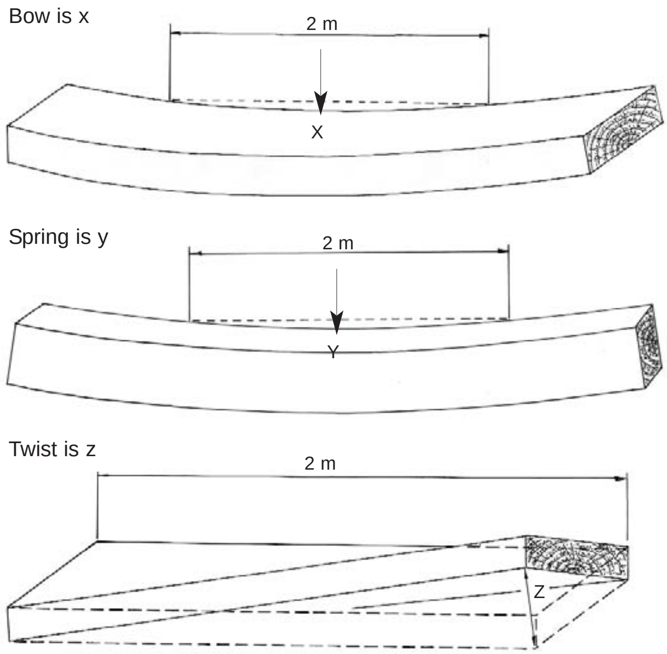


Figure AII.12 Measurement of initial green distortion – bow, spring and twist

Note: The carpenter or manufacturer specifies to the sawmill the initial straightness required (see Chapters 4 and 6). Whilst the timber is being worked green, distortion in pieces prone to the effect will not have fully developed. The nature and extent of later distortion depends upon the cutting pattern used in conversion, as well as the exact arrangements of the parts within the assembly and their final location within the building. Close control of slope of grain, (see Appendix II.4.2), improves the likelihood of members remaining straight whilst they are drying in situ.

By taking steps such as installing joists "crown up," some lack of straightness can be accommodated. However, it should be appreciated that through the calculations, the engineer is taking into account serviceability design considerations, and in some cases, safety aspects, that depend upon straightness. With heavy oak timbers, spring and twist in particular, result from large internal forces that are difficult or impossible to restrain once built. Hence significant distortion of this type may lead to structural instability or, where masonry walls or glazing is in close proximity, to cracking of these types of brittle material.

If deliberately curved or cambered members are required, the supplier needs to be given tolerances on the ideal shape, to assist in economical supply. The supplier's specification should also state requirements for trueness of section, which includes squareness, and overall size tolerances.

AII.4.7 Abnormal defects – members of all types

It is usual for strength grading rules to contain a clause excluding material containing abnormal defects. European oak is not prone to any unique abnormal features. Those which should be controlled following principles indicated in BS EN 518 (Ref: AII.6) include: tension wood (possibly indicated by ring shakes, see Appendix II.4.5); excessive insect damage or that suspected of being still alive; fungal decay; mechanical damage; combinations of knots with other adverse features.

Note: Grading standards such as BS EN 518 include the concept that allows minor occurrences of abnormalities. These are those adjudged to be non-progressive with time, and not worse in strength reducing effect than the normal features allowed within the grade.

AII 4.8 Stain – members of all types

Brown stained wood indicates fungal presence, and as such, material should be classified as containing abnormality, and be dealt with accordingly (see AII.4.7). Blue-black staining from ferrous contact is not a structural defect.

Note: When there is contact between green oak and any type of ferrous metal, dark blue-black staining always occurs, very rapidly. Even the normal use of tools may induce this. Whilst this type of stain has no structural significance, it may be considered unsightly. Carpenters are aware of the means of avoidance, minimisation, or later removal of this type of stain from completed frames (see Section 6.4).

AII.5 Grade limits

AII.5.1 General

The following are the grade limits for the green oak strength grades A, B and C. These are the maximum permissible sizes of the strength reducing features for each grade. The relevant definitions are in Appendix II.3 and the measurement methods are given in Appendix II.4.

AII.5.2 Knot fraction

For conciseness, Appendix II.5.3 states the knot limits using the term "knot fraction" (*Figure AII.13*). This relates to the equivalent knot size "d" (see Appendix II.3.3). The knot fraction is the knot size expressed as a percentage of the full lateral or transverse dimension of the surface.

Note: This term should not be confused with "knot area ratio." This is a concept used in the visual strength grading of softwoods (BS 4978 (Ref: 6)) and accordingly having another quite different definition.

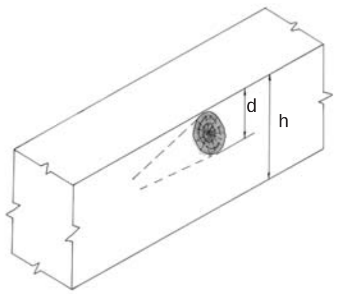


Figure AII.13 Example of a knot fraction for a margin knot. The fraction in this case is d/h Evaluate other knot types on the same principle. For knots on upper or lower surfaces, the knot fraction relates to "b" - transverse section dimension

AII.5.3 Knot limits

AII.5.3.1 Knots in bending members

Table AII.2 Maximum permissible knot fractions (%)* for medium sized ** green oak bending members

Knot location	Grade		
	A	B	C
Upper or lower surface	33%	40%	60%
Lateral surfaces: centre	33%	40%	55%
Lateral surfaces: margins***	20%	25%	33%

* "Knot fraction" relates to the equivalent knot size expressed as a percentage of the full lateral or traverse dimension of the surface.
** Size range – breadth (b) 50 mm to 150 mm inclusive and depth (h) 125 mm to 300 mm inclusive.
*** For members subjected to simple bending over a single span, the permissible knot fraction may be increased outside the middle third of the span. In these outer zones, the fraction may be increased proportionally to the distance away from the third points, until becoming 33% greater than the tabulated limit at the ends of the member.

Table AII.3 Maximum permissible knot fractions (%) for large* green oak bending members

Knot location	Grade		
	A	B	C
Upper or lower surface	25%	30%	50%
Lateral surfaces: centre	30%	33%	50%
Lateral surfaces: margins***	15%	20%	30%

* Size range – breadth (b) above 150 mm and/or depth (h) above 300 mm.
** For members subjected to simple bending over a single span, the permissible knot fraction may be increased outside the middle third of the span. In these outer zones, the fraction may be increased proportionally to the distance away from the third points, until becoming 33% greater than the tabulated limit at the ends of the member.

AII.5.3.2 Knots in posts and columns

Table AII.4 Maximum permissible knot fractions (%) on any surface in posts and columns

Grade		
A	B	C
25%	30%	50%

Note: In posts and columns, there is no margin condition. Arris knots are allocated the same knot fractions as other types.

AII.5.3.3 Knots in tension members

These are treated according to the overall structural duty of the member - see Appendix II.4.1.3. Table AII.2 or Table AII.3 applies. For limits, the alternatives are:

- *Strict case – significant tensile action*: Limit the knots in all positions and on all surfaces as if they were in the margins of a beam.

- *Moderate case – some tension with mainly bending action:* Treat the member as a simple beam.

AII.5.4 Slope of grain limits

The following limits refer to all surfaces. Combined slope of grain on adjacent surfaces should be assessed as indicated in Appendix II.4.2.

Table AII.5 Maximum permissible slope of grain

Slope of grain	Grade		
	A	B	C
Bending & tension members	1 in 13	1 in 10	1 in 7
Compression members	1 in 9	1 in 7	1 in 5

AII.5.5 Rate of growth

There is no requirement to control rate of growth.

AII.5.6 Wane

The following limits are indicative, and may be varied according to individual engineering requirements: -

Grade A: None permitted.
Grade B: 12% of whichever lateral surface displays the greater amount of wane.
Grade C: 20% of whichever lateral surface displays the greater amount of wane.

AII.5.7 Fissures

Timbers containing ring shakes should be rejected (see Appendix II.3.4).

Note: Fissures are not a prominent feature of green oak, but the following are indicative limits to assist in controlling those that may occur during frame building. The length limits relate to the wider transverse dimension of the member (depth, "h" for a beam, or the larger width for a column or post).

End splits: Small end splits are acceptable, provided their length does not exceed the wider transverse dimension, and provided they do not compromise carpentry joints or mechanical connections

Note: End splits are unusual, since they affect the carpenter's selection process (see Chapter 6), and are therefore normally eliminated before strength grading takes place. There are also practical measures to control splits in tenons after manufacture and before final assembly.

Other fissures: When measured with a 0.2 mm feeler gauge, fissures should not be more than 25 mm deep, and should not be longer than one and a half times the wider transverse dimension.

Note: On posts and columns, the above indicative fissure limits may be increased by 50%.

AII.5.8 Geometrical characteristics – members of all types

Distortion: Recommended limits to assist in restricting initial distortion in the green state are given in Table AII.6.

Table AII.6 Maximum distortion (in mm) over 2 m of length (see AII.4.6 and *Figure AII.12*).

Distortion	Grade		
	A	B	C
Bow	10	10	20
Spring	8	8	12
Twist	1 mm/25 mm of width	1 mm/25 mm of width	2 mm/25 mm of width

Note: Distortion is linked with moisture content and is therefore likely to alter with time. See Chapter 6.

Note: The discretion of the frame maker or manufacturer should be applied, since it is a merit of green oak construction that some forms of distortion can be accommodated and precision member surfacing is not normally required, especially where hand-building by traditional carpentry (see Chapter 6).

Note: Regarding cross-sectional geometry, it is not possible to give formal rules. It is the general practice in the temperate hardwood trade to supply sawn dimensions "full to nominal size." For green oak members that are subject to engineering calculations, general guidance on sawn size tolerances and reductions for processing (where applicable) may conservatively be taken from softwood standards.

AII.5.9 Abnormal defects – members of all types

Excluded from all grades: Tension wood (including that indicated by ring shakes as noted in Appendix II.5.7); excessive insect damage or that suspected of being still alive; fungal decay, including significant brown staining (see Appendix II.4.7); severe mechanical damage; combinations of knots with other adverse features.

Note: At the discretion of the frame maker or manufacturer, minor abnormalities may be accepted. These should only be features adjudged to be non-progressive with time, and not worse in strength reducing effect than the normal features allowed within the grade. In such cases, appearance criteria will also apply.

AII.6 Reference documentation

The 1984 edition of BS 5268-2 introduced grade stresses for individual species or species groups of tropical hardwoods, to be visually graded in accordance with BS 5756. For developing the design properties with these, and in setting the levels for the estimation and limitation of grading features, reference was made to an ASTM standard practice, whose current designation is D245-00 (2002)e1. Additionally, checks were made against the results of structural-sized tests conducted in the UK, in accordance with BS EN 408.

A similar approach was adopted in developing these green oak rules, and for deriving the tables of design properties accompanying them. Comparison with the results of structural-sized testing was more limited than was possible for tropical hardwoods. However, this is compensated for by the long history of satisfactory structural use of European oak in the UK.

The former BSI Code of practice for the structural use of timber, CP 112: 1952, as well as the Editions of 1967 and 1971, contained design data and grading rules for four grades of European oak. Their derivation was partially guided by principles for establishing grades and properties published in Wood Handbook No. 72, and these principles became a basis for the current standard ASTM D245. The basis of the data for the grades in CP 112 was published in Forest Products Research Bulletin No. 47.

Further guidance on the derivation of the present rules has been obtained from BS EN 518: 1995. This gives the general requirements for visual strength grading standards. Also consulted was Draft International Standard ISO/DIS 9809. This establishes basic principles for rules and procedures governing the visual sorting of timber for use in structures.

AII.6.1. Reference titles

Agriculture Handbook No 72 Wood Handbook - Basic information on wood as a material of construction with data for its use in design and specification. Washington 25, D.C. 1955.

BS EN 408: 2003 Timber structures – Structural timber and glued laminated timber – Determination of some physical and mechanical properties.

BS EN 518: 1995 Structural timber – Grading- Requirements for visual strength grading standards.

BS EN 844 Round and sawn timber. Terminology. (in various parts)

D245-00 (Reapproved 2002)e1 Standard Practice for Establishing Structural Grades and Related Allowable Properties for Visually Graded Lumber. ASTM International, Active Standard, 2004.

Forest Products Research Bulletin No. 47, Working stresses for structural timbers, 2nd. Ed. HMSO, 1965.

ISO/DIS 9709.2 Structural timber - Visual strength grading - Basic principles. International Organization for Standardization, 2004.

Appendix III Engineering design data

This Appendix gives the information which is needed to design green oak structures in accordance with BS 5268-2 (Ref: 7) and BS EN 1995-1.1 and its National Annex (Ref: 20). It is a requirement for the safe application of this data that the timber is visually strength graded by an experienced person at, or near the time of frame fabrication in accordance with Appendix II.

NOTE: The apparent inconsistency of some recommendations relating to service classes arises from the fact that both codes are written to refer to dry, rather than green material properties.

AIII.1 Strength design to BS 5268-2: 2002

Table AIII.1 gives grade stresses and moduli of elasticity for the three grades of the Green Oak Strength Grading Rules given in Appendix II.

Table AIII.1 Grade stresses for green European oak, graded in accordance with AII.4 for use in ALL Service classes

Grade	Bending parallel to grain 1) N/mm^2	Tension parallel to grain 1) N/mm^2	Compression		Shear parallel to grain N/mm^2	Modulus of elasticity	
			parallel to grain N/mm^2	perpendicular to grain 2) N/mm^2		Mean N/mm^2	Minimum N/mm^2
A	10.50	6.30	8.51	3.29	1.64	10 650	8100
B	9.17	5.50	7.43	2.65	1.43	9260	7130
C	7.10	4.26	5.75	2.05	1.11	7740	5960

1) Stresses are applicable to timber 300 mm deep (bending members) or 300 mm wide (tension members); for other sections, see BS 5268 : Part 2, Clauses 2.10.6 and 2.12.2.

2) When the specification prohibits wane at bearing areas (including those in joints), the basic perpendicular to grain stress of 3.29 N/mm^2 may be used for all grades.

AIII.1.1 Permissible stress design in green oak

The values in Table AIII.1 may be used directly for the calculation of permissible stresses in accordance with the rules in BS 5268-2 EXCEPT that the reduction factor k_2 should not be included. The resulting stresses will apply to green oak installed in ALL service classes (defined in Table AIII.3).

AIII.1.2 Design of joints with metal fasteners

BS 5268-2 Section 6 contains tables of basic loads for various fasteners. For fasteners in green oak, the ‘dry’ basic load should first be found from the tables for timber of strength class D30/40, and then modified by the factor for moisture content given for a joint in service class 3. This will give ‘green’ basic loads which should be used for timber installed in ALL service classes. Permissible loads are then calculated in accordance with BS 5268-2 Section 6.

There is a further modification for bolts where a joint made of timber in service class 3 and used in service classes 1 and 2 (in other words, a green oak joint inside a building) suffers a very large reduction factor. This addresses a concern that the green oak might split along a line of bolts as it dries out. Because of their larger diameters, the same concern does not apply to split ring and shear plate connectors.

BS 5268-2 Annex G contains the generalised formulae for calculating basic loads which are derived from the expressions in Eurocode 5 (see below).

AIII.2 Strength design to Eurocode 5 Part 1-1

Table AIII.2 gives characteristic strengths and moduli of elasticity for the three grades of the Green Oak Strength Grading Rules given in Appendix II.

Table AIII.2 Characteristic strength properties and stiffness values for green European oak, graded in accordance with AII.4, for use in ALL Service classes

Grade	Bending parallel to grain 1) ($f_{m,k}$) N/mm^2	Tension parallel to grain 1) ($f_{t,0,k}$) N/mm^2	Compression		Shear parallel to grain ($f_{v,k}$) N/mm^2	Modulus of elasticity	
			parallel to grain ($f_{c,0,k}$) N/mm^2	perpendicular to grain 2) ($f_{c,90,k}$) N/mm^2		Mean ($E_{0,mean}$) N/mm^2	Minimum ($E_{0,05}$) N/mm^2
A	31.8	19.1	19.7	7.6	4.60	10650	8100
B	27.8	16.7	17.2	6.1	4.01	9260	7130
C	21.5	12.9	13.3	4.7	3.11	7740	5960

1) Strengths are applicable to timber 150 mm deep (bending members) or 150 mm wide (tension members); for larger sections, there is no adjustment. For lesser depths or widths, the increase factor k_h should be applied, see BS EN 1995-1-1 Clause 3.2 (4).

2) When the specification prohibits wane at bearing areas (including those in joints), the clear characteristic perpendicular to grain strength of 7.60 N/mm^2 may be used for all grades.

AIII.2.1 Limit states design in green oak

The values given in Table AIII.2 may be used directly for the calculation of design strengths in accordance with the rules of Eurocode 5 Part 1-1, using a value of k_{mod} appropriate to service classes 1 and 2 for oak in ALL of the service classes.

AIII.2.2 Design of joints with metal fasteners

Section 8 of Eurocode 5 Part 1-1 gives expressions for the determination of the characteristic strength of various connections using metal fasteners. The expressions should be entered using the characteristic density of 'dry' oak, ρ_k of 530 kg/m^3. To calculate the design strength, use the service class 3 value of k_{mod} for fasteners installed in ALL the service classes.

AIII.3 The deflection of beams

The deflection of a beam under a particular load is found by using the tabulated value of E_{green} in the appropriate deflection formula.

As noted in Section 4.6, all timber beams are, in addition to their instantaneous deflection, subject to creep deflection. For dry timber in a dry environment, the creep component is small, but becomes more significant for green beams drying out in service. Eurocode 5 was the first code to introduce rules for calculating creep deflection, and they can be found in Sections 2.2.3, 3.2 and 7.2 of that code. The following is a simplified method, based on the full rules.

Creep deflection is a function of the 'permanent' load on a beam, generally made up of the self-weight of the structure (the true permanent load) together with the notional average superimposed load over time, known as the 'quasi-permanent' load. This is determined by multiplying the superimposed load by the factor Ψ_2, given in Eurocode 0 (UK National Annex, Table

A1.1 (Ref: 19)). For domestic and office structures the value is 0.3. The instantaneous deflection resulting from these combined loads ($u_{inst,G}$) is then multiplied by k_{def}, given in Eurocode 5, Table 3.2 (and in Table AIII.3) for various service classes to give the creep deflection u_{creep}. Note that the value of k_{def} should be increased by 1 for green timber installed in an internal environment. It is assumed that under permanent service class 3 conditions (ie exposed to the weather), the member will not fully dry out; hence k_{def} = 2.0, as indicated in the code.

A worked example is given below. More detailed information on the calculation of deflection is given in 'How to calculate deformations in timber structures using Eurocodes' (Ref: 44).

Table AIII.3 Values of k_{def} based on Eurocode 5 and its National Annex

Service class	**Type of construction** 1)	**Deformation factor k_{def}** 2)	
		(Dry timber)	**Green timber**
1	Warm roofs, intermediate floors, internal walls	(0.6)	1.6
2	Cold roofs, ground floors, external (protected from rain)	(0.8)	1.8
3	External, fully exposed	(2.0)	2.0

1) Extract from UK National Annex to Eurocode 5, BS EN 1995-1-1: 2004
2) Table 3.2, BS EN 1995-1.1: 2004

AIII.3.1 Example calculation of creep deflection

Beam:
Span: 4 m
Loaded width: 2.5 m
Dimensions: 165 mm x 250 mm
Grade: GOSGR /B

Loading:
self weight (permanent action) 0.35 kN/m^2
imposed (variable action) 1.5 kN/m^2 (domestic)

Actions on the beam
Permanent action
(self weight) 0.35 x 4 x 2.5 = 3.5 kN

Variable action
(imposed load) 1.5 x 4 x 2.5 = 15 kN

* quasi-permanent value of variable action
Ψ_2 x 15 = 0.3 x 15 = 4.5 kN
Therefore the quasi-permanent action combination = 8.0 kN

** Instantaneous deflection under quasi-permanent action combination:

$$u_{inst,G} = \frac{5}{384}\frac{Wl^3}{EI} = \frac{5}{384}\frac{8000}{9260}\frac{4000^3}{215\times10^6} = 3.4 \text{ mm}$$

*** Therefore creep deflection:
$u_{creep} = u_{inst,G} \times k_{def}$ = 3.4 x 1.6 = 5.4 mm

Final total deflection = $u_{inst,G} + u_{creep}$ = 8.8 mm

* Ψ_2 value: 0.3
EC 0 (UKNA Table A1.1)

** E_{mean} value for GOSGR/B oak:
9260 N/mm^2 (Table AIII.2)

Value of I: $\frac{bd^3}{12} = 215\times10^6 \text{ mm}^4$

*** Value of k_{def}: EC5, Table 3.2.
For service class 1, k_{def} = 0.6 +1.0 for green timber, see EC5 Clause 3.2 (4)

AIII.4 The self-weight of frames

For the purpose of calculating the weight of frame components and assemblies, freshly cut oak, with the cells, as well as the cell walls, full of water, should be assumed to weigh 950 kg/m^3.

AIII.5 The strength of pegged joints in tension

As noted in Section 5.3.1, the large majority of pegged joints are loaded in compression and/or shear, but an engineer may occasionally want to estimate the notional strength in tension of a pegged joint. A recent paper on the subject (Ref: 41) presents the results of a series of tests, in which typical mortice and tenon joints were loaded to failure.

Preliminary tests compared the tensile strength of joints using the three basic peg types: cleft and tapered, die driven and lathe turned (the latter as used in frames fabricated by the automated process described in Section 6.2). As might be expected, the tapered pegs gave weaker joints, due to the reduced cross section at one end. All of the peg types, however, exhibited significant post-yield ductility, with displacements of up to 20 mm before actual failure.

The main pull-out tests were made on fifteen mortice and tenon joints constructed as shown in Figure AIII.1. The results varied from 6 kN to 8 kN, with displacements of between 1 mm and 3 mm before yield. Thus for a well-made mortice and tenon joint which complied with Figure AIII.1, the short-term characteristic strength for limit state design could be taken at around 5 kN. The equivalent long-term permissible load would be between 1.5 and 2 kN. Joint slip at the service limit, ie working load, would be less than 1 mm. Figure AIII.2 shows a joint after test. More details and other tests are given in the paper.

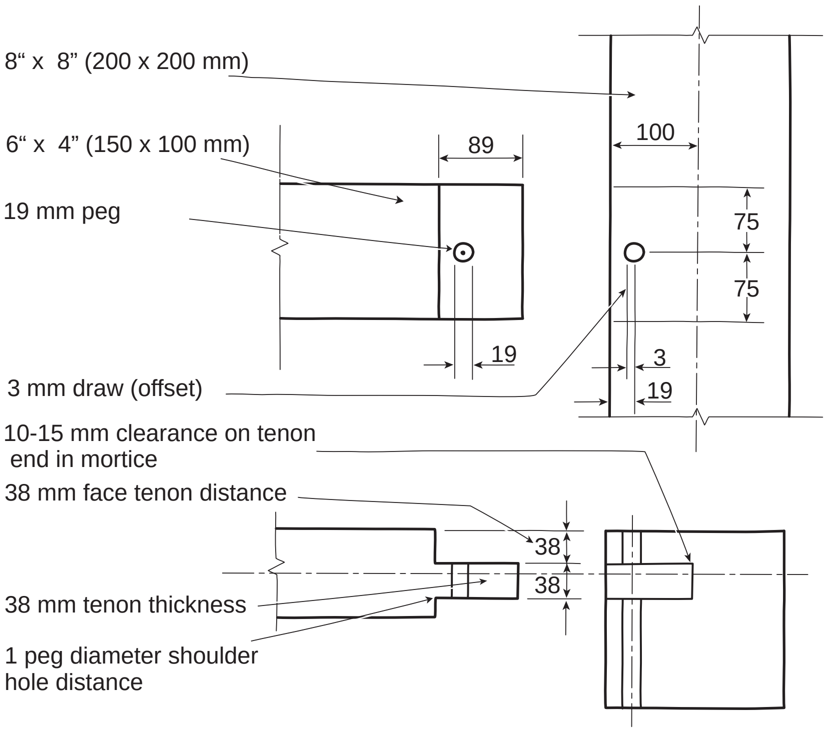
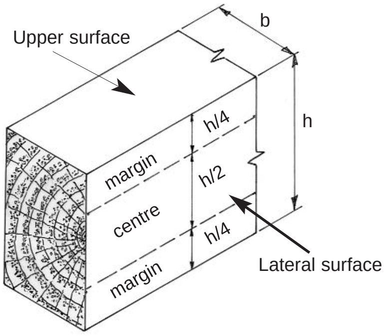


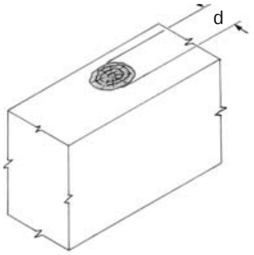
Figure AIII.1 (left) Mortice and tenon test joint (after Shanks and Walker (Ref: 41)

Figure AIII.2 “Freeze frame” specimen technique developed by J. Shanks at University of Bath - transparent epoxy resin is poured into the joint whilst it is still deformed under test. The specimen is sectioned after the resin has cured
Photo: C.Mettem

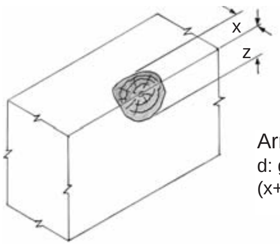
Beam zones



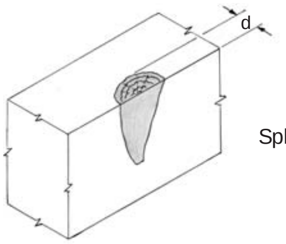
Equivalent knot size, d



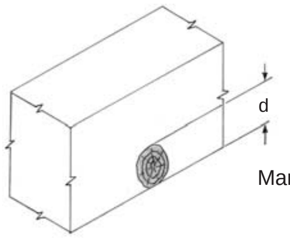
Upper (or lower) surface knot



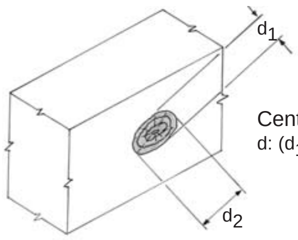
Arris knot
d: greater of (x+z/2) or (z+x/2)



Splay knot



Margin knot



Centre knot
d: $(d_1+d_2)/2$

Appendix IV Green oak strength grading rules: Quick reference sheet

This quick reference sheet can be photocopied for use when grading. Detailed guidance on strength grading is given in Appendix II.

Knot rules

Limiting knot sizes for other dimensions should be calculated from Appendix II.

Bending members

Dimension	Allowable knot size: Upper and lower surfaces (mm)			Allowable knot size: Lateral surfaces (mm)					
				Margins			Central zone		
	Grade A	Grade B	Grade C	Grade A	Grade B	Grade C	Grade A	Grade B	Grade C
75	25	32	45	12	20	25	25	35	44
100	32	44	60	20	25	35	30	40	50
125	40	50	70	25	30	40	38	50	64
150	44	64	83	30	35	50	50	64	90
175	50	67	90	32	45	60	55	75	100
200	55	70	95	40	47	65	65	83	115
225	57	76	100	42	50	75	70	95	125
250	60	80	110	45	60	85	75	100	140
300	64	88	115	50	70	95	95	120	165

Compression members

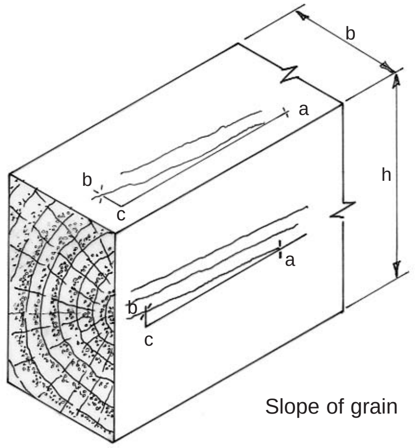
Dimension (mm)	Allowable knot size: All surfaces (mm)		
	Grade A	Grade B	Grade C
75	19	23	38
100	25	30	50
125	31	38	63
150	38	45	75
175	44	52	88
200	50	60	100
225	56	67	113
250	62	75	125
300	75	90	150

Tension members

Dimension (mm)	Allowable knot size: All surfaces (mm)		
	Grade A	Grade B	Grade C
75	12	20	25
100	20	25	35
125	25	30	40
150	30	35	50
175	32	45	60
200	40	47	65
225	42	50	75
250	45	60	85
300	50	70	95

Slope of grain

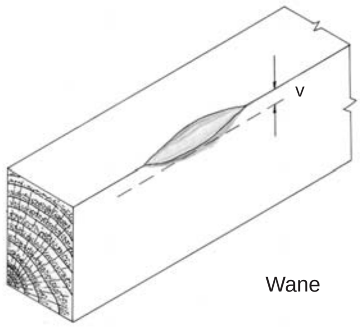
Structural duty of member	Allowable slope of grain		
	Grade A	**Grade B**	**Grade C**
Bending or tension	1 in 13	1 in 10	1 in 7
Compression	1 in 9	1 in 7	1 in 5



Slope of grain

Wane

Assessed on the lateral surface displaying the greater amount of wane	Grade A	Grade B	Grade C
Allowable proportion	0%	12%	20%



Wane

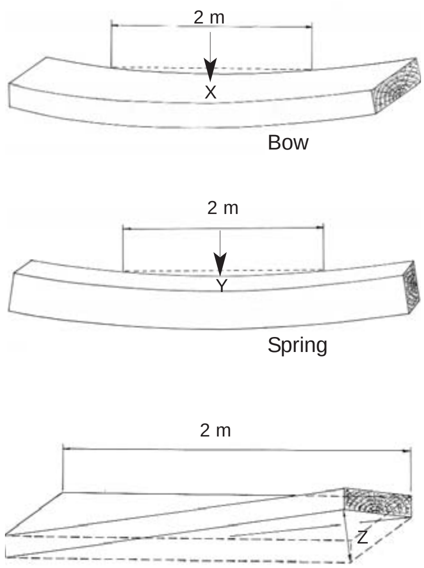
Fissures

(Pieces with ring shakes should be excluded)

	All grades
End splits	Length not greater than the wider transverse dimension
Other fissures	Not more than 25 mm deep and not longer than 1½ times the wider transverse dimension (may be exceeded by agreement with the specifier)

Distortion

Max distortion over 2m length	Grade A	Grade B	Grade C
Bow, X	10	10	20
Spring, Y	8	8	12
Twist per 25 mm of width, Z	1	1	2



Distortion

Insect/fungal and abnormal damage

	All grades
Ring shakes	Excluded
Tension wood	Excluded
Excessive insect damage or live infestation	Excluded
Fungal decay, significant brown staining	Excluded
Severe mechanical damage	Excluded
Combinations of limiting knots with other adverse features	Excluded

General notes

1	To qualify for a particular grade, a member should not contain characteristics which exceed the sizes given above.
2	For flexural members there are relaxations towards the end of simply supported spans.
3	Fissures: end splits should not compromise carpentry joints or mechanical connections.

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Glossary of terms

A selected glossary of commonly encountered terms associated with green oak construction

Adventitious growth
Shoots of fresh wood which emerge from a mature trunk or limb. See Section 6.3.4.6.

Adze
A tool similar to an axe used for roughly shaping and surfacing timber. The cutting blade is perpendicular to the shaft, while that of an axe is in the same plane.

Air dry
Timber which has been air dried by exposure to natural atmospheric conditions while protected from rain. In the UK air dry timber varies from about 19 – 23% moisture content, depending upon the species and the season of the year.

Aisle
Subsidiary space alongside the body of a building, separated from it by columns, piers or posts.

Anisotropic
A term used to describe materials whose elastic properties are directionally dependent.

Annual ring
The layer of wood produced by a tree in one growing season. See also Growth ring.

Arched braces
Curved paired braces forming an arch in a timber roof, connecting wall or post below with tie-beam or collar beam above. See *Figure 5.19*.

Arris
See *Figure 6.15*.

Arris knot
See *Figure 6.10*, *Figure 6.17* and *Figure AII.7* with their accompanying texts.

Bay
Division of an interior space as defined by regular vertical features such as arches, columns, windows etc.

Botanical names
The scientific naming of plants is based on a system adopted by a Swedish botanist, Carl Linnaeus and published in his 'Species Plantarum' in 1753. Each plant has two Latin names; a generic, or genus name and a specific, or species name which is applicable to it alone. The species name may be followed by the name (often abbreviated) of the botanist who discovered or named it. Thus *Quercus robur* L. is the botanical name of one of the species of European oak. *Quercus* indicates that it belongs to the genus of oaks, *robur* the particular species, and the botanist who published the original description of the tree was Linnaeus, abbreviated to L.

Bow
Lengthwise curvature of a piece of timber normal to the wider face. See *Figure AII.12*.

Boxed heart
Timber that contains pith but cut so that the pith is not visible on any face or edge. See *Figure 6.12* and associated text.

Brace
Subsidiary member of a structural frame or roof, generally triangulating the main frame.

Breather membrane
Membrane with a vapour resistance of less than or equal to 0.6 MN·s/g (Ref BS 4016: 1997 Specification for flexible breather membranes (breather type)).

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. See *Figure 5.29a*.

Broad-leaved trees or timbers
Broad-leaved trees produce hardwood timber. Their seeds are in an enclosed case or ovary, such as an acorn or walnut. In temperate climates they are usually deciduous, ie they lose their leaves in winter.

Cambium
Actively dividing layer of cells between wood and bark.

Carpentry
Structural woodwork.

Carpentry joints
Timber joints formed without the use of metal components.

Capillary action, capillarity
Ability of fine tubes or channels within or between materials to raise a liquid within them by surface tension.

Cats paw
A group of pin knots surrounding a central feature. Cluster of tightly packed pin knots. See *Figure 6.17* and *Figure 6.19* with its accompanying text and AII.4.1.4.

Cell
Microscopic units that make up the structure of wood and other plant tissues. The type and configuration of cells can be used in the identification of different timber species.

Cellulose
Cellulose and the related hemicellulose are complex chemicals made from sugars which provide strength and elasticity to timber.

Centre knot
The common round or slightly oval knot on the lateral surface of a beam, close to the centreline of a lateral surface. See *Figure 6.17* and AII.4.1.

Characteristic value
Value of a material property having a prescribed probability of not being attained a hypothetical unlimited test series; used directly as a basis of design in the Eurocode series and as a basis of grade properties in the BS 5268 series.

Check
Short, narrow and shallow fissure.

Cill
See Sill.

Cleft timber
Timber brought to approximately the required cross section by cleaving along the grain.

Cladding
The non loadbearing skin of walls (and roofs) used to keep the weather out.

Cogged joint
Joint where one member is supported upon another that it crosses and part of the width of one member is housed (across the grain) in the other. See *Figure 5.27*.

Collar, collar beam
Horizontal transverse roof timber connecting a pair of rafters or cruck blades, set between the apex and the wall-plate.

Condensation
Process whereby liquid water is deposited from air containing water vapour when its temperature drops to, or below, dewpoint.

Conifer, coniferous
Belonging to the Coniferae family of Gymnosperms. The trees are chiefly evergreen, with needle-like leaves and are cone-bearing. The timber is usually resinous and is classified as softwood.

Conversion
The process of cutting logs by sawing into usable sections of timber, such as beams and planks.

Corbel
Projecting block supporting something above.

Creep
The additional deformation that occurs with time after the initial elastic deformation has taken place.

Cross cutting
Cutting of timber across the grain.

Cross grain
Grain deviating considerably from the general direction of the longitudinal axis, forming an angle with the edge of a piece.

Cross-section
Section at right angles to the longitudinal axis of a log or piece.

Crown-post
A vertical timber in a roof structure, set centrally on a tie-beam and supporting a collar purlin, with longitudinal braces to it. See *Figure 5.18*.

Crucks
Pairs of inclined timbers (blades), usually naturally curved, set at bay-length intervals in a building; they support the roof timbers and, in timber frames, also stabilise the walls. See *Figure 5.12*.

CPET Central Point of Expertise for Timber Procurement
A service to provide information on the UK Government's timber procurement policy and advice on how public sector buyers and their suppliers can meet these policy requirements in practice. See www.proforest.net/cpet.

Cup
Curvature of a piece of timber across the width of the face.

Defect
Feature that mars the appearance or lowers the quality of a piece of timber.

Deflection
Deformations caused by forces applied directly to the structure.

Density
Mass per unit of volume, measured in kilogrammes per cubic metre. The strength of timber is broadly related to density. See Section 4.2.

Differential movement
Typically occurs between a timber frame and brick or block cladding supported on its own foundations as a result of shrinkage in horizontal timber elements and expansion of clay bricks or shrinkage of blocks or calcium silicate bricks.

Distortion
Change in the shape of a piece of timber or timber-based material, eg bowing, twisting or cupping, brought about by shrinkage as the timber dries. See *Figure AII.12*.

Dowel
A cylindrical rod, with or without a head, fitting into prebored holes and used for transferring loads perpendicular to the dowel axis. In timber engineering dowels are usually steel and fit tightly into the hole; in carpentry the peg is of dry hardwood fitting into a draw bored hole.

Draw boring
Boring holes slightly out of line through a morticed member and tenon and driving a timber peg or pin through the holes so the shoulders of the tenon are drawn up tight. See Section 5.3.1.6.

Drying
Process of bringing timber to a moisture content range appropriate for an intended use.

Durability
The inherent resistance of timber or timber-based products to attack by wood-destroying organisms. See Section 4.4.

Earlywood
The less dense wood formed during the early stage of a growth season, eg the spring or rainy season, when the tree is growing quickly. Also sometimes called springwood. Earlywood and latewood together form the growth rings of a tree.

End grain
Grain in which the general direction of the fibres is at right angles to the surface.

Erection
The positioning and fixing of the parts of a frame.

Equilibrium moisture content
Moisture content at which timber neither gains nor loses moisture when exposed to a given constant condition of temperature and humidity.

Extractives
Complex organic compounds, varying in composition between timber species which impart natural durability and colour to the heartwood of some species.

Feature
Physical, morphological or growth characteristics of timber.

Fibre saturation point
Hypothetical point at which all the free moisture has been removed from the cell cavities but the cell walls are still saturated with bound moisture.

Figure
Ornamental markings seen on a cut surface of timber, formed by the structural features of the wood.

Fissure
Longitudinal separation of fibres. Also sometimes called check or shake. See Sections 4.3.2 and AII.4.5.

Formaldehyde adhesives (glues)
One of a family of synthetic resins in commercial use since the 1930s. They are immune from attack by moulds and bacteria and are highly water resistant.

Framing, framed building
One in which the structure is carried by a framework, eg of timber. instead of by massive load-bearing walls.

Forest Stewardship Council. FSC
An international network to promote responsible management of the world's forests. See www.fsc.org.

General framing (GF)
Carpenters' selection class for green oak. See Section 6.3.1 and Appendix I.

Gib and cotter joint
Joint formed with a steel strap drawn tightly into position by means of steel clips and wedges. See *Figure 5.37d*.

Glued laminated timber (glulam)
Structural timber member formed by bonding together timber laminations with their grain essentially parallel.

Grade
A classification of timber and wood-based materials according to quality or performance.

Grade stress
Stress which can safely be permanently sustained by timber of a specific section size and strength class or grade; used in conjunction with BS 5268.

Grain
The general direction or alignment of wood fibres.

Green timber
Timber, freshly felled, or still containing original free moisture, ie it has not been dried to, or below its fibre saturation point.

Growth ring
The layer of wood produced by a tree during one growing season. Growth rings may be visible on the cut ends of logs and on timber sections; in temperate zones growth rings relate to annual rings.

Halves, Halved members
See *Figure 6.12* with its associated text and *Figure 6.14*.

Halved joint
A form of scarf joint in which the timber is simply divided along the face (upper surface) or side (lateral surface); often secured by pegs. See Section 5.3.1.6 ‘Scarf joints’, *Figure 5.29* and *Figure 5.30*.

Hammer beams
Transverse roof timber, akin to an interrupted tie beam, supported on a brace and bearing on a hammer post. See *Figure 2.5* and *Figure 2.6*.

Hammer posts
Vertical timber resting on a hammer beam and forming a triangle between the beam and a principal rafter.

Hardness
The resistance of wood to indentation.

Hardwood
Timber produced from broad-leaved trees.

Heart
Portion of timber that includes the pith and associated defective wood.

Heartwood
The inner zone of a tree trunk or log that, when the tree was growing, had ceased to contain living cells and reserve materials, such as starch. The heartwood may be darker in colour than the outer sapwood though it is not clearly differentiated in all species. Heartwood is normally more durable than sapwood.

Hewn timber
Timber finished to size by axe or adze; the ends are sometimes sawn.

Interstitial condensation
Condensation occurring within or between the layers of the building envelope.

Jetty
Cantilevered overhang of a storey or gable, over the storey below. See Section 5.3.1.2 and *Figure 5.14*.

Joinery
Assembly of worked timber components and panel products for purposes other than as structural timber or cladding.

Joists
Horizontal timbers laid in parallel to support the floor of a building.

Kiln dried
Timber which has been dried in a kiln, usually to a moisture content of 12% or below.

King post
A vertical roof timber set centrally on a tie-beam, rising to the apex of the roof to support a ridge-piece. *See Figure 5.35*.

Knot
Portion of a branch embedded in the wood.

Knot cluster
Groups of knots around which the fibres are deflected.

Knot fraction
Knot size compared with surface width. See Section 6.3.4.1 and AII.5.2.

Lap or lapped joint
A joining, rather than a lengthening, or scarf joint. In a lap joint, the members are connected at an angle to one another. See 5.3.1.6 'Lap joints'.

Lateral surface
See Section 6.3.4.4 and *Figure 6.16*.

Latewood
The denser wood formed during the later stages in a season, when growth slows down, eg summer and autumn or the dry season. Also sometimes called summerwood. Earlywood and latewood together form the growth rings of a tree.

Lignin
Acts as a bonding agent in the cellular structure of timber.

Limit state
States beyond which a structure no longer fulfils the relevant design criteria; used the Eurocode series.

Lintel
Horizontal beam bridging an opening.

Load
The external forces acting on a structure.

Log
Cross cut length of round timber with, or without, bark.

Machined sections
Timber sections which have been planed or fine sawn to produce an even depth and/or width.

Margin knot
A round or slightly oval knot emerging on the lateral surface, but close to an arris. See Section 6.3.4.5 and *Figure 6.17*.

Modulus of elasticity (E)
A measure of the elasticity of a material or its power of recovery after being strained.

Modulus of rupture
The extreme fibre stress at maximum load. A constant used in structural design, obtained by experiment by loading numerous pieces of the material to destruction.

Moisture content
The amount of moisture, bound or free, in timber or wood-based materials, usually expressed as a percentage of the oven dry mass.

Moisture meter
An electrical device used to measure moisture content. The electrical resistance between two probes inserted into the timber provides a reading, which should be calibrated for species or type of product from data provided.

Mortice
A socket cut in one timber to receive the tenon of another. See *Figure 5.22* and associated text.

Moulding
Sectional profile cut or machined into a member. The profiled member.

Movement
The swelling and shrinkage of wood with changing moisture content in service.

PEFC Programme for Endorsement of Forest Certification
Promotes sustainably managed forests through independent third party certification. See www.pefc.org.

Peg
A wood dowel or treenail. See Section 5.3.1.5, Pegs and pegged joints.

Permeability
The ease with which liquids, such as preservatives or flame retardants can be impregnated into timber. Permeability varies with species, though the sapwood of all species is more permeable than the heartwood. Permeability ratings relate to the heartwood of the species.

Permissible stress
Stress that can safely be sustained by a structural material under a particular condition; used in BS 5268.

Pin knot
Round or oval knot, sound, with a maximum diameter of 5 mm.

Pith
Central core of the tree that consists chiefly of soft tissue.

Plain sawn timber
Timber section produced by 'through and through' sawing where the growth rings meet the face at an angle of less than 45°.

Plank
A piece of square or waney edged sawn timber more than 50 mm in thickness.

Plate
Timber section used as a bearing for other members (always supported along its length).

Pore
Principal vascular or water conducting cell of hardwoods as seen on the end grain.

Post
Upright support in a structure.

Preservative treatment
The treatment of timber with chemicals to improve its resistance to attack by biological organisms, such as fungi, insects and marine borers.

Purlin
Horizontal longitudinal timber in a roof structure.

Quarters, Quartered log
Log sawn or split into four parts along two diameters roughly at right angles. See *Figure 6.12*, *Figure 6.15* and Section 6.3.4.1 'Quarters'.

Quartered member
Piece resulting from quartered log.

Quarter sawn timber
Quarter sawn timber has been converted so that the growth rings meet the face at an angle of more than 45°. Quarter sawing produces boards which are most stable during drying and which show attractive ray or stripe

figures. However, repeated turning of the log during cutting increases costs and produces narrow boards. Quarter sawing is therefore mostly used for producing decorative hardwoods.

Queen posts
Paired vertical or near-vertical timbers placed symmetrically on a tie-beam of a roof to support purlins. See *Figure 5.36*.

Radial section
Lengthwise section in a plane that passes through the centre ie along the radius of the tree or log.

Rafters
Inclined lateral timbers supporting the roof covering.

Rate of growth
Growth expressed as the number of growth rings per 25 mm measured radially on the end grain of a log or piece of converted timber. See AII.4.3.

Ray
Strip or ribbon of tissue extending radially in the stem. See *Figure 4.3* and associated text.

Reaction wood
Abnormal wood formed typically in branches and in leaning or crooked trunks of trees; it tends to restore the normal direction of growth.

Rebate
Step-shaped reduction formed at the edge of a member.

Ridge beam
Horizontal longitudinal timber at the apex of a roof, supporting the ends of the rafters.

Ring shake
Shake following the line of a growth ring. See AII.3.4 and *Figure AII.3*.

Ring porous
Wood in which the pores of the earlywood are distinctly larger than those of the late wood and form a well-defined zone or ring. Oak is a ring porous timber. See Section 4.2 and *Figure 4.3*.

Roll moulding
Moulding of semi-circular, or more than semi-circular, section.

Sap
Liquid, mostly water, contained in cells in a tree or timber. Sap is the means by which dissolved food and salts are moved around the tree.

Sapwood
The outer zone of a tree trunk or log, which in the growing tree contains living cells and conducts sap. Sapwood is generally lighter in colour than the inner heartwood, though they are not clearly differentiated in all species. The sapwood is more vulnerable to attack by biological organisms such as fungi and insects but is also usually more permeable than the heartwood making it easier to treat with preservatives.

Scarf joint
A joint between two timbers meeting end-to-end; a lengthening joint. See *Figures 5.29* and *5.30*.

Seasoning
– see Drying.

Serviceability limit state
A state that corresponds to conditions beyond which specified service requirements for a structure or structural member are no longer met (eg deflection limits). Used in the Eurocode series.

Short grain
Grain deviating considerably from the general direction of the longitudinal axis, forming a relatively sharp angle with the edge of a piece.

Shake
Separation of fibres along the grain. Note: European Standards use the term fissure, rather than shake.

Shear
A tendency for one part to slide over another.

Sheathing
Manufactured sheet or board used as a bracing.

Shrinkage
The reduction in size of a piece of wood which occurs during drying.

Sill
The lowest member horizontal member of a framed partition, of framed construction, or of a frame for a window or door.

Slab
Exterior portion of a log, removed by a saw in the process of conversion, that has one sawn surface, the other being the outside of a log.

Slope of grain
Angle between the direction of the grain and the axis of a piece. See *Figure 6.7* and AII.4.2.

Softwood
Timber from coniferous trees.

Span
The distance between the supports of a structural member or component.

Species
The botanical classification of trees and timber. The Latin species name defines a timber more accurately than common names which are sometimes used for more than one species of timber, or may vary between countries.

Spiral grain
Grain that follows a spiral course in one direction around a log.

Splay knot
Knot cut more or less parallel to its axis so that the exposed section is elongated and emerges on an arris. See *Figure 6.17* and associated text, and AII.4.1.

Sprocket
Short rafter fixed at a lower pitch than the rest of the roof.

Sole plate
Plate at the base of a wall.

Special framing (SF)
Carpenters' selection of green oak. See Section 6.3.1 and Appendix I.

Split
Separation of fibres along the grain forming a crack or fissure that extends through the timber or veneer from one surface to the other. Note: European Standards use the term fissure, rather than split.

Spring
Lengthwise curvature of a piece of timber in a plane normal to the edge. See AII.4.6 and *Figure AII.12*.

Spring wood
– see Early wood

Straight grain
Grain that is straight and parallel or nearly parallel to the longitudinal axis of a piece.

Strength class
The strength of timber varies with species and is also affected by characteristics such as knots, slope of grain, splits etc. Each piece of timber used structurally therefore is graded, either by visual inspection or by machine. Species and grade combinations of similar strength properties are grouped together into strength classes for solid timber, defined in BS EN 338.

Strength grade
The strength of a piece of timber is affected by characteristics such as knots, slope of grain , splits etc. Classifications arising from the assessment of such factors are known as strength grades. See Sections 6.3.2 and 6.3.3.

Strength ratio
The hypothetical ratio of the maximum strength of the actual graded piece compared with that a perfect timber.

Structural timber
Timber used in framing and load bearing structures where strength is a major factor in its selection and use.

Stud
Vertical member in a framed construction or partition.

Summer wood
– see Latewood.

Sustainably sourced timber
'Sustainable source' in the context of the timber procurement policy refers to production and process methods that minimise harm to ecosystems, sustain forest productivity, ensure that forest ecosystem health and vitality is maintained and ensure forest biodiversity is maintained. (Ref: CPET)

Tongued and grooved T&G
An interlocking joint, commonly used in flooring, where a protruding tongue on one edge of a board fits into a matching groove in the edge of the adjacent board.

Tangential section
Lengthwise section in a plane tangential to a growth ring, ie at right angles to the radius.

Tannin
An acid contained in the bark, wood and excrescences of many species of trees. It influences the colour and increases the durability of wood. See Section 4.8.

Tenon
A rectangular projection, usually of less than the full section, cut at the end of one timber to enable it to fit into the mortice of another. See *Figure 5.22* and associated text.

Tension wood
Reaction wood formed typically on upper sides of branches and of leaning or crooked trunks of hardwood trees.

Texture
The structural character of timber as revealed by touch or reaction to cutting tools. The texture of timber is determined by the distribution and size of the various cell types.

Thermal conductance
Thermal transmission through a unit area of material, or a structure, divided by the temperature difference between the hot and cold faces in a steady state condition.

Thermal resistance
Reciprocal of thermal conductance.

Through and through sawing
Method of sawing logs by parallel cuts in the general direction of the grain.

Tie beam
Main horizontal transverse timber in a roof structure, which carries the feet of the principal rafters at wall level.

Treenail
A hardwood pin driven into a hole bored across a mortice and tenon joint or other joints in carpentry. (Now more often referred to as a peg).

Truss
A triangulated roof component, usually spaced at distinct centres, often carrying purlins that in turn support common rafters.

Twist
Lengthwise spiral distortion of a piece of timber. See AII.4.6 and *Figure AII.12.*

Ultimate limit state
A state associated with collapse or other similar forms of structural failure. Used in the Eurocode series.

UKWAS UK Woodland Assurance Standard
An independent certification standard for verifying sustainable forest and woodland management in the United Kingdom. See www.ukwas.org.uk.

U-value
Thermal transmittance or a measurement of heat loss. Expressed as W/m^2 K.

Upper surface
See Section 6.3.4.4 and *Figure 6.16*.

Vapour control layer (VCL)
Material (usually a membrane) that substantially reduces the water vapour transfer through any building component in which it is incorporated by limiting both vapour diffusion and air movement.

Vapour resistance
Measure of the resistance to water vapour diffusion of a material or combination of materials of specific thickness.

Visual strength grading
Process by which a piece of timber is sorted into categories in order to allocate reliable strength and stiffness values to it, and that can be carried out entirely by visual inspection of surface or cross-sectional characteristics or defects. See Sections 6.3.2 and 6.3.3.

Wane
The original rounded surface of a log, with or without bark, remaining on any surface of a sawn timber.

Additional references used in compiling this glossary

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