Practical engineering considerations when using solid hardwood to replace steel and concrete structure

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Abstract

This paper by a practising engineer discusses opportunities and challenges in the use of solid timber and particularly local hardwoods in a rapidly evolving market. Case studies are taken from both the restoration of historic buildings and the provision of genuine low-carbon structures in new-build.

The Author argues that the timber industry needs to prepare for a surge in demand from construction as structural alternatives are sought to high-carbon steel and concrete. This need will be particularly exacerbated once the hazards from carbon emissions start to be included in risk assessments. Opinions from a survey of engineers indicate that timescales could be very short and that many codes of practice will need to be revised to meet the new challenges.

There is a need for hardwood to be prepared and made ready for use in the construction industry, and this would add significant value to the timber. Data is also needed for all the varieties of local timbers that could be adopted for structural use covering curing, shrinkage, practical methods to assess the structural capacity of one-off old or new logs, and guidance on the strength of timber connections for the various and diverse species. Regional expertise and education in timber engineering needs to be developed and this could be assisted through widespread research at universities.

1 Introduction

The use of timber in construction is on the cusp of a revolution and is already entering very exciting times. Approaches that were reserved for historic monuments are now being introduced to public buildings and domestic houses. Varieties of solid timber are being used in structural ways probably not previously considered in current codes of practice. Joints are being created such as moment connections in mortice and tenon sway frames and in curved knee braces, which by definition fall well outside the normal visual grading requirements.

There is growing demand for green buildings that utilise well-established timber stud panels (timber framing), but which also need to use solid chunky timber or glued laminated sections in place of steelwork or precast concrete beams and lintels. It is worth noting that this usage already has to compete with growing demand for logs for domestic fuel and commercial power stations. With the onset of measures to fight global warming, timber will shortly be needed in forms and quantities that are difficult to grasp. This paper sets out to illustrate some of the issues and challenges for a re-emerging rural industry.

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2 Use of Hardwoods

2.1 Challenges with solid hardwood in typical projects

While the design and supply of sawn softwood, ply sheets and engineered products appear to be very efficiently managed, engineers working on historic structures have long been aware of the problems of assessing the structural capacity of historic timbers and with replacing them if necessary (see paper by Kennedy and McGregor). As new buildings increasingly seek authentic or low carbon solutions, the design team face several challenges:

1. Finding a source of suitable timber, especially if there is a requirement for it to be locally sourced and a structural need for a hardwood grade to take high loads. Leaving the sourcing in the hands of the contractor raises its own problems.

2. Deciding on the structural properties of the timber logs and the connections based on a visual assessment of the members and tables of properties that are readily available (Figure 1).

Summary of Properties of Structural Timber

From British Grown Hardwoods by Trada Technology Ltd

Structural & Civil Consultants Ltd

	Density	MOR	E	Charring rate	Properties	Workability		Moisture movement	Sizes	Chemical	Colour
	kg/m3	N/mm²	kN/mm²	mm per 30min							
Ash (Fraxinus excelsior)	710	116	11.9	15mm	Resistant to split	Drill nail holes	Internal only. Difficult to treat.	Med movement in varying humidity	250mm	Not significant	Pale
Beech (Fagus sylvatica)	720	118	12.6	15mm		Drill nail and screw holes	Internal only - easy to treat	Large	250mm	ferrous stains when wet	
English Oak (Quercus robur, Quercus petraea)	720	97	10.1	15mm		Drill nail and screw holes	heartwood durable	Large when green. Med in varying humidity	250mm	highly acid- fixings to be protected or non-ferrous	Light yellow brown sapwood. Darker heartwood
Sweet chestnut (Castanaea sativa)	560	79	8.2	20mm	Poor impact resistance. Splits	Drill nail and screw holes to prevent splitting.	Heartwood durable, sapwood difficult to preserve.	Small movement	250mm	highly acid- fixings to be protected or non-ferrous	Light yellow brown sapwood. Darker heartwood
Sycamore (Acer pseudoplatanus)	630	99	9.4	20mm	Medium resistance to impact	Drill nail and screw holes to prevent splitting.	Internal only - easy to treat	Med movement in varying humidity	250mm	Not significant	No difference in colour between heart and sap

Figure 1 Extent of easily available data on British hardwoods

3. Having confidence that any critical structural member does not have a hidden weaknesss, especially if it is an un-sawn log or second-hand beam. Assessing timbers in the round that have “history” is very different from grading straight-sawn new hardwood to BS 5756.

4. Finding a manufacturing facility or a carpenter either to follow the engineering drawings, or to design and draw the required details.

5. Having some measure of confidence that curing has progressed far enough to prevent major defects appearing as the timber dries.

6. Gaining agreement from the client on the degree of movement that might be expected as the timber dries out and as it moves with each season change.

For most clients and design teams, these problems are currently almost insurmountable. Design teams and their clients need to be very dedicated to avoid using engineered timbers, steel sections or the precast concrete.

2.2 Case Study 1 – School Building in Oak

Figures: 2-4 School Structure in oak, but it was fortunate that the major shake occurred at the bearing above the ceiling line and could only be seen from a service area.

Several typical problems arose when trying to use local timber instead of steel at the central hub and in the library of a primary school.

- The timber was not seasoned – it was fortunate that the large shake was not structurally or visually significant.
- The timber could not be supplied from local woods as they were not certified as “sustainable”, so the timber supplier insisted on importing the oak.
- Oak was not the best type of timber for such internal use.
- Other hardwood timbers with more suitable properties than oak were not available (at any price).
- No official grading was carried out.

- There were numerous telephone calls from concerned architects, builders and timber suppliers.

2.3 Promotion of regional use for local timbers

There appear to be several impediments to improving use of local timbers at a regional level:

1. Very few engineers and architects appear to have knowledge of timber frame sheathed construction never mind other timbers, grading techniques etc.

2. Timber research in the UK appears to take place at very few locations and there are no trade bodies to promote use of small-scale production.

3. Most universities have little or no expertise with structural timber and timber engineering does not generally appear to be taught to undergraduates.

4. The steel and concrete industries have powerful trade bodies, which even appear to state that use of steel or concrete is more carbon-friendly than timber. Small-scale isolate suppliers of hardwoods have no such support and even sustainability measures prevent them using timber in construction (Case Study 1).

5. The growing need of bio-fuel industrial furnaces and domestic stoves provide a convenient outlet for all timber .

On the other hand, hardwoods could be used as a valuable rural or even urban resource. Although British woods have not usually been managed for timber production (as in France), most trees could yield at least a lintel if harvested before decay sets in.

The author’s practice, with help from Sustainability Development Grants from the Yorkshire National Parks, set up GreenBeams.com as a way to develop and add value to unused hardwoods by preparation for use in construction. The web site acts as a forum to pass on the limited knowledge on hardwoods, but was particularly intended to promote the storage of hardwoods to allow curing to commence.

After training for the visual grading of hardwoods to BS5756, the practice realised that it also needed to fabricate a mobile test rig so that the stiffness of un-graded species, structurally critical members, or possibly sub-standard logs could be checked on site, in the forest or at the sawmill (Figure 5). It has also been interesting to correlate the ultimate capacity of sawn members with their visual grading

While the Institution of Civil Engineers and the Centre for Timber Engineering expressed initial interest with helping with this development project, another official research body has strongly opposed the initiative.

It was effectively suggested that there is already sufficient data about a few hardwoods. There was also denial that the codes allow scope for engineering from first principals but stated that the capacity of a log should be determined via a series of grade stresses tests to EN408 on samples in a lab, with analysis to EN384. It then suggested that the capacity of the log could be derived using visual grading.

Ignoring the cost of such testing, unfortunately, even the visual grading aspect is not very practical when dealing with many unsawn hardwood logs in construction. Most existing old hardwood beams would fail aspects of the visual grading, yet clearly have much structural capacity (Figure 5). Conversely with uncut timber there are concerns about relying solely on visual techniques to reveal possible hidden defects in important structural members.

It is very reassuring to note that many of the papers at this conference seek to address the issues of curing, shrinkage and strength grading by alternative techniques.

Figure 5 Portable test rig capable of 10Tonnes point load for checking the ultimate strengthen or the stiffness of beams between 2 to 6m long. It would not be considered practical or safe to determine the capacity of this uncut and curved sycamore log by using just visual grading and currently available data.

3 Historical Perspective on Structural Timber

3.1 Observations on hardwoods

From working with both historic buildings and insurance claims on recent framed timber buidings, there has been scope to consider the use of various hardwoods. Other historical evidence also suggests that there may be more to some hardwoods than is currently known.

1 Oak is the preferred structural timber, and its durability is much appreciated for external use. However as only oak (and chestnut in the South of England) are considered durable, there is concern that current stocks of oak might be soon exhausted. Preservation of oak stocks has been a constant concern in England since the C16th.

2 For internal use, the curing times for oak and its continuing dimensional changes with moisture is a problem. Other hardwoods might have better properties, (Figure 1) while Douglas Fir will often suffice and is much more geometrically stable if appearance is not critical.

3 Elm was usually only used where anti-splitting properties were needed and 6 million elm trees were destroyed in the 80s after Duch Elm Disease. Timber in the open decayed within months and very little now remains of the stock. However elm was frequently used for structural members in C19th and is usually now in an extremely hard and durable condition.

4 Similarly, alder was historically renowned for its soft texture, which then became hard and durable once cured. (See reported problems with decaying alder piles in the reconstructed crannog on Loch Tay)

5 In the Pennines, buildings were historically constructed in ash yet local sawmills refused to sell for that purpose until recently. The Author is now involved with the design of a whole building in ash.

While oak has properties that allow it to endure for centuries, another major advantage of oak is that it has value, so it is stored for profit and made available over a range of moisture contents. Other British hardwoods timbers are not generally available in this way, mainly because no one has developed a market so the trees are left to rot, or are cut up for firewood. As previously discussed, there is much scope to research other hardwoods to reveal ‘lost’ knowledge of their properties and to develop a market for timbers that have been cured and are ready for construction

3.2 Case Study 2 – Historical Church Roof

A fire destroyed the roofs to the Norman and Mediaeval Grade I Listed St Michael and All Angels, Newburn on the banks of the River Tyne in 2006. It was hoped that the nave roof could be reconstruct with trusses similar to the single surviving Victorian member, but in a local timber such as beech or ash. As such timbers were not available at a reasonable moisture content, it was decided to follow the Victorian precedent and use imported pitch pine.

The Victorians used wrought iron strap at connections which were a conveniently clue to their construction date. The new trusses would have used Black Bolts if they had been constructed in the late C20th. As an indication of the green C21st, the trusses were designed with all timber joints. It is generally found that relatively high loads are easier to design with timber connections than with many common bolted joints. However the characteristics of the joints reflect the species, and there was surprise over how weak the tenons were to shear or shrinkage on a tangential plane to the growth of the pine. More advice needs to be given on this crucial aspect of timber engineering.

The trusses were intended to be manufactured off site under the management of the contractor. While this approach works in the steel industry, the timber industry has inadequate experience and much time had to be spent on site assembling the elements that had inadequate tolerances for mortice and tenons (Figures 6-8).

Figures 6 & 7 New trusses constructed in Caribbean pitch pine as no British dry beech or ash was available. Note connections in timber.

When it came to the new spire, the new structure was designed around the known experience of the site carpenters using Douglas Fir (Figure 9). It was initially prepared at ground level in a nearby unit before being dismantled for re-erection on top of the Norman tower.

Figure 8 & 9 The pitch pine trusses were delivered as the worst flat-pack nightmare. The spire was constructed without difficulty on site using Douglas Fir, although this was imported rather Scottish..

4 Green revolution and timber

4.1 The effects of needing to address carbon emissions on timber

Even avid supporters of timber will probably have a few surprises concerning how timber will be used in the future. At present only a tiny fraction of structures make use of timber, but recent steady developments may significantly change the need for genuine low-carbon materials in construction:

1. The 2009 State of the Nation Report on climate change by the Institution of Civil Engineers advised that carbon should become a key feature of all design.
2. The Engineering Council (UK) issued advice in 2009 that risk assessments should be carried out on all projects to include the long-term effects of carbon emissions.
3. The early May 2010 edition of the Structural Engineer will have a paper by R Thorniley-Walker on “Data for Inclusion of Carbon Emissions in Risk Assessments”.

This last paper uses “reasonable” values for dangers and probabilities derived with opinions from a questionnaire survey of members of both the Institution of Structural Engineers (IStructE) and the Institution of Civil Engineers (ICE) and their associates in the Northeast of England, supplemented by data from IPCC(2007). The hazards and the probabilities are orders of magnitude higher than normal civilian projects and it is suggested that risk assessments should assume that one person will die from climate change for every twenty tonnes of CO_2 released. Furthermore, the paper suggests that mitigation of emissions from construction should not consider benefits beyond 10 years into the future.

Although it is possible that climate change will continue to be ignored for a few more years, clients, consultants and site staff may be looking much harder for green alternatives to high carbon materials such as steel, concrete, bricks and blocks and the timber industry could face an insatiable demand.

Another linked aspect of such foreseeable change is that timber codes will need to be revised to cater for new conditions associated with global warming, but also to realign the new definitions of ‘safe’ under the new forms of risk assessment (Figure 10).

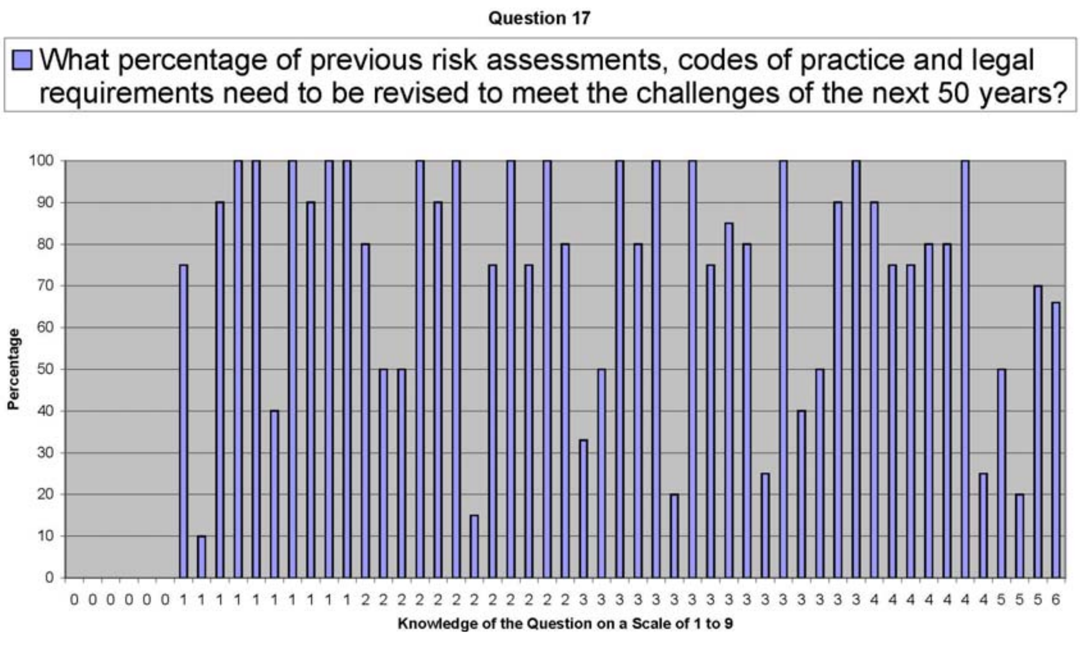

Figure 10 Results of questionnaire survey from and engineering-based study of attitudes to climate change indicating a mean of 73%

4.2 Case Study 3 – North York Moors National Park Visitor Centre

This 2006 project illustrates a project where the client wanted a low carbon structure and was delighted to find that the structure could be sourced locally. By rejecting the sedum roof, the steel in the concept design could be replaced by timber. The project had the following unusual characteristics:

- The oak was felled and sawn to order and was therefore very green on arrival at site.
- The architects took some persuasion that clean Ikea-type sharp edges would not be advisable due to shrinkage and distortion. All arises needed to be shamfered and the caretaker had to remove further sharp edges a year after installation where shakes had raised splinters.
- At the end of the project the design team questioned whether there might have been scope to cut the concrete foundations to reduce the carbon footprint still further.
- 6.7 Tonnes of CO_2 were saved by avoiding a steel frame and 9.3 Tonnes of CO_2 have been captured in the oak for the next few centuries.

Figures: 11-13 Use of local oak felled and processed for the purpose and detailed to allow for shrinkage.

5 Concluding Study

5.1 Conclusion

The engineering profession has and an excellent choice of sawn softwood joists, ply and engineered beams available for most engineering applications. However such members are not suitable for all locations and there can be real challenges for structural engineers when trying to assess existing timbers or when using large solid timbers that have not been through the normal quality control measures. There is much scope to develop the training of engineers along with the supply and fabrication processes to timber engineering up to standards expected with steelwork. Engineers need to be equipped with research data on how the timbers will behave structurally and during the process of moisture changes.

5.2 Case Study 4 – Three planned Park and Ride Terminals

Figure 14 – One of three terminals which would ideally be constructed with a timber sub-structure and super-structure

Many projects use cedar cladding to disguise high-carbon construction but still achieve very good BREEAM assessments. A set of three projects for the City of York gave an opportunity to try from the concept stage to minimise the carbon footprint of the structure. Potential timber aspects include:

1. One of the terminal buildings will be sat on 5m of household waste. It is proposed to use 35 Scots Pine timber piles, 10m long, which would have the following advantages:

   a. "Stout" poles 285 tapering to 190mm would be adequate to take the 110kN required load down to the ground beneath the waste.

b. The poles would be naturally tapered so that negative skin friction will be reduced as the waste settles, but resistance in the underlying clay would be increased.

c. The tapered and pointed piles would minimise risk of contamination of underlying aquifers by driving through the waste rather than displacing it in the manner of rectangular concrete piles..

d. The timber would not be durable, but the pine can be thoroughly treated to give the 50 year life expectancy.

e. Timber piles are rarely used in the UK but can be easily driven and cut to length. Many historic buildings have timber piles.

2 The terminal building will have a completely timber structure making use of stud walling and large section timber beams and posts. These would ideally be ash or beech if they can be supplied at the reasonable moisture content, but can be engineered beams if necessary.

3 There have been discussions over using timber poles to support lighting. Limited research found recent examples where varnished timber poles were manufactured using dried and glued strips bonded around a steel pole. The design team had reservations that timber could comply with the codes of practice (EN40), but these boiled down to aspects such as fatigue (a problem with metals) and flexure (a structural problem). Field research found plenty of impregnated timber poles dating back to 1951 and last inspected in 2002 that had never needed any maintenance while adjacent street furniture was about to be replaced for the third generation.

With such features, the project stands a good chance of gaining the landmark status that the client is seeking.

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Results of questionnaire in advance of a paper presented by Robert Thorniley-Walker MA(Oxon) CEng FICE FISructE MIHT IHBC to a joint meeting of the Institution of Civil Engineers with the Institution of Structural Engineers and guests held at Teesside University in November 2008, professor David Lilley in the chair www.Structural.org.uk/Climate.html