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Behaviour and modelling of timber structures with reference to robustness

Sven Thelandersson
Lund University, Sweden

Daniel Honfi
Lund University, Sweden

Summary

A general description of the behaviour and modelling of timber structures in relation to requirements for robustness of structural systems is given. Basic material characteristics for wood and different types of wood products are described as well as the most common types of joints. A brief review of expected failure modes for elements, joints and typical wood based structural systems is included. Structural properties such as resistance, ductility and redundancy are described for timber elements and typical timber structural systems.

The properties of timber and various wood based products are not ideal for achieving robust systems due to the risk for brittle behaviour and the anisotropic nature of wood in certain loading modes. Timber also exhibits large spatial variability which must be accounted for in modelling and assessment of reliability. On the other hand, dowel type joints which are frequently used in timber structures show high ductility when properly designed. The relatively low self weight of timber structures implies low loads in post failure scenarios and limited dynamic effects. Appropriate models are available to analyse structural timber systems in post failure modes. Good results can often be achieved by elastic material models for timber components and non-linear models for joints combined with geometrically non-linear analysis.

Keywords

Timber, engineered wood products, joints, ductility, brittleness, anisotropy, shear walls, robustness

Background / Introduction

According to the Memorandum of Understanding, Activity 5 of COST TU0601 deals with structural behaviour models of relevance for robustness. This fact sheet gives an overview of the behaviour of timber structures in relation to requirements for robustness of structural systems. Structural properties such as resistance, ductility and redundancy are described for timber elements and typical timber structural systems. Basic material characteristics and different types of wood products are described as well as the most common types of joints. A brief review of different failure modes for elements, joints and typical wood based structural systems is included.

Problem statement / Key issues

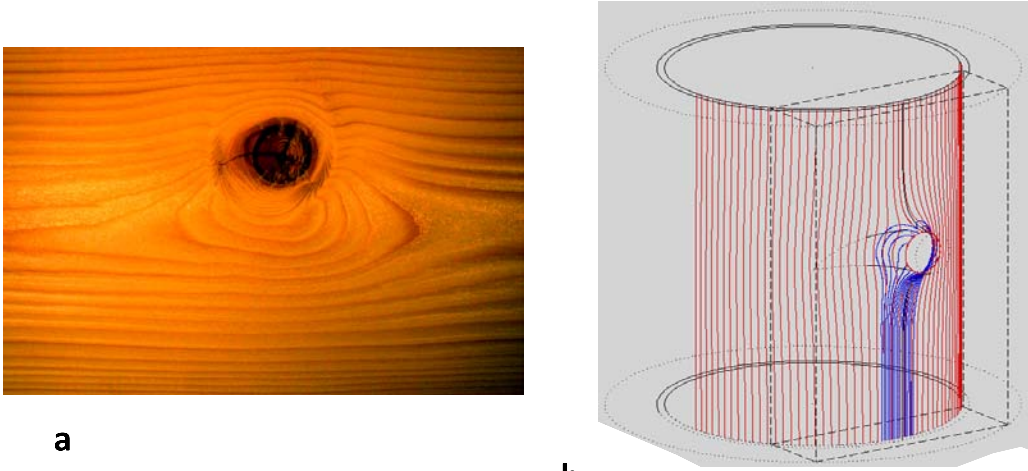
In the context of robustness the main use of structural models is to describe the degree of sensitivity of structural systems to extraordinary types of exposures often leading to local failure. The requirements on the structural model should be that it must predict the mode of failure and post-failure behaviour in a realistic manner. Key issues are ductility, energy absorption, redundancy and geometrical non-linearity. When considering timber structures as a class it is also important to include different types of engineering wood products apart from sawn timber. Such products can have different properties of importance for the structural response. Furthermore, a very important part of structural systems are its joints. This is particularly important for timber structures, where a great variety of joints can be found in practice.

Limitations

The discussion in this fact sheet mainly concerns issues of relevance for such timber structural systems where robustness can be expected to be an issue due to the importance of the built facility.

Basic material characteristics of wood

The material wood is biologically “produced” in the growing tree to meet the needs of the tree itself. The wood cells are predominantly oriented in one direction, called the fibre direction or grain direction. This is the strong direction, generally parallel with the longitudinal axis of the stem. In the vicinity of branches, the fibres are redirected to form very efficient “structural” joints between the stem and the branches, see Figure 1.



a

b

Figure 1: a) The fibre orientation around a knot creates a structurally efficient joint between branch and stem; b) The fibre structure resembles flow lines around the knot

Both strength and stiffness in the fibre direction are very large in relation to the weight of the material, especially in tension. Table 1 shows a comparison of strength/density ratios for some structural materials.

Material	Density kg/m^3	Strength, MPa	Strength/Density 10^{-3} MPa· m^3 /kg
Structural steel	7800	400-1000	50-130
Aluminium	2700	100-300	40-110
Concrete, compression	2300	30- 120	13-50
Clear softwood, tension	400-600	40-200	100-300
Clear softwood, compression	400-600	30-90	70-150
Structural timber, tension	400-600	15-40	30-80

Table 1: Strength/density ratios for some structural materials

For clear wood this ratio is significantly higher than for other building materials. Also in the case of structural timber, where natural defects reduce strength, the strength in relation to weight is of the same order of magnitude as ordinary structural steel.

Structural timber

Sawn timber in structural dimensions is a non-homogeneous material, which contains growth defects in the form of knots, zones with compression wood, oblique fibre orientation, etc. Such growth characteristics, which once were created to serve the needs of the tree, will usually reduce the strength significantly when the timber is cut and used for other purposes. This is illustrated in Figure 2.

Clear wood

Structural timber

Figure 2: The difference between clear wood and structural timber

Due to the large spatial and random variability in strength and stiffness, the mechanical behaviour of timber can not be derived with any reliability from properties of clear wood. The presence and character of knots and other defects vary from one timber board to another, which means that the structural properties of sawn timber exhibit a significant variability. Strength properties of structural timber are therefore usually determined by direct testing of timber elements according to a standardised methodology, and strength is defined on the element level rather than on the material level. Strength data associated with structural timber therefore reflects moment, tension, compression and shear capacity of a timber element, even if the data are expressed in stress units, obtained assuming that the theory of elasticity is valid. The bending strength, for instance, is defined as the moment capacity of a timber beam determined by testing, divided by the elastic section modulus. The influence of defects is implicitly included in the strength values specified, and they can only be applied if the stresses are determined by elastic theory.

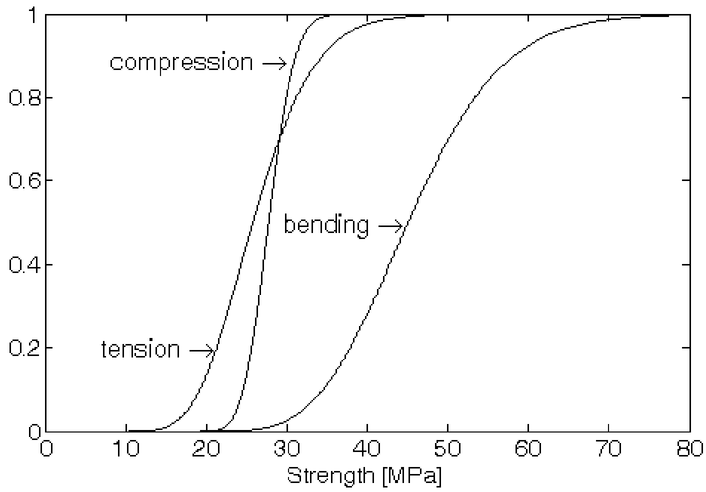


Figure 3: Typical cumulative distributions for strength of structural timber (Spruce, Picea Abies, grown in Scandinavia) in different loading modes. Hansson & Thelandersson (2001)

Consequently, different strength values are valid for different loading modes such as bending, tension and compression. Figure 3 shows typical cumulative distribution functions for strength of timber in tension, compression and bending. The coefficient of variation for bending strength of structural timber is in the range 20-40 %, depending on species and growth conditions as well as on the method and strategy used to grade the timber.

Anisotropy of wood

Wood is anisotropic, i.e. its physical properties depend on direction. The tension strength is 30-50 times smaller perpendicular to grain than in the fibre direction. The weakness exhibited by wood in cross grain directions must always be carefully considered in design and detailing of timber structures. Tension failure in this direction is also highly brittle.

Failures of timber structures observed in practice are often due to tension perpendicular to grain, which commonly occurs e.g. in curved elements, in joints in timber structures, see Figure 4 , and in discontinuities created by wholes and notches in timber members. The effective load bearing capacity of timber members under tension perpendicular to grain depends on the magnitude of the stressed volume since the probability of failure increases with volume.

Our present understanding of fracture processes related to perpendicular to grain failure is limited. In engineering design, empirical rules for detailing, such as minimum recommended distance between fasteners as well as edge distances in mechanical joints, are commonly employed to avoid the risk for splitting failure. The reliability of such design methods is limited, however, especially when they are applied in large scale real world situations, different from the laboratory tests they are derived from.

Wood has also low strength in compression perpendicular to grain, but here the behaviour is very ductile, which may be utilised in design for robustness.

The strong anisotropy in wood is also valid for stiffness properties. The elastic modulus perpendicular to grain is typically 50-80 times smaller than parallel to grain. When wood is subjected to compression perpendicular to grain significant deformations will occur already at low load levels.

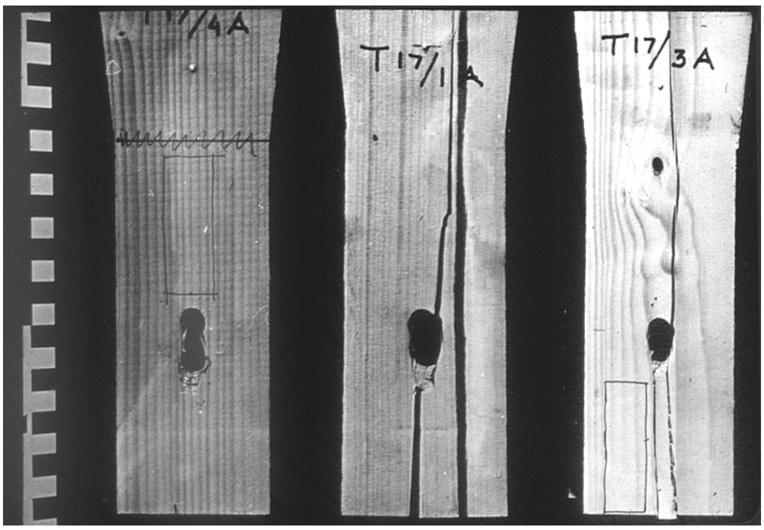


Figure 4: Failure in tension perpendicular to grain in timber joint.

Engineered wood products

Engineered wood products (EWP) represent a broad class of materials intended for structural use. They are typically produced from wood which has been processed to smaller fractions by sawing, peeling, chipping, slicing or defibration. The wood constituents used for EWP can be sawn laminations, veneers, strands, flakes or sawdust. The constituents are bonded together to form panel products, timber-like elements in different sizes, or shaped structural products. The bonding between constituents is most often made with adhesives mixed with the constituents or sprayed on their surfaces, with application of heat and pressure in the production process. One type of products is made by gluing solid sawn timber or laminations into larger structural members. Some examples are shown in Figure 5.

Among advantages with EWP can be mentioned that the strength reducing effects of defects present in solid wood will be more or less neutralised, depending on the type of product. The growth defects of solid wood are either removed in the production process or distributed in the finished product so that the strength is less affected and the variability of the product becomes smaller. This means a more efficient utilisation of the material. As an example, the probability density functions for glulam and structural timber are compared in Figure 6. Although glulam is made from laminations of structural timber, the decisive strength, defined as the 5th percentile, is significantly higher for glulam than for timber. The reason for this is the load sharing between laminations in the glulam, which allows locally weak zones to redistribute stress to adjacent stronger regions. Similar mechanisms affect the properties for other types of EWP.

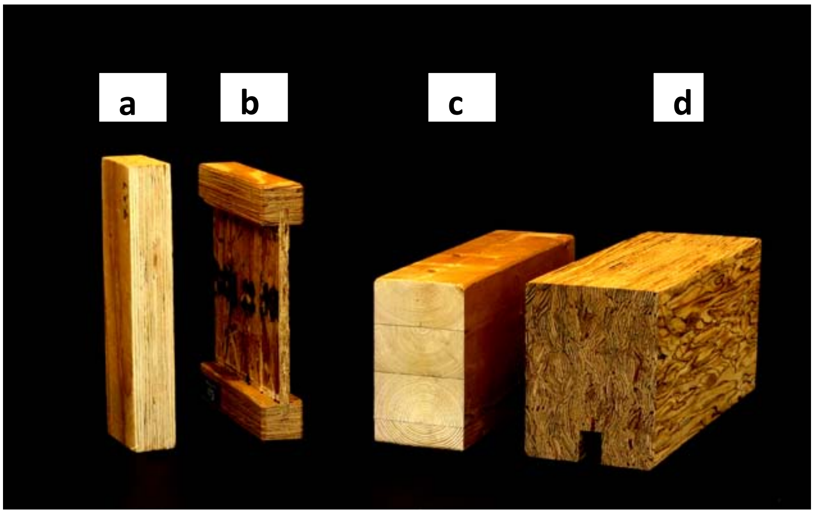


Figure 5: Some examples of Engineered Wood Products.

a) LVL b) Composite I-beam c) Glulam d) Parallel strand lumber

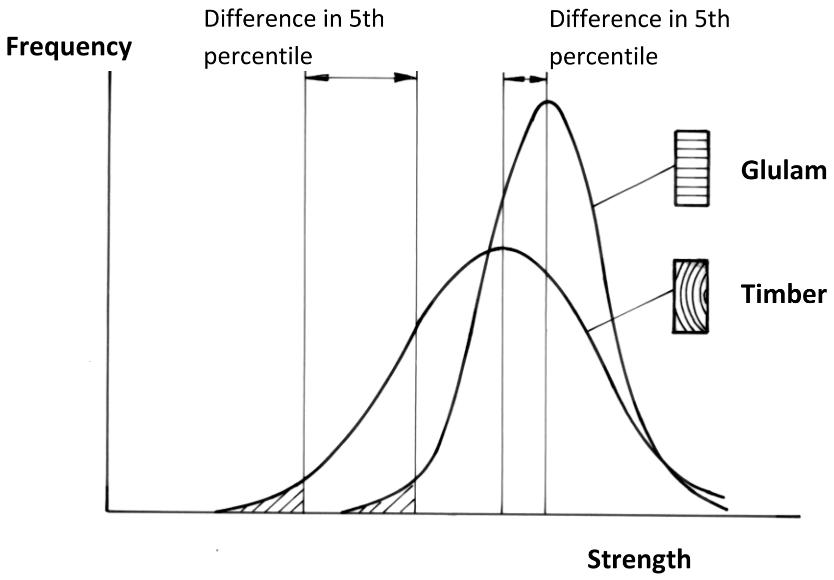


Figure 6: Typical probability density functions for structural timber and glulam.

Ductility/brittleness characteristics

One of the features related to robustness is the ability to redistribute stresses in structural systems, which normally requires large deformation capacity. On a local level, timber has generally low deformation capacity and often displays brittle type behaviour. This makes it difficult to utilize redundancy as a mean to achieve robustness.

The response depends strongly on direction and type of loading. When subjected to compression the response is rather ductile for loading both in the grain direction and perpendicular to grain. However when loaded in tension, shear or bending the response is brittle with very little deformation capacity. Fracture energy dissipation in tension and shear is normally negligible in relation to the ductility required for robustness. The weakness in tension perpendicular to grain makes it necessary to use some type of reinforcement if ductility is desired. Reinforcement with fibre composites or metal screws has been shown to be possible, but is presently little used in practice.

Non-linear material models for timber under compression are available and used for special purposes. The most relevant, yet reasonably simple model for loading in tension or shear is an elastic-brittle model. However, for investigations of brittle failure modes, advanced models based on linear or non-linear fracture mechanics are being used, see e.g. Gustafsson (2003). But the latter types of models are seldom relevant for problems where large deformations are necessary.

Some types of engineered wood products have slightly more advantageous properties from ductility point of view, but in general loading modes involving tension show limited ductility.

Joints in timber structures

Joints with dowel-type fasteners are the most common joints in timber structures. Dowel-type fasteners include nails, staples, screws, drift pins, threaded rods and bolts. Figure 7 shows an opened nailed connection loaded in single shear after a test to determine the load-carrying capacity. Different phenomena are observed:

- A relative displacement between the middle member and the side members occurred.
- The nails show plastic deformations due to bending.
- The timber close to the joint between the members is deformed plastically under the action of the nails.
- The nail on the left is partly pulled out.

Since the load is transferred through compression in the wood the response is usually very ductile. Another contribution to ductility comes from plastic yielding of the dowels. Joints with other types of dowels such as bolts, screws or threaded rods show similar behaviour.

From these observations, three main parameters influencing the load-carrying behaviour of joints with dowel-type fasteners like nails can be identified:

- The bending capacity of the dowel. The bending capacity is mainly influenced by the dowel diameter and the yield strength of the dowel material. Plastic deformation capacity is essential to provide bending capacity also after considerable deformation of the dowel.
- The embedding capacity of the timber or wood-based material. The embedding *strength* primarily depends on the timber density, whereas the embedding *capacity* because of the contact area also depends on the fastener diameter and penetration depth.
- The withdrawal strength of the dowel. Threaded fasteners provide higher withdrawal capacities than smooth fasteners.

A simple limit state theory to predict the load capacity of timber connections with dowel-type fasteners loaded perpendicular to the fastener axis was developed by Johansen (1949). Johansen considered the dowel as a beam embedded in the timber. Apart from the joint's geometry, the bearing capacity of the joint members and the bending capacity of the fastener determine the failure mode and the load-carrying capacity of the joint.

Figure 7: Opened nailed connection after a test to determine the load-carrying capacity in shear. Blass (2003)

More advanced models are available to predict of the load-slip behaviour of dowel type joint, which is necessary from a robustness point of view. E.g. Foschi and Bonac (1977) used non-linear finite-element analysis to derive load-slip characteristics for nailed connections, properties required for a sophisticated non-linear analysis of structural systems in post damage scenarios.

Although less common, adhesive joints are also used for timber structures. Commonly used adhesive joints today have usually limited ductility. Energy absorbing and ductile adhesive joints are being developed to some extent but are not ready for commercial applications.

Typical timber structural systems and behaviour related to robustness

As described above brittleness and material response of timber and other wood based products are not ideal for achieving redundancy and load redistribution in structural timber systems. However, there are some commonly used structural components which are favourable for providing ductility and redundancy in structural systems. Widely used systems with such properties are

- Light weight timber frame building systems
- Building systems based on solid planar wood panels

Timber frame buildings are built up by a skeleton of timber joists and studs covered with panels fastened to the wood skeleton by metal fasteners. Two principal structural components can be found in such systems:

- Shear walls (usually vertical)
- Diaphragms (usually horizontal)

The function of these components in a building is illustrated in Figure 8. The anatomy of a typical shear wall is illustrated in Figure 9a and the behaviour under shear loading is illustrated in Figure 9b.

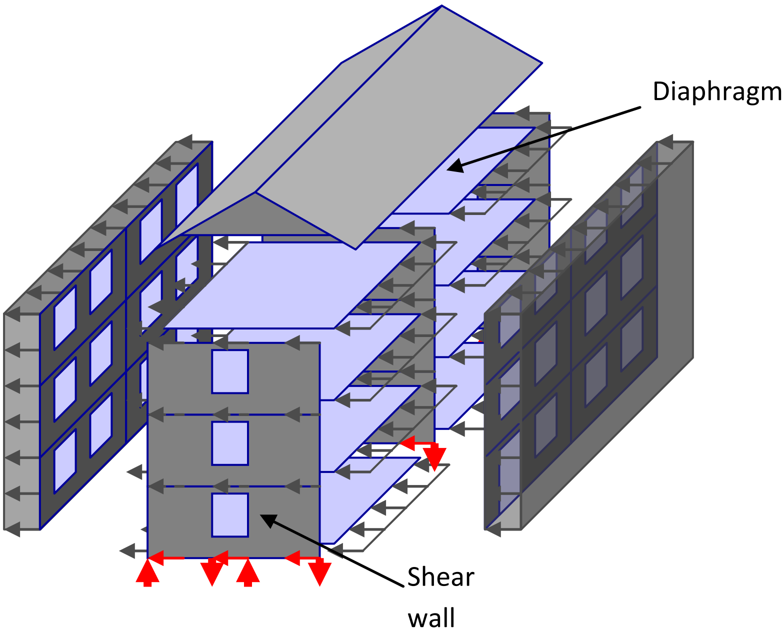


Figure 8: Force transfer in multi-storey timber frame building under lateral loading.

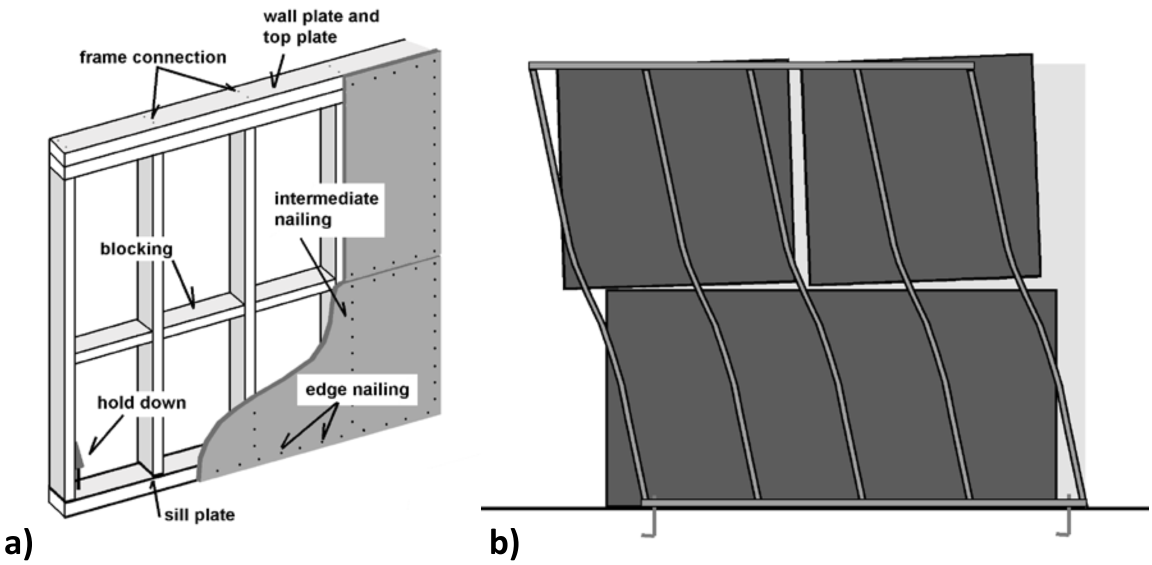
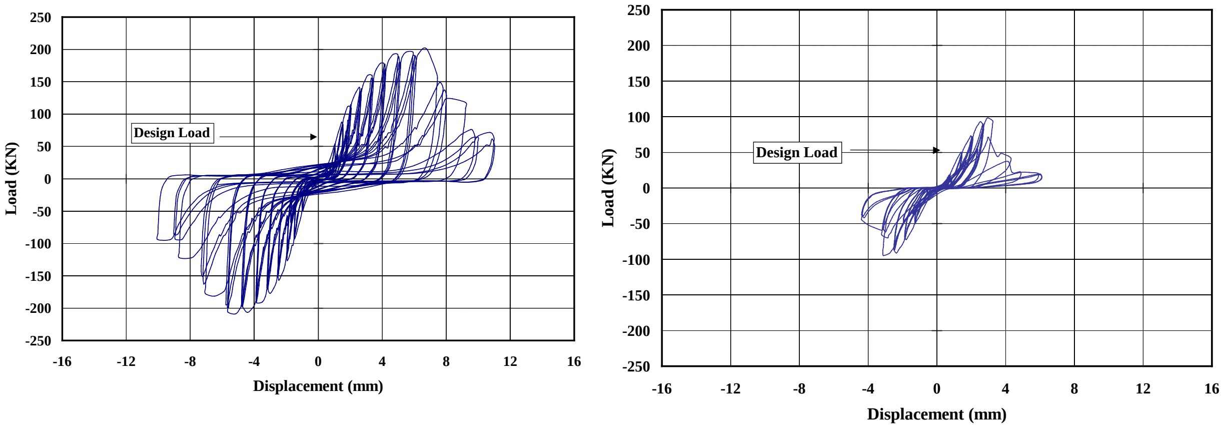


Figure 9a: Wood frame shear wall with plywood sheathing

Figure 9b: Shear load transfer in sheathed wall element

Shear walls as well as diaphragms designed in this way exhibit high ductility for in-plane loading. This is achieved by the ductility in the metal connections between panels and framing. Timber frame shear walls and diaphragms display large deformation capacity, when properly designed. Such components are very effective in absorbing energy as illustrated in Figure 10, showing the response under cyclic loading.



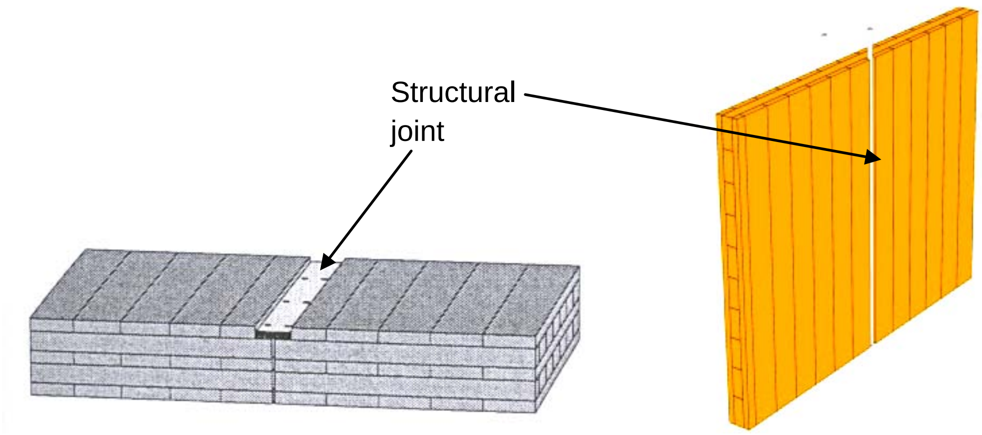
a b

Figure 10: a) Typical response of shear wall with high ductility and energy absorbing capacity. b) Typical response of shear wall with less ductility

Advanced methods for non-linear modelling of composite timber frame structures under dynamic loading have been developed to a large extent, mainly in connection with research related to earthquake resistance, see e.g. Karacabeily & Cecotti (2000). These analysis methods can also be used to analyse and verify robustness performance.

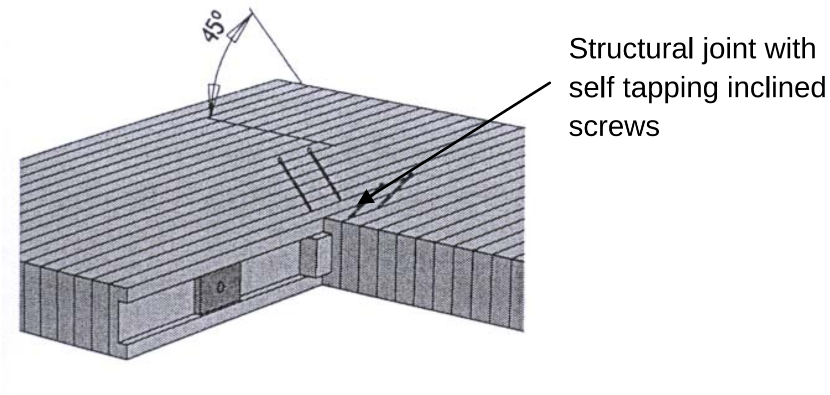
Robust building structures can be designed on the basis of these types of timber frame wall and floor components. Lightweight timber frame has also the advantage of low self weight which reduces dynamic effects and required load bearing capacity in post failure situations.

Similar advantages can be achieved with solid wood planar panels which are now being developed and used in buildings and bridges. Some of these products are shown in Figure 11. Modelling of robustness characteristics for structural systems built up from these types of elements may be done by rather simple sub-models for the elements and non-linear models for the joints connecting the elements.



Cross laminated floor element

Cross laminated wall element



Prestressed floor element

Figure 11: Typical solid planar wood elements

Robustness of long-span timber structures

Timber is often used for primary load-bearing elements in single storey long-span structures for public buildings and arenas, where severe consequences can be expected if one or more of the primary load bearing elements fail. A typical topology of such buildings is shown in Figure 12. The system consists of main frames, secondary elements and bracing elements. The main frame or columns and girders can be seen as key elements in the system and should be designed with high safety against failure and under strict quality control. The main frames may sometimes be designed with moment resisting joints between columns and horizontal girders, but it is generally difficult to provide ductility in such timber frames due to the inherent brittleness of the material. For this reason, scenarios, where one or more of these key elements, fail should be considered at least for high consequence buildings. Two alternative strategies may be applied:

- Isolation of collapsing sections
- Provision of alternate load paths

The first one is rather easy to provide by deliberately designing the secondary structural system less strong and stiff or by using so called fuse elements in joints. But for large spans and typical center distances large roof areas are still affected, leading to severe consequences of failure of one main girder in buildings where many people may be present. In that case it is desirable to design the secondary structural system and the bracing system so that loss of capacity in the main girder or in one of the columns does not lead to collapse. This may be achieved by appropriate joint design and utilization of e.g. catenary action, even if it is often expensive and difficult for systems with timber as the main structural material.

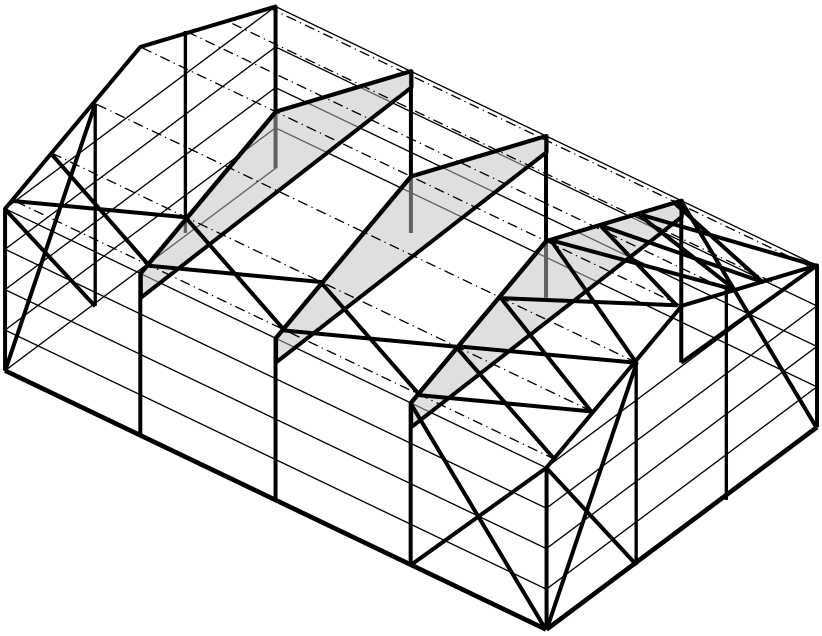


Figure 12: Typical topology of long-span timber building

Summary and conclusions

The properties of timber and various wood based products are not ideal for achieving robust systems due to the risk for brittle behaviour and the anisotropic nature of wood in certain loading modes. Timber also exhibits large spatial variability which must be accounted for in modelling and assessment of reliability. On the contrary, dowel type joints which are frequently used in timber structures show high ductility when properly designed. The relatively low self weight of timber structures implies low loads in post failure scenarios and reduces dynamic effects. Appropriate models are available to analyse structural timber systems in post failure modes. Good results can often be achieved by elastic material models for timber components and non-linear models for joints combined with geometrically non-linear analysis

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