1

Timber Engineering – General Introduction

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1.1 TIMBER – OUR OLDEST BUILDING MATERIAL

Protection and shelter against wind, rain and cold is a very basic need for mankind. Since ancient times, wood has been the most important material used for this purpose. In developed cultures, the art of house construction was already quite advanced several thousand years ago. Figure 1.1 shows an archaeological reconstruction of a so-called long house in Central Europe from 3000 BC (Kuklik, 2000). The width of this type of house was in the range of 5.5–7 m and the length varied from 20–45 m. The main structural elements were made from round timber. This can be seen as an early example of a timber framed house, which in various forms has been used ever since, especially in forested regions.

Some parts of Asia have a very long history of timber construction. In Japan the oldest timber structure still in existence is from the seventh century (Yasumura, 2000). A typical historical timber building is the three storey pagoda, shown in Figure 1.2. This building, which still exists, was constructed in 730 AD. It has a double roof in each storey supported by a central wooden pole.

Another region with a long tradition of timber construction is Scandinavia, where wood is a resource that has always been easily available. The oldest existing timber building in Scandinavia is the Borgund church in Norway, built in the twelfth century (see Figure 1.3). The load-bearing
structure is a three-dimensional frame with round-wood poles and horizontal timber trusses connected by semi-rigid arch-shaped joints.

Another important application for timber construction is bridges. Before the emergence of modern structural materials such as steel and concrete, timber was the dominating structural material in bridge construction. In 55 BC, the emperor Julius Caesar had a 140 m long temporary timber bridge built across the Rhine (Figure 1.4). The bridge was 5–6 m wide, and allowed two lane traffic. Only 10 days were needed to complete the bridge (Timber Bridges, 1996).

One of the oldest existing timber bridges is the 222 m long Chapel Bridge in Luzern, Switzerland, which was built in 1333 (Stadelmann, 1990). This bridge is a well-known tourist attraction. As with many other bridges in Switzerland, it is covered by a roof, which effectively protects the wood from biological deterioration. Unfortunately, the bridge was partly destroyed by a fire in 1993, but has been rebuilt in its original form (see Figure 1.5).

Although historic timber structures have disappeared to a greater degree than, for example, structures made of stone, these examples show that timber has excellent durability provided that the structures are properly designed and maintained. One aspect of long-term durability of timber structures is that they are often designed in such a way that damaged elements can easily be replaced.

The fact that timber has been used extensively as a building material for a very long time does not mean that we have a deep scientific understanding
of the behaviour of the material. On the contrary, timber construction has to a large extent been based on empirical experience and craftsmanship. Wood is therefore often seen as a material with inadequate control and documentation of its properties and behaviour. The purpose with this book is to present recent advances in research to improve our understanding of the structural performance of timber.

1.2 MODERN TIMBER CONSTRUCTION

Today, the growing stock volume of wood worldwide is estimated to 490 billion m$^3$ (FAO, 2000a). The total world production of timber in 1999 was 3275 million m$^3$ (FAO, 2000b). It is estimated that around 55% of this volume is used as fuel. A substantial part of the raw material is used for pulp and paper, and 317 million tons of paper was produced worldwide in 1999. The total volume of sawn timber and panel products produced in the same year was 592 million m$^3$, which is 18% of the total raw material production. The relative amounts of different wood products are shown in Table 1.1.

Timber is used as a major structural material in a great variety of building and civil engineering applications. Lightweight timber frame systems (based on structural timber, engineered wood products and panels) may be used for single family houses, multi-storey residential buildings and commercial buildings. Similar elements are used as walls and roofs in industrial buildings. Timber is often used for roof construction in buildings, even

| Table 1.1 Production of sawn goods and wood-based panels in the world, 1999 (FAO, 2000b) |
|---------------------------------------------|-------------|
| Product                      | Volume, 10$^6$ m$^3$ | Volume, % |
| Sawn goods, softwood       | 323.2       | 55          |
| Sawn goods, hardwood       | 108.5       | 18          |
| Fibreboard                  | 30.2        | 5           |
| Particle board              | 75.2        | 13          |
| Veneer sheets               | 6.4         | 1           |
| Plywood                     | 48.1        | 8           |
| Total                       | 591.6       | 100         |
if the rest of the structure is made from concrete or steel. Large-scale timber systems (based on glu-lam, LVL and other engineered wood products) may be used for industrial and commercial buildings with long spans, as well as for bridges, parking decks, etc. Worldwide, the potential to increase the utilisation of timber for these applications in the future is large.

There are many general advantages in using timber for building purposes. It is an environmentally friendly, easily recyclable material. The energy consumption during production is very low compared to that of other building materials. Timber has a low weight in relation to strength, which is advantageous for transport, erection and production. The foundation can be simplified and low inertia forces make the building less sensitive to earthquakes. Furthermore, wood has aesthetic qualities, which give great possibilities in architectural design.

Building systems based on wood has a great potential to be rational and cost-effective. Experiences from North America, where timber frame building systems have a dominating position in the market, indicate that it is possible to reduce the cost of low-to-medium rise buildings significantly by using lightweight building systems based on timber and panel products. These systems have the advantage of simple construction techniques at the building site, and very short construction times can be achieved.

1.3 THE TIMBER FRAME BUILDING CONCEPT

Timber frame buildings are built up by a skeleton of timber joists and studs, covered with panels fastened to the wood elements. Wood-based panels, such as plywood, OSB, fibre-board or chipboard, with structural quality, are commonly used in timber frame buildings. Gypsum panels or similar products are also widely used in combination with timber, mainly to provide fire resistance. A typical timber frame house is shown in Figure 1.6.

The timber frame concept is also very competitive for multi-storey, multi-residential buildings up to 5–6 storeys (see Figure 1.7).

Figure 1.6 The anatomy of a typical timber frame small house

Timber frame systems can be conceived as composite wall and floor units built up from timber framing, panel products, insulation, cladding, etc., with good possibilities to adapt the design to various requirements. One and the same composite unit in a timber frame system can be utilised for the

- transfer of vertical loads,
- stabilization of wind and earthquake loads,
- physical separation,
- fire separation,
- sound insulation, and
- thermal insulation.

It is important that the design is made so that all the relevant requirements are met in an optimal way. In the design of walls and floors, different aspects can be identified as critical. The factors governing the design of walls are, in order of priority:

- fire resistance,
- horizontal stabilisation,
- sound insulation, and
- vertical loading.

A typical design of a load-bearing, stabilising wall used for separation between flats is shown in Figure 1.8.

For the design of floors, the most important factors are, in order of priority:

- impact sound insulation,
- vibration control,
In many countries, customers expect acoustic performance of a high standard. It is possible to meet these requirements with lightweight floor structures, but the solutions often become complicated and expensive. For this reason, there is a need to develop better floor solutions. One alternative could be to use floors based on laminated timber decking, where the material cost is higher, but the floor is still competitive due to a simpler production process. Composite floors with concrete on top of timber decking, or in combination with timber joists are to some extent used in Central Europe.

A very crucial issue for the efficiency of a timber frame system is the solution of wall-floor joints. In the design of such joints, a number of aspects must be taken into account:

- simplicity in production, and
- possibility for the installation of services.

In the platform frame system commonly used in North America, standard solutions are available for wall/floor joints (see Figure 1.9a). Since the vertical forces are transferred in compression perpendicular to the grain in the whole joint, substantial shrinkage and vertical settlements will occur. The deformations created by this can be quite difficult to handle in a multi-storey building. An example of a wall-floor joint solution, designed to minimise shrinkage settlements in the joint, is shown in Figure 1.9b.
In concrete and masonry buildings, staircase and elevator shafts as well as cross walls can be used to stabilise the building. In timber frame construction, timber frame shear walls are used for lateral stabilisation against wind and earthquakes (see Figure 1.10). For multi-storey timber framed buildings, the issue of stabilisation is not trivial. A trend towards narrow houses to provide good daylight, as well as requirements of high acoustic performance, makes it more difficult to stabilise the buildings in an economical manner. To ensure good acoustic performance, double walls are used between flats (see Figure 1.8), and to prevent flanking transmission, the horizontal floor diaphragms should be disconnected at the double walls. However, continuity in the floor diaphragms is needed for efficient horizontal stabilisation. This conflict must be resolved by the structural engineer. Recent research has shown that a better understanding of the force transfer in timber frame systems can contribute towards achieving a more economical and flexible design of the stabilising system in timber frame buildings (e.g. see Andreasson (2000) and Paevere (2001)).

The economy of multi-storey timber houses depends very much upon whether a simple bracing system is sufficient, i.e. if the forces can be transferred through the wall boards required for fire protection, or whether it is necessary to use more expensive wood-based panels and extra studs and anchorages.
1.4 LARGE-SCALE TIMBER CONSTRUCTION

The maximum dimension of solid timber sawn from logs is of the order of 300 mm or even less, depending on species and growth region. This means that the maximum possible span of structural timber beams in practice is limited to 5–7 m. Before the appearance of engineered wood products such as glulam, timber trusses were therefore commonly used to achieve larger spans, which is often needed in roof and bridge construction. Timber trusses produced from structural timber are still the most common solution for roof structures in small residential houses (Figure 1.11). This type of truss is today almost exclusively designed with punched metal plate fasteners, creating stiff and strong truss joints at a low cost. Timber roof trusses are frequently used for spans of up to 12 m, but can be designed for spans up to 30–40 m.

Another possibility to extend the spans for timber structures is to use laminated beams, i.e. timber laminations stacked on top of each other and structurally connected to form members with large cross-sections. Early applications used mechanical fasteners, such as bolts, dowels and rods, to connect the laminations. The potential of the lamination technique was, however, not fully exploited until synthetic glues became generally available in the early twentieth century (see Figure 1.12). Glued laminated timber or glulam became one of the first engineered wood products, and is still very competitive in modern construction. By bending the laminations before gluing, it can be produced in curved shapes. The cross-section depth is in principle unlimited, but for practical reasons maximum depths are of the order of 2 m. This makes glulam an ideal material to create structures for large spans. A variety of structural systems based on straight and curved glulam members has been developed for roofs with spans of up to 100 m (see Figure 1.13). Today, several other wood-based products are available for large-scale timber structures, such as Laminated Veneer Lumber (LVL) and Parallel Strand Lumber (PSL) (see Chapter 4 in Part One). These products are suitable for larger spans in a similar way as straight glulam members.

For straight and tapered beams, spans of 30 m and more can be achieved. Figure 1.14 shows a typical glulam roof with straight tapered beams for hall buildings.

Spans of up to 50 m can be realised by three hinge frames built up by two curved glulam elements, as shown in Figures 1.13 and 1.15. Frames can also be made from straight members, with...
the moment resisting frame corners manufactured using a finger jointing technique. Several types of mechanical joints are also commonly used for such frame corners, but they are generally less effective in resisting moments.

Similarly, plane arches can be constructed by pre-manufactured curved glulam elements for spans of up to 100 m. An example is shown in Figure 1.16. For spans larger than 60 m, the difficulty associated with transport of the curved elements is usually a restricting factor. Glulam arches are normally designed as three-hinged, which gives simpler joints to be arranged at the building site. Also, a statically determinate system is usually preferred to avoid restraint forces from moisture movements in the wood.

### Figure 1.13 Structural systems for glulam (Glulam Manual, 1995. Reproduced by permission of Svenskt Limträ AB)

<table>
<thead>
<tr>
<th>SYSTEM</th>
<th>DESCRIPTION</th>
<th>SPAN m</th>
<th>SECTION DEPTHS</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Image of straight beam]</td>
<td>Straight beam</td>
<td>&lt; 30</td>
<td>( h \approx l/17 )</td>
</tr>
</tbody>
</table>
| [Image of tapered beam]    | Tapered beam                     | 10–30  | \( h \approx l/30 \)  
|                             |                                  |        | \( H \approx l/16 \)  |
| [Image of pitched cambered beam] | Pitched cambered beam            | 10–20  | \( h \approx l/30 \)  
|                             |                                  |        | \( H \approx l/16 \)  |
| [Image of three-hinged truss with tie-rod] | Three-hinged truss with tie-rod | 15–50  | \( h \approx l/30 \)  |
| [Image of three-hinged truss with tie-rod and trussed beams] | Three-hinged truss with tie-rod and trussed beams | 20–100 | \( h \approx l/40 \)  |
| [Image of three-hinged arch] | Three-hinged arch                | 20–100 | \( h \approx l/50 \)  |
| [Image of three-hinged curved frame] | Three-hinged curved frame        | 15–50  | \( h = (s_1 + s_2) /15 \)  |
| [Image of three-hinged frame with finger-jointed knee] | Three-hinged frame with finger-jointed knee | 10–35  | \( h = (s_1 + s_2) /13 \)  |
| [Image of three-hinged frame with trussed knee] | Three-hinged frame with trussed knee | 10–35  | \( h = (s_1 + s_2) /15 \)  |
Figure 1.14 Roof structures with straight glulam beams can be used for spans of up to 30–40 m. Steel wires are used for diagonal wind bracing.

Figure 1.15 Three-hinged glulam curved frame. Reproduced by permission of Svenskt Limträ AB.

Figure 1.16 Glulam arch structure made from two curved glulam elements. Reproduced by permission of Svenskt Limträ AB.

For very large spans, glulam trusses may be used. Very efficient truss joints can be made by slotted-in steel plates combined with dowel fasteners. Rational methods for manufacturing such joints have been developed, making truss systems of this type competitive. Examples of trussed glulam structures are shown in Figures 1.17 and 1.18.

Glulam or other engineered wood products may also be used efficiently for spatial frames and dome structures. Special detailing solutions are usually

Figure 1.17 Glulam arch truss with a free span of 86 m for a sports facility in Lillehammer, Norway (Photo: Sven Thelandersson).

Figure 1.18 Roof structure for Gardemoen air terminal, Oslo, Norway. The main girder is a slightly curved glulam truss, covered by plywood for the sake of appearance. Reproduced by permission of Svenskt Limträ AB.
developed for the three-dimensional joints in such systems. Figure 1.19 shows one of the largest timber structures in the world, with a diameter of 162 m.

Many good architects around the world prefer to work with wood as a major structural material. There are numerous examples worldwide of large span timber buildings with excellent architecture and innovative design. An example is shown in Figure 1.20.

Another important application for large-scale timber construction is bridges. For small spans, straight beams of solid wood, glulam or other engineered wood products can be used as the primary load-bearing elements. Trusses, arches or framed structures can be used as primary structures for larger spans. A very common solution for the bridge deck is to use laterally prestressed timber plates of the type shown in Figure 1.21. As an alternative to lateral prestress, the planks can be nailed to each other, although this gives lower transverse stiffness of the deck.

In modern bridge construction, timber is growing in popularity for foot and bicycle bridges as well as road bridges with moderate spans, especially in the USA, Central Europe and Scandinavia. One reason for this is environmental awareness and the trend towards the use of ecologically sound materials in construction. New efficient jointing techniques developed in recent years are also very important for competitiveness in timber bridge construction. An excellent example of a modern timber bridge for road traffic is shown in Figure 1.22.
A key factor for timber bridge design is durability. Preservative chemical treatment is not an attractive alternative considering environmental policies of today. However, by careful design and detailing, the wood material in a timber bridge can be kept more or less constantly dry, so that biological decay is avoided and long lifetimes can be achieved with or without very limited use of preservative treatment.

Laminated decks of the type shown in Figure 3.16 have also become popular for floors in house construction. With such floor structures, combined with concrete or other materials, good solutions for sound insulation and fire can be achieved at reasonable costs. Massive timber constructions are sometimes also used for the whole structural building system, including wall units.

REFERENCES


FAO (2000b) Yearbook of Forest Products.


