Construction of sustainable mid-rise and tall wooden buildings

Knowledge Alliance for Sustainable Mid-Rise and Tall Wooden Buildings (KnoWood)

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INTRODUCTION TO SUSTAINABLE TIMBER CONSTRUCTION

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1.1 Sustainable building with timber

The concept of sustainable development was first formulated in the 1990s with the statement that "humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1987).

The three most important dimensions in the concept of sustainable development are the following (Turcu, 2013).

- Environmental (environmental quality and integrity)
- Economic (economic prosperity in harmony with the nature)
- Social (social cohesion and quality of life)

In 2015, the new 2030 Agenda for Sustainable Development was introduced with 17 Sustainable Development Goals (SDGs) and 169 targets (see Figure 1.1).

Fig. 1.1 Sustainable Development Goals (Wikimedia Commons)

The goals and targets will stimulate actions in areas of critical importance for humanity and the planet, namely in terms of (United Nations, 2015):

1. People: to end poverty and hunger, in all their forms and dimensions, and to ensure that all human beings can fulfil their potential in dignity and equality and in a healthy environment.

2. Planet: to protect the planet from degradation, including through sustainable consumption and production, sustainably managing its natural resources and taking urgent action on climate change, so that it can support the needs of the present and future generations.

3. Prosperity: to ensure that all human beings can enjoy prosperous and fulfilling lives and that economic, social and technological progress occurs in harmony with nature.

4. Peace: to foster peaceful, just and inclusive societies which are free from fear and violence. There can be no sustainable development without peace and no peace without sustainable development.

5. Partnership: to mobilize the means required to implement the Agenda through a revitalised Global Partnership for Sustainable Development, based on a spirit of strengthened global solidarity, focussed in particular on the needs of the poorest and most vulnerable and with the participation of all countries, all stakeholders and all people.

In line with sustainable development goals and dimensions, the EU presented an ambitious Green Deal strategy in December 2019. Its overarching objective is for the

EU to become the first climate neutral continent by 2050, thus resulting in a cleaner environment, more affordable energy, smarter transport, new jobs, and an overall better quality of life (European Commission, 2020).

Sustainable development is particularly relevant in the construction sector, because the built environment has a significant impact on many sectors of the economy, as well as on local jobs and quality of life. The *2020 Global Status Report for Buildings and Construction* revealed that global building energy consumption remained steady year-on-year, although energy-related CO_2 emissions increased to 9.95 $GtCO_2$ in 2019. Adding emissions from the building construction industry on top of operational emissions, the sector accounted for 38% of total global energy-related CO_2 emissions (Alliance for Buildings and Construction, 2020).

The EU's statistics show that the built environment uses about 50% of all extracted material and that the construction sector is responsible for over 35% of the EU's total waste generation. Material extraction, the manufacture of construction products, and building and renovation are producing 5–12% of total national greenhouse gas (GHG) emissions. "Greater material efficiency could save 80% of those emissions" (European Commission, 2021). One of the options for increasing material efficiency and reducing climate impact is to build with timber, because timber construction contributes to all dimensions of sustainable development (Tupenaite et al., 2021).

Environmental benefits

Timber construction is increasingly being proposed as a way to preserve nature and create a sustainable environment. The use of timber reduces the environmental impact of a building for several reasons, which are discussed in detail in Chapter 1.4:

1. Wood is the only renewable construction material that requires very little energy for processing it.

2. All timber products store carbon.

3. Timber construction can reduce energy consumption and CO_2 emissions from the manufacture of construction products, as well as reduce overall material use and thereby the amount of waste.

4. Timber products are reusable and recyclable.

Economic benefits

Timber construction has numerous economic benefits, including the generation of green jobs. Timber products used in construction are cost-effective, since they are structurally efficient, lightweight, and can be installed quickly and easily, especially in the case of prefabrication. According to Hurmekoski (2017), because wood weighs far less than concrete, "a wood-based structural frame can cut the total material consumption of construction by half." The higher speed at which prefabricated timber structures are assembled contributes to reducing labour hours and project costs.

Despite the itemized benefits, the economic competitiveness of wood construction varies between regions and market segments (Sathre & Gustavsson, 2009). In wood-frame multi-storey markets, a wood-based building is usually still more expensive when compared to building with steel and concrete. This is partly due to national construction regulations. However, one can expect in the future that wood construction will become cost competitive due to learning-by-doing as the numbers of pilot projects increase and modern wood construction techniques ultimately become standardized (Hurmekoski, 2017).

Social benefits

Because people spend 80–90% of their time indoors, importance should be given to the social aspects of buildings, such as public acceptance and appreciation of them.

Choosing the right materials can ensure the welfare of a building's occupants. Timber systems are designed to maximise thermal performance and minimise air leakage, and they offer a well-insulated solution without any need for additional technologies. Wood has been proven to lower the human sympathetic nervous system, which can contribute to stress, increase blood pressure, and inhibit digestion and recovery (Blackwell, 2017).

Studies carried out in Norway, Japan, Canada, and Austria reveal that wood may have positive effects on the emotional state of people. Living environments with timber structures cause a drop in blood pressure and heart rate while having a calming effect. For example, some studies have shown that touching aluminium at room temperature, cool plastic, or stainless steel caused a rise in blood pressure while no such reaction resulted from touching a wooden surface. A comparison of different work rooms showed that stress levels, measured as the skin's capacity to conduct electricity, were lowest in a room with wooden furniture. Not even plants brought into a room fitted out in white had the same effect (Wallenius, 2014).

A study led by Holzcluster Steiermark in Austria in 2010, called "Schule ohne Stress" (School without Stress), compared the behaviour of four different classes: two in classrooms constructed with timber and wooden interior furniture; and two in classrooms built with traditional methods. The study, conducted with 32 school pupils over the course of one school year, revealed that pupils in the timber classrooms were more relaxed, slept better, and experienced a significant drop in heart rates. In comparison, the students in the standard classroom saw an increase in heart rate over the school year. Stress levels remained the same for the pupils from timber classrooms, whereas the stress levels of the other students also saw an increase over the year. There were also less errors in concentration committed by students in the timber classroom (Blackwell, 2017).

The study concluded that not only did timber offer benefits in terms of speedy construction, sustainability, and aesthetics, but that the long-term effects on health and wellbeing were largely positive. The use of timber engineering can also promote mental and physical wellbeing in hospitals and care facilities (Blackwell, 2017).

Wood in sustainable building rating systems

To make it easier to identify sustainable buildings in the construction market, various frameworks and standards have been developed (Tupenaite et al., 2021). One of the first methods for assessing the environmental sustainability of buildings is BREEAM (Building Research Establishment Environmental Assessment Method), which was developed in 1990 by the British organisation BRE Global (BREEAM, 2022). Another widely used sustainable building rating system is LEED (Leadership in Energy and Environmental Design), which was developed by the United States Green Building Council (USGBC) in 1998 (LEED, 2022). Other systems developed around the world are mostly applied at a national level, e.g., the German sustainable building standard DGNB (Deutsche Geselleshaft für Nachhhaltiges Bauen), the Australian Green Star, and the increasingly popular WELL standard (Tupenaite et al., 2021).

Generally, every sustainable building rating system offers a certain percentage of credits that can be achieved with the use of timber in construction. Wood is recognized in the following areas (WoodWorks, n.d.):

- Certified wood. Credits are awarded for wood that has been third-party certified as coming from a sustainably managed forest.
- Recycled/reused/salvaged materials. Many rating systems give credits for the use of products with recycled content. Wood products that qualify include finger-jointed studs, medium-density fibreboard, and insulation board.
- Local sourcing of materials. A number of systems place special emphasis on the use of local materials as an approach to reducing the environmental impacts of construction projects, rewarding materials sourced from within a certain radius – commonly 500 miles (approx. 805 km). Wood is locally sourced in many countries.
- Materials efficiency. Many rating systems, such as BREEAM, LEED, Green Globes, Built Green Canada, reward efficient use of building materials.
- Waste minimization. Credit is often awarded for avoiding or diverting construction waste, e.g., through off-site production of building modules.
- Indoor air quality. Most rating systems have strict limits on the use of products that contain volatile organic compounds (VOCs). Many wood products are available that verifiably meet or exceed these guidelines.

High-rise timber buildings are already receiving awards for their sustainability. One example is HAUT, which was built in Amsterdam. At a height of 73 meters spanning 21 floors, HAUT is set to become the tallest wooden residential building in the Netherlands (HAUT, 2022) (see Figure 1.2).

Fig. 1.2
HAUT building
(Wikimedia Commons)

In 2018, the project won the prestigious International BREEAM Award in the category Homes – Design. At 90.8%, HAUT received the highest BREEAM score in its category. The jury agreed that this project significantly extends high-rise timber modular construction. The focus of the design team on the efficient use of materials and circular economy principles was considered "impressive, innovative and highly replicable" (Team V Architectuur, 2018).

1.2 Sustainable forest management

To assess the sustainability of timber construction, the entire building life cycle must be considered. The life cycle starts with the extraction of resources. If primal forests are simply cut down to provide timber, like what happened in the Amazon, Indonesia, and the Pacific Northwest of the United States, that does not represent a sustainable resource and, in such cases, timber construction would not be considered sustainable. To ensure sustainability, timber must be extracted from **sustainably managed forests**.

The Forest Principles were first adopted at the Earth Summit (United Nations Conference on Environment and Development) in Rio de Janeiro in 1992. The principles set forth there covered the general international understanding of **sustainable forest management** (SFM). Various sets of criteria and indicators have since been developed to evaluate SFM at the global, regional, country, and management level (Dennehymarch, 2014).

In 2007, the United Nations General Assembly adopted the Non-Legally Binding Instrument on All Types of Forests. "The instrument was the first of its kind, and reflected the strong international commitment to promote implementation of sustainable forest management through a new approach that brings all stakeholders together" (Dennehymarch, 2014).

A definition of SFM was developed in Europe by the Ministerial Conference on the Protection of Forests in Europe (FOREST EUROPE) and has since been adopted by the Food and Agriculture Organization (FAO). It defines sustainable forest management as:

> *The stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfill, now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems.* (European Commission, 2018)

Sustainable forest management creates outcomes based on the three pillars of sustainability: social, environmental, and economic. All pillars must be considered as an integrated system. "If one pillar is missing, we cannot protect our forests, forest-dependent communities and rural economies cannot thrive, illegal logging will not be abated and development opportunities will not be captured" (PEFC, 2022).

All national sustainable forest management requirements shall include the following (PEFC, 2022):

- Maintenance, conservation and enhancement of ecosystem biodiversity
- Protection of ecologically important forest areas
- Prohibition of forest conversions
- Recognition of free, prior, and informed consent of indigenous peoples
- Promotion of gender equality and commitment to equal treatment of workers
- Promotion of the health and well-being of forest communities
- Respect for human rights in forest operations
- Respect for the multiple functions of forests to society
- Provisions for consultation with local people, communities, and other stakeholders
- Respect for property and land tenure rights as well as customary and traditional rights
- Compliance with all fundamental conventions for worker rights
- Working from minimum wage towards living wage levels
- Prohibition of genetically modified trees and most hazardous chemicals
- Exclusion of certification of plantations established by conversions, including conversions of ecologically important non-forest lands (e.g., peatlands)

– Climate-positive practices such as reducing greenhouse gas (GHG) emissions in forest operations

Forestry is a long-term business in which the forest management cycle could take as much as 40 to 60 years to complete a harvest and replant. Planning is an essential part of maintaining a sustainable forestry operation and sustaining the business. Stewardship, planning, and investment are keys to this longevity (Forests & Fish, 2022).

Some may think that that the bigger and older the tree, the more carbon it absorbs; but this is not correct. In fact, young forests are much more efficient at absorbing carbon than old forests. Mature trees absorb carbon more slowly the older they get. In addition, as trees get older, they start to naturally decompose, which releases carbon and other greenhouse gases back into the atmosphere. Therefore, to maximize the carbon storage that trees can provide, we need young healthy forests, where trees are regularly harvested and replanted. For every tree that is logged in managed forests, three to four trees must be replanted (International Paper, 2022) (see Table 1.1).

Table 1.1. Sustainable forest management (International Paper, 2022)

Seedings	**1–15 years Thinning 1 out of 5**	**15–25 years Thinning 1 out of 4**	**50–75 years Thinning 1 out of 3**	**As of 75 years**	**Seedings**
Usage: paper pulp, heating and particle panels					
	100%	**85%**	**50%**	**15%**	
Usage: sawmill (Furniture and construction)					
		15%	**50%**	**85%**	

The Consortium for Research on Renewable Industrial Materials (CORRIM) found that different methods of forest management affect the level of carbon sequestration in trees (Perez-Garcia et al., 2005). They found that shorter rotation harvests can sequester more total carbon than longer rotation harvests (Falk, 2010).

There are more than 50 different forest certification systems in the world, although the most popular ones are the Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification (PEFC). "These are independent market-based, non-regulatory tools designed to recognise, independently accredit and promote environmentally responsible forestry and sustainability of forest resources" (Jeffree, 2019).

The FSC promotes environmentally appropriate, socially beneficial, and economically viable management of the world's forests. It has a set of 70 criteria and 10 principles that are internationally applied to sustainable forest management and forest product chain of custody, for which individual businesses and state forestry are third-party audited (Jeffree, 2019; FSC, 2022).

The PEFC is an umbrella organization that endorses national forest certification systems that have been developed through multi-stakeholder processes and tailored to local priorities and conditions. It accredits national forest certification schemes that meet its standards, along with associated chain-of-custody systems, for which companies must also undergo an independent audit (Jeffree, 2019; PEFC, 2022).

FSC and PEFC certifications cover nearly 500 million ha (11% of total global forest area), and this amount is increasing. Breaking it down, 196 million ha fall under the FSC scheme and 300 million ha under the PEFC scheme, with the former having issued 36,000 product chain of custody certificates and the latter 20,000 (Jeffree, 2019).

In 2019, a quarter of global certified forest area was in Western Europe. The country with the highest proportion of certified forest was Finland, at 81%, followed by Austria, Poland, and Estonia. The coverage was lower in southern countries, with Portugal and Spain at 12% and Italy at 9% (Jeffree, 2019).

1.3 Benefits of wood as a sustainable resource

"As a renewable resource with proven low embodied energy, wood is both an environmentally responsible and a highly practical choice as a construction material" (Coulson, 2014).

Many authors, organizations and companies worldwide recognize the possible environmental benefits of substituting the most common building materials with wood-based products. In particular, wood construction can reduce the energy consumption and CO_2 emissions related to the manufacture of construction products, as well as contribute to reducing the overall material use and thereby the amount of waste (Hurmekoski, 2017).

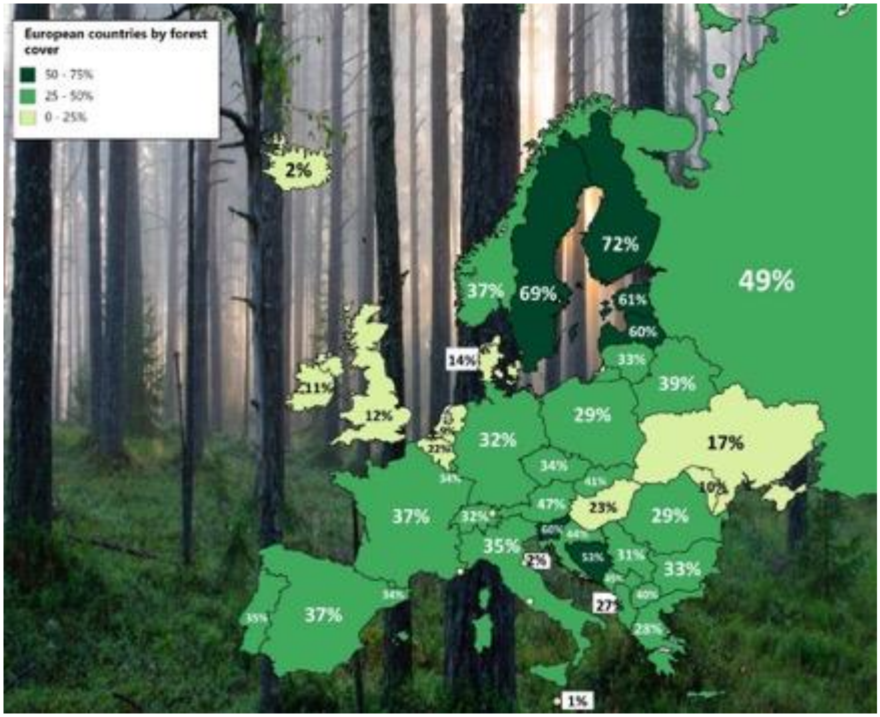
Green and renewable resource

Wood is considered to be a green resource because it is sustainable, renewable, recyclable, grown locally, versatile, and biodegradable while, in addition, its energy, water, and carbon life cycle footprints are smaller than other products (Idaho Forest Products Commission, 2022).

Unlike metals and fossil-fuel-based products like plastics, wood is renewable and can be grown and harvested multiple times. Wood construction shall in no way be linked to deforestation and, therefore, sourcing in the EU builds on the principles of sustainable forest management (Hurmekoski, 2017) (see Chapter 1.2).

Figure 1.3 shows a forest map of Europe for the year 2011.

Fig. 1.3
Forest map of Europe, based on CIA World Factbook 2011 (Wikimedia Commons)



Tree cover corresponds overall to 43% of total EU land area. The European Union (EU) accounts for approximately 5% of the world's forests and, contrary to what is happening in many other parts of the world, the forested area of the EU is slowly increasing (Eurostat, 2022a).

According to the newest available data provided by Eurostat for the year 2020, the EU had an estimated 159 million hectares of forests (excluding other wooded land), with the area having increased by almost 10% since 1990. The growing stocks of timber in the EU's forests totalled an estimated 28.4 billion m^3 (over bark) in 2019. Germany accounted for the largest share of the stock (13.4%), followed by Sweden (12.5%), and France (11.8%). Growing stocks of timber in EU forests increased in every Member State, representing 29% growth at the EU level over the period 2000–2019. The largest increase was estimated for Ireland (115%), France (61%), and Italy (57%), while a moderate increase was observed in Sweden (13%) as well as Czechia and Germany (15% each) (Eurostat, 2022a). "This growth is being achieved through planting and natural regeneration outstripping timber harvest in established woodlands. Surplus agricultural and brownfield land is also being converted to forestry" (Jeffree, 2019).

The EU's forests are productive. In 2019, around 83% (or 134 million ha) were available for timber production, with an annual output of 470 million m^3 of roundwood (that is, logs). An estimated 63% of the net annual increment of timber in EU forests was logged

(Eurostat, 2022a). Sweden was the biggest EU roundwood producer in 2017, supplying 73 million m^3; while, per annum, Finland, Germany, and France all produce more than 50 million m^3 (Jeffree, 2019). Changes in roundwood production across the EU countries over 20 years are depicted in Figure 1.4. The highest increase in production was observed in the Netherlands (185%), Czechia (126%), and Slovenia (73%). However, production decreased in Cyprus (–58%), France (–28%), Hungary (–16%), and Italy (–4%) (Eurostat, 2022b).

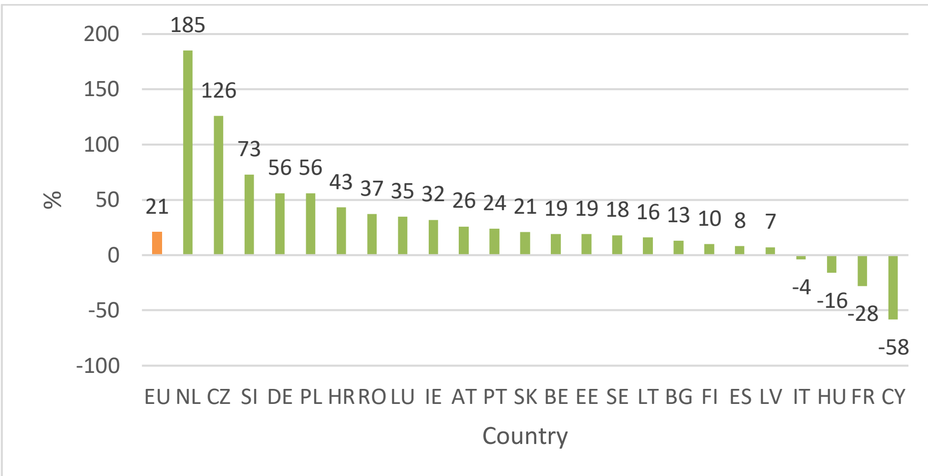


Fig. 1.4
Change in EU roundwood production, 2000–2020 (based on Eurostat, 2022b)

Note: Data for Czechia, Denmark, Greece, and Ireland for the EU aggregate are estimated for 2020. Ireland shows comparisons for 2000–2018 because 2020 and 2019 data are not available. Czechia shows comparison for 2000–2019 because 2020 data are not available.

Note that only 23% of the EU's roundwood production in 2020 was used as fuelwood while the rest was used for sawnwood, veneers, pulp, and paper production (Eurostat, 2022b).

Statistical data reveal that EU wood is a readily available resource which, if sustainably managed, is not going to run out soon. Hurmekoski (2017) made a number of assumptions regarding the sustainability of wood resources for construction purposes. A hypothetical 100% market share of wood construction would require a maximum of 400 million m^3 of roundwood in the EU per annum, translating to 50% of the annual forest growth. With realistic assumptions, this would account for a relatively small impact on the demand for wood resources due to an increased use of wood in construction (Hurmekoski, 2017).

Embodied energy

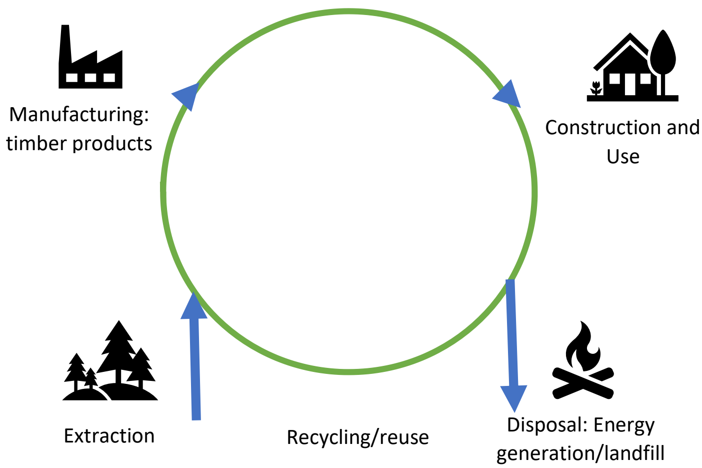
Embodied energy can be defined as all the energy that is required to produce a material or product, including harvesting, mining, manufacturing, and transport. Energy is usually sourced from fossil fuels and can be a significant component of the total life cycle energy consumption of a material. "Generally, the more highly processed a material is, the higher its embodied energy" (Wood Solutions, n.d.). Lower embodied energy is beneficial to the environment as it contributes to a lower impact over the life of a product or material (Timber Queensland, 2022).

The embodied energy of a building can be lowered by using durable and recyclable local, natural materials. The design also has to incorporate components that are easy to recover and reuse while ensuring that the structure is easy to disassemble and dismantle (Wood Solutions, n.d.).

In general, the whole-of-life impact of wood is low, because it is often locally available, natural, renewable, durable, and recyclable (see the timber life cycle in Figure 1.5).

The sun provides the energy to grow the trees from which wood products are

Fig. 1.5
Timber life cycle



produced; in contrast, fossil fuels are the primary energy source for manufacturing steel and concrete (Falk, 2010). Wood is a material that requires a minimal amount of energy-based processing and, therefore, it has a low level of embodied energy relative to many other materials used in construction (such as steel, concrete, aluminium, and plastic) (Falk, 2010). For example, an elevated timber floor has less than half the embodied energy of a concrete slab (Milne, 2013). Up to ten times more energy is needed to produce a steel beam than a timber beam (Tas Timber, n.d.).

A comparison of embodied energy for timber, concrete, and steel is provided in Figure 1.6.

Solid sawn wood products have the lowest level of embodied energy while, on the other hand, more energy is required to produce wood products that need more processing steps, such as plywood and other engineered wood products (Falk, 2010). Nevertheless, these still have much less embodied energy than other alternatives.

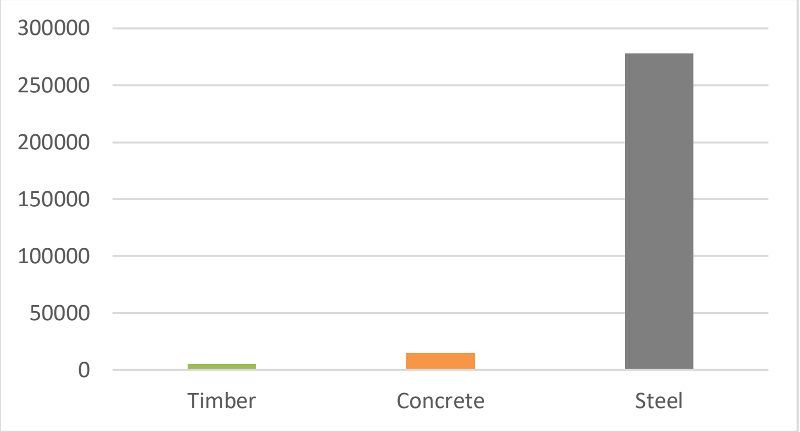


Fig. 1.6
Embodied energy in construction materials, MJ/m3 (source:Timber Queensland, 2022.)

Furthermore, wood has improved thermal performance in buildings due to the reduced energy costs (Timber Queensland, 2022). Because of its versatility and light weight, wooden structures can be designed for easy disassembly, recovery, reuse, and/or recycling (Wood Solutions, n.d.). Wood by-products such as bark and shavings can additionally be used for biofuel, thus offsetting the energy used in the production process.

Carbon footprint

The manufacture of construction materials has significant negative impacts on the environment. In Europe for instance, the production of steel, cement, and aluminium are responsible for the largest share of energy consumption and CO_2 emissions in the manufacture of building products (Herczeg et al., 2014). Hurmekoski (2017) provides additional statistics:

– Steel production releases 2 tonnes of CO_2 per 1 tonne of steel produced on average.

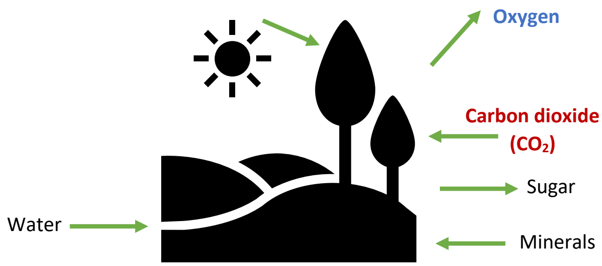
– One tonne of cement produced releases around 1 tonne of CO_2. The cement industry accounted for almost 5% of the annual EU CO_2 emissions in 2014 (Hasanbeigi et al., 2012).

In contrast, wood-based products contribute to mitigating climate change by means of two main mechanisms: carbon storage and substitution.

Forests play a major role in the Earth's carbon cycle because trees sequester CO_2 in standing forests through photosynthesis (Figure 1.7). This process converts carbon dioxide and water into sugars for tree growth and releases oxygen into the atmosphere (Falk, 2010):

energy (sunlight) + $6H_2O$ + $6CO_2 \rightarrow C_6H_{12}O_6 + 6O_2$.

Fig. 1.7
Photosynthesis process



Carbon in wood remains stored until the wood deteriorates or is burned. A tree that remains in the forest and dies releases a portion of its carbon back into the atmosphere as the woody material decomposes. On the other hand, if the tree is used to produce a wood or paper product, these products store carbon while in use. At the end of a building's life, wood can be recovered for re-use in another structure, chipped for use as fuel or mulch, or sent to a landfill (the usual case). If burned or mulched, stored carbon is released when the wood decomposes, which is essentially the reverse process of photosynthesis (Falk, 2010):

$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$.

If wood is substituted for steel, concrete, and other products that use more energy in their manufacture, fossil fuel consumption is greatly reduced and, consequently, CO_2 emissions. This is known as substitution. Using sawmill residues for bioenergy recovery also improves the energy balance of wood products (Hurmekoski, 2017).

According to Falk (2010), carbon emitted to produce a tonne of concrete is about eightfold more than what is emitted to produce a tonne of framing lumber. A similar comparison for steel indicates that its production emits about 21 times as much carbon as an equal weight of framing lumber. Wood products also mitigate carbon emissions to such a degree that they can be viable substitutes for steel or concrete, which emit more greenhouse gases in their production.

Meta-analyses for the average impact of using wood instead of concrete suggest an average reduction of 2.1 tonnes of CO_2 emissions per 1 tonne of wood products used (Sathre &Gustavsson, 2009; Sathre & O'Connor, 2010). If the mass of all new buildings were constructed with approximately 50% wood, this would offset the CO_2 emissions caused by producing cement for the building sector (3.5% of total EU emissions) (Hurmekoski, 2017).

A 2011 study by the European Commission's Directorate-General for Energy determined that greenhouse gas can be reduced in the European building sector by using wood as the main construction material for new buildings instead of mineral materials such as brick, stone, and concrete. The key findings are as follows:

1. On an individual building level, > 90% of greenhouse gas emissions can be currently saved relative to manufacturing and construction when using wood as the main construction material instead of the usual combination of mineral materials – without even considering the CO_2-storage effect of wood.

2. 62 Mt of greenhouse gas emissions can be avoided in the year 2050, and 827 Mt cumulatively until 2050 by substituting mineral materials in new buildings if the current wood market share for new buildings steadily increases from 5.5% in 2020 to 75% by 2050 (assuming the current energy mix and processes).

3. In addition to the substitution effect, wood as a building material can store up to 83 Mt of CO_2 in the form of carbon in the year 2050 (compared to approx. 6 Mt of CO_2 today). Over the entire time span until 2050, wood buildings could accumulate a total of 1,112 Mt of CO_2 and continue to store it for a long time. This is quite significant compared to the GHG emissions for the use phase of current buildings, which equals approx. 650 Mt CO_2_eq per year.

4. The storage effect of wooden buildings could be maintained for a long time, as long as disposed or burned wood is replaced with new wood products. In this way the carbon sink of the building sector would eventually become saturated, but the carbon removed from the atmosphere would be permanent. However, wood should be reused as a material as often as possible in order to avoid the carbon content that will be released.

5. In total, the substitution and storage effect account for up to 145 Mt in 2050 and a cumulated 1939 Mt until 2050.

Circular Economy

The current economy follows a linear process in which materials are extracted from the Earth, then used to make products that are eventually thrown away as waste. The circular economy, by contrast, is driven by design and based on the following three principles:

– Eliminate waste and pollution

– Circulate products and materials (at their highest value)

– Regenerate nature

Construction is one of the most significant sectors that is depleting natural resources at such an intensity that the sector will increasingly have to acknowledge circular thinking. A circular economy aims for a closed system in the following way (Sitra, 2016):

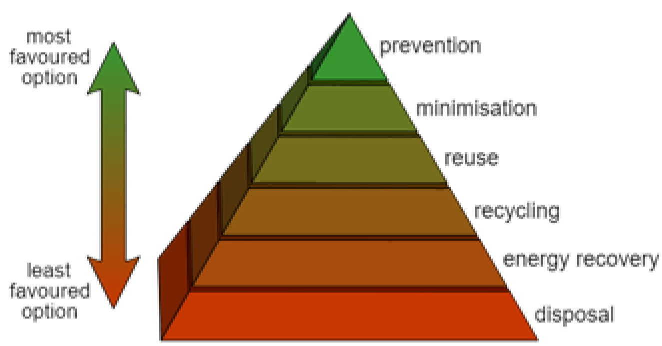
– Maximizing the circulation of product, component, and material flows by reducing material input and waste, recycling, reuse, and sharing

– Maximizing the value of materials

The renewability (bio-degradability) of wood means that demolition wood can eventually be combusted and the emissions reabsorbed into growing forests, which could justify characterising the use of wood as a circular process (Hurmekoski, 2017). There is very little waste when wooden products are made, whether as floorboards, doors, or windows; and any residual chips can be burned as an energy source or used as sawdust during manufacture. The Forestry Commission says “There is no waste in timber production. For example, offcuts and by-products from wood processing industries like furniture-making can be used to create chipboard and generate renewable heat and energy.” The waste that is produced is 100% biodegradable, meaning that it eventually decomposes and breaks down back into earth, making it better for the environment (Jowaheer, 2018).

In terms of reducing material input and thereby waste, wood construction has benefits. From a waste hierarchy perspective (see Figure 1.8), prevention of waste is the best option. Substituting a wooden frame for a concrete frame significantly reduces the total material input of a building, meaning that it avoids greater material use and waste because the weight of wood is four to five times lower than that of concrete. A wood-based structural frame can cut the total material consumption of construction by half and the weight of the structural frame by 70% (Pasanen et al., 2019). A lighter structural frame also allows reducing the material input to the foundation. Industrial prefabrication provides an efficient way of minimizing waste at the construction site. The residues from the manufacture of wood products (e.g., for use in construction), such as chips, sawdust and bark, are used for producing wood-based panels, bioenergy, and biochemicals that can substitute fossil-based raw materials (Hurmekoski, 2017).

Fig. 1.8
A waste hierarchy based on Waste Framework Directive 2008/98/EC (Wikimedia Commons)



The European sawmill industries are pioneers in their work toward the principle of resource efficiency, as they endeavour to maximise the added value of wood resources in a zero-waste, highly mechanized production circle. New technology enables them to maximise lumber output and the quality of by-products. Logs are sawn into planks or other dimensioned goods. Sawn timber can be further processed into profiled cladding, decking, mouldings, flooring, joinery, furniture components, and a wide range of other products (Jeffree, 2019).

It can also be pressure laminated into high performance multi-layer products known as engineered wood. This includes highly stable and strong components for joinery and other products such as glue-laminated timber (glulam), laminated veneer lumber (LVL) beams, and cross-laminated timber panels (CLT). These are becoming increasingly core structural elements in ever larger, more technically advanced timber-based buildings (Jeffree, 2019).

Sawdust and other sawmill residues are processed into other wood-based products or used for bio-energy production. Co-generation facilities also produce power for the mills themselves and feed any excess into the grid. Bark can be burned for heat and power, or used for landscaping, while wood pellets made from sawdust also offer high performance, clean solutions for commercial and residential heating (Jeffree, 2019).

Wood waste products can be recycled and transformed into new products. One-third of demolition wood is used directly for energy production, which from the waste hierarchy perspective is regarded as the least favourable option. Finding more efficient recycling options for demolition wood will be a challenge, due to the chemical impregnation of wood or the use of oil-based glues, paints, and other material mixes.

On 16 July 2021, the new EU Forest Strategy for 2030 was introduced. The strategy is set “to enhance the multifunctional role of forests in achieving climate neutrality, putting biodiversity on the path to recovery and supporting a circular bioeconomy. To achieve these goals, the new Strategy calls the forest-based sector to optimise the use of wood in accordance with the **cascading principle**, which also entails prioritising the resource-efficient production of long-lived building materials to replace carbon-intensive and fossil-based ones” (Interreg Europe, 2021). For example, the following sequence of the cascading principle can be used: beam → floor board → window frame → oriented strand board → fibreboard → combustion (Hurmekoski, 2017).

Furthermore, emphasis must be placed on the better design of buildings and building products, not only to guarantee their flexibility and modularity in order to extend their lifetimes, but also to make building products more cost-efficient and convenient to maintain, reuse, refurbish, and remanufacture (Judl et al., 2016; Hurmekoski, 2017). For instance, The Wood Innovation and Design Centre in Canada was designed with a deep focus on repeatable, reusable, prefabricated construction (Figure 1.9). The vast majority of the building is made of cross-laminated timber (CLT) panels and glue-laminated timber (glulam) columns and beams, which, at the end of its functional life, can be disassembled and the wood products used in a future structure (Naturally:wood, 2021).

Fig. 1.9
The Wood Innovation and Design Centre (Flicrl.com)

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→ 2

General properties of wood

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Wood is an abundant renewable resource that exhibits interesting properties for its use as building material. However, we should keep in mind that wood comes from tree trunks, which purpose is to grow and develop cells and tissues to perform the fundamental functions of the tree; conduct the sap, transform and store food and finally form the resistant or load-bearing structure of the tree. Properties of wood depend on the species, on the composition, but also on the arrangement of the different elements that constitute wood. In this chapter we want to highlight some aspects of wood that will help us to understand its behaviour and how to design and construct with this material.

2.1. Classification of wood

Recent studies estimate that there exist more than 70000 species of trees on the Earth [1]. They cover areas in different latitudes and altitudes; therefore, the growing conditions are different and consequently there are large kinds of timber with different properties. Wood is classified in two big categories: softwood and hardwood [2].

- Softwoods: wood from gymnosperm trees. Usually evergreen conifers with needle like leaves, such as pine or spruce.
- Hardwoods: wood from dicotyledon angiosperm trees. These trees are usually deciduous with broad leaves and can be subdivided into temperate and tropical hardwoods. Temperate hardwoods are oak, beech or elm, while examples of tropical hardwoods are iroko and ebony.

2.2. Composition and anatomy

Wood is formed by the secondary xylem tissue found in stems, roots and branches of woody plants like trees and shrubs. Wood is a heterogeneous and anisotropic material made of specialised cells [3]. In this section, the concepts of wood composition, microstructure and macrostructure will be discussed in a simplified way.

Composition and microscopic structure

Wood is an organic material composed mainly of three natural polymers: cellulose, hemicellulose and lignin. It also contains a small proportion of organic compounds of lower molecular weight as well as mineral salts grouped under the term extractives [4]. In table 2.1 are shown the proportion of these molecules in softwood and hardwood [5]. The elemental composition of wood is mostly carbon (47-50%), oxygen (44-45%) and hydrogen (6%) [4].

Table 2.1. Molecular and chemical composition of wood. Adapted from [5].	Softwood	Hardwood
Cellulose (%)	40-44	40-44
Hemicellulose (%)	30-32	15-35
Lignin (%)	25-32	18-25
Extractives (%)	5	2

Wood can be considered as a set of elongated cells in the form of tubes, parallel to the axis of the tree, which vary greatly in length and shape, as well as in the thickness of their walls and interior dimensions. These cells are joined together by a substance called intercellular matter or middle lamella, and are in turn joined by another type of cell, placed perpendicularly to the previous ones and in the radial direction of the trunk, forming the so-called woody rays. The walls of the tubes are made up of a series of layers composed of cellulose microfibrils embedded in a matrix of lignin [6].

Wood cells are also known as fibres and, their longitudinal distribution within the cross section are responsible of the anisotropy of wood resulting in a higher resistance on the axial direction.

Softwoods contain around 90% of longitudinal cells of tracheid and the remaining tissue is mainly radial parenchyma. Hardwoods exhibit a more complex anatomical structure than softwoods. The distribution and proportion of the cells and tissues depends on the species, but the main constituents are vessel members, fibres and parenchyma.

Macroscopic structure

Macroscopic structure are the elements that can be distinguished when a piece of wood is observed with naked eye. Figure 2.1 shows the different parts of a trunk cross section: pith, heartwood, sapwood, cambium, inner bark, outer bark and rays. It can also be observed the growth rings.

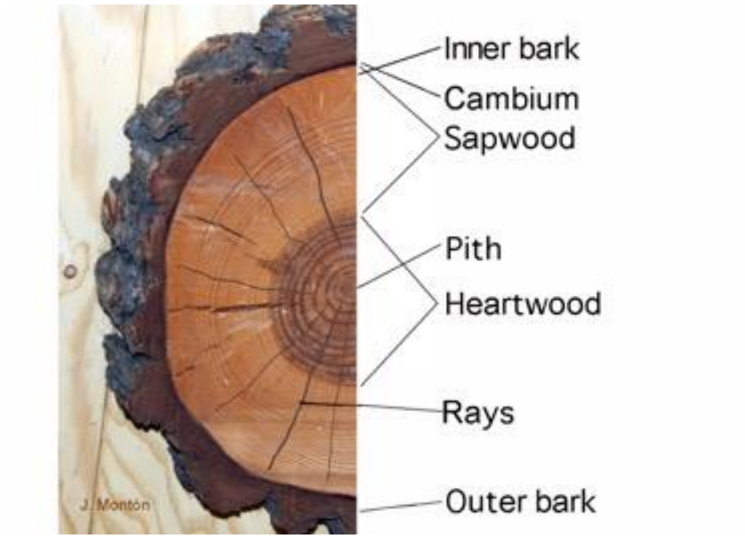

Fig. 2.1. Macroscopic structure of wood.

Pith is the centre of the trunk. It presents an old and often cracked fibrous and porous tissue. The diameter is small and it is a part usually discarded in the wood industry.

Heartwood is the inner part of the trunk and constitutes a highly developed wood tissue. Usually has a darker colour due to the lignification process that has experienced during the growth of the tree. Heartwood has a higher density, mechanical resistance and durability in front of biotic agents.

Sapwood is the outside part of the trunk. It is a young tissue still in a growth process. It is where the sap flows from the roots to the top of the tree. During the life cycle of the tree the inner layers of the sapwood are lignified and become part of the heartwood.

Cambium is the layer between bark and sapwood. It is the base of the tree growth. It produces two types of cells: sapwood towards the inside and bark towards the outside.

The inner bark is the young part of the bark. It is a weak, fibrous tissue.

The outer bark is the surface of the trunk. It protects the inner part of the trunk from the rain.

Rays are layers of cells oriented in the radial direction. They act as nutrient stores of the tree and as brace of the radial fibres of the trunk. Therefore, the presence of rays will have an influence on wood shrinkage.

Growth rings correspond to the annual growth of the tree. In each ring can be found two zones: earlywood and latewood. Earlywood is formed in spring, when the tree has a lot of activity and high amounts of sap have to be conducted through the cells.

Latewood is formed at the end of the growing season and the cells are smaller and the walls are thicker Therefore, earlywood is clearer and less dense that latewood. However, in tropical regions where there are no climatic variations between seasons earlywood and latewood do not exhibit these differences.

2.3. Anisotropy

Wood is anisotropic because its properties depend on the direction in which the stress is applied. As it is shown in figure 2.2, wood presents three directions:

Longitudinal or axial: Parallel to the axis of the trunk and therefore parallel to the grain.

Radial: Perpendicular to the axis and the grain, but crossing the pith.

Tangential: Perpendicular to the axis and the grain, but tangent to the growth rings.

Fig. 2.2. Directions in a wood trunk.

These directions should be considered when analysing mechanical and physical properties of wood.

2.4. Wood moisture

The relationship of wood with water is a crucial factor because moisture content will affect other properties, such as, mechanical strength, dimensional stability or durability.

Water in wood could be found in three forms:

- Constitution water: it is part of the molecules that constitute wood and it is not possible to remove it without destroying the material.

- Bound water: it is the water located in the cell walls. Changes in humidity and ambient temperatures cause changes in the bound water content. Variations in bound water contents give raise to wood swelling and shrinkage. Usually the saturation point of the fibre is around 30%. Above this value the fibres cannot admit more bound water. It is possible to remove bound water by heating the wood at 100-110 ºC.
- Free water: This water appears above the saturation point of the fibres. It is liquid water found in cell lumens and other void spaces in wood. It can be found in living trees. After cutting the tree and drying the wood it can only appear if wood is immersed in water.

The moisture content of wood is defined by:

U(%); Moisture content

m_u; mass of moist wood

m_o; mass of oven-dried wood

$$U(\%) = (\mathrm{m}u - mo / mo)x100$$

Table 2.2 shows a classification of wood according its moisture content (U_m).

Table 2.2. Classification of wood according to the moisture content.	Area	
	≤ 200cm^2	>200 cm^2
Green	U_m>30%	U_m>35%
Semi dry	20%<U_m<30%	20%<U_m<35%
Dry	U_m≤20%	U_m≤20%

Wood is a hygroscopic material that will modify its moisture content to equilibrate with the environmental conditions of humidity and temperature. These changes should be taken into account to control shrinkage or swelling of timber elements.

2.5. Shrinkage and swelling

Dimensional changes in wood are due to the increase or decrease of its moisture content up to the fibre saturation point (around 30%). If moisture increases, the wood suffers swelling, but if it decreases wood undergoes shrinkage. The volumetric shrinkage can be calculated as follows:

C_v; coefficient of volumetric shrinkage

V_s; Volume of bound wood

V_o; Volume of dried wood

$$Cv(\%) = \frac{Vs - Vo}{Vo} x100$$

The coefficient of volumetric shrinkage should be considered for the three directions of wood: axial, radial and tangential. Higher shrinkage is found in tangential direction, while the axial direction exhibits high dimensional stability (figure 2.3). Differences between, radial and tangential shrinkage are the cause of distortions in timber during drying.

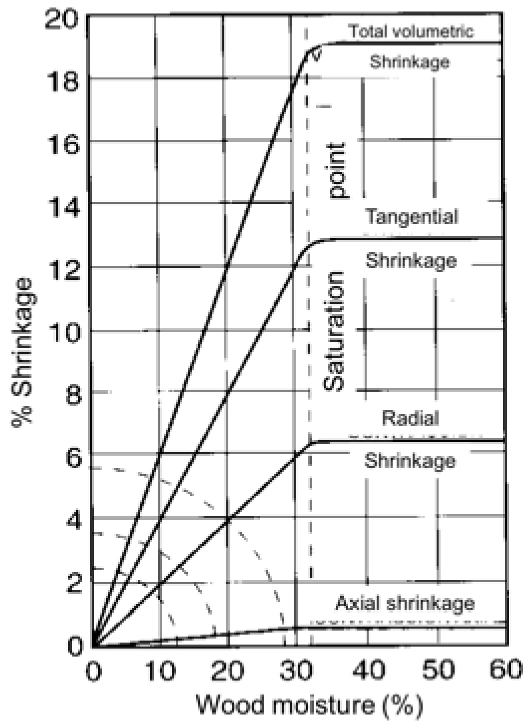

Fig. 2.3. Shrinkages coefficients in timber [3].

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→ 3

Mid- and high-rise mass timber buildings: Building codes and standards in different countries

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Mass timber has disrupted the built environment in part due to a resurgence of tall wood buildings since 2009. This has led to changes in the building codes and standards that govern wood construction, which will be the focus of this chapter. The following learning outcomes are defined:

1. Review current global construction trends for mid-and high-rise buildings.
2. Identify the mid- and high-rise wood buildings throughout the KnoWood countries.
3. Review ISO standards for timber construction.
4. Identify wood and mass timber design codes in Canada and North America.
5. Review EU and UK codes for timber construction.

3.1 Trends in mid- and high-rise wood construction

Timber construction has become trendy and more widely accepted in various sectors of the construction market. For example, WoodWorks calculated that between March 2020 and March 2022, the numbers of mass timber projects being constructed or under design across the US increased from nearly 800 to over 1,300 projects.

The rapid growth and interest in taller wood buildings have led to recent changes in Canadian and US building codes, which now allow up to 12- and 18-storeys, respectively. Conversely, England has extended its ban on combustible materials for major building types while lowering the maximum height to 18 m (source: https://www.buildersmerchantsnews.co.uk/New-height-restrictions-A-potential-barrier-on-the-road-to-net-zero-targets/49684).

Constraints on taller wood buildings are imposed primarily from fire regulations. Hence, mid-rise wood construction is expected to see more attention and growth. Because building codes allow for mid-rise wood buildings, construction is faster, and installation costs are lower, the number of mid-rise wood buildings has increased across the spectrum of residential, commercial, and institutional construction.

3.2 Mid- and high-rise wood construction across the KnoWood countries

The concept of mid- and high-rise construction is hard to define because there are no specific rules. Furthermore, the definition of each type of building tends to vary from country to country. Some common practices use the number of storeys to define buildings according to the following:

– Low-rise building: up to 4 storeys

– Mid-rise building: between 4 and 10 storeys

– High-rise buildings: 10 storeys and above

The following projects are some examples of light-frame mid-rise building construction projects in Canada.

Fig. 3.1
Mid-rise (5-storey) light-frame residential construction in Canada

In addition to height limits or number of storeys, the building codes establish a maximum area, which depends on the type of occupancy and is directly related to fire resistance ratings.

High-rise wood construction is a very recent phenomenon. Amongst the KnoWood project countries, Canada once stands out for once having the world's tallest mass timber building in 2017, known as the Brock Commons Tallwood House, which still stands at 18 storeys atop a 1-storey concrete podium (figure 3.2).

Fig. 3.2
Construction of Brock Commons (ThinkWood)

3.3 The ISO Standards for timber construction

What is the ISO?

The ISO is the International Organization for Standardization, a federated body comprised of national standards associations and bodies who usually form various technical committees to carry out its work.

Timber structures are standardized under ISO/TC 165, which was created in 1976. It standardizes the structural applications of timber, wood-based panels, other wood-based products, and related lignocellulosic fibrous materials. This generally includes design requirements;

structural properties; performance; the design values of materials, products, components, and assemblies; test methods; the requirements for establishing related structural, mechanical and physical properties; and performance (source: https://www.iso.org/committee/53584.html).

In 2019, ISO 16696-1:2019 (Timber structures – cross-laminated timber) was published to define the principles for component performance and the minimum production requirements for cross-laminated 38timber (source: https://www.iso.org/obp/ui/#iso:std:iso:16696:-1:ed-1:v1:en).

3.4 Canadian wood design and building codes

In Canada, the engineering design of structural wood products and systems follows the requirements of the National Building Code of Canada (NBC). In addition, a standard is applied to the engineered design of structural wood products (see Canada Wood Council).

Before the most recent update to the building code in 2020, the first edition of NBC in 1941 had a provision limiting timber buildings to a height of 23 m (75 ft). The most recent update to the National Building Code, NBC 2020, allows for buildings of up to 12 storeys using wood and mass timber construction methods, whereas the previous version, NBC 2015, capped wood-frame buildings at 6 storeys.

For wood design and construction, the standard CSA O86 is referenced in the National Building Code and in provincial building codes. It provides the criteria and standards for the structural design and evaluation of wood structures and structural elements. It is written in the limit states design (LSD) format and provides resistance formulas and specified strength values for structural wood products, including: graded lumber, glue-laminated timber (GLT), cross-laminated timber (CLT), unsanded plywood, oriented strand boards (OSB), composite building components, light-frame shear walls, diaphragms, timber piling, and pole type.

The structural design of wood buildings and systems is based primarily on limit states design, using:

- The loads as defined in Part 4 of the National Building Code.
- The material resistance values obtained using the CSA O86 standard.

There is, however, an exclusion in the National Building Code of Canada for the design of single detached houses and other small buildings. It is outlined in Part 9 of the building code and is titled “Housing and Small Buildings”. This prescriptive design allows for building under certain requirements.

The CSA O86 standard is a standard reference, as it provides the key criteria, resistance equations, and specified strength values for structural wood products, including: graded lumber, glue-laminated timber, cross-laminated timber (CLT), unsanded plywood, oriented strand board (OSB), composite building components, light-frame shear walls, diaphragms, timber piling, pole-type construction, prefabricated wood I-joists, structural composite lumber (SCL) products, permanent wood foundations (PWF), and structural connections.

In the United States, the National Design Specification (NDS) serves as the standard for wood construction. The NDS is developed by the American Wood Council and presents both Allowable Stress Design (ASD) and Limit Resistance Factor Design (LRFD). To allow for tall wood buildings in the US, the 2021 International Building Code (IBC) includes three new construction categories that allow using mass timber and non-combustible materials in buildings of up to 18, 12, and 9 storeys. Just like in Canada, local state and municipal jurisdictions can adopt and implement the building code with addenda or amendments.

The National Building Code of Canada revolves around the following requirements:

- Fire protection, occupant safety, and accessibility
- Structural design
- Environmental separation
- Heating, ventilating, and air-conditioning
- Plumbing services
- Safety measures at construction and demolition sites

In addition to NBC, new building construction as well as retrofits need to comply with the National Energy Code of Canada for Buildings (NECB).

3.5 The EU and UK codes and standards for wood construction

The following describes the standards for wood construction amongst several EU countries and the UK.

Denmark

In Denmark, the technical requirements for designing and constructing mid-rise and high-rise wood buildings are governed by the Executive Order on Building Regulations 2018 (BR18 –/http://bygningsreglementet.dk/) and national technical requirements. Those requirements include:

- Mechanical resistance and stability

BR18, Chapter 15 –Structures, regulates the planning, construction, operation, and maintenance of structures and building parts. Wood-based structures must be planned and built to resist normal static and dynamic effects related to the location and use of the structure. BR18, Chapter 15 – § 348, refers to Eurocode 5 (DS/EN 1995) as a special provision for wooden structures.

Planning and constructing wooden structures must be carried out in accordance with Eurocode 5 (source: http://bygningsreglementet.dk/).

- Fire safety requirements

These must follow BR18, Chapter 5 – Fire, and Appendix 2 – Pre-accepted solutions. Buildings must be constructed, laid out, and fitted to achieve satisfactory protection against fire and the spread of fire to other buildings on the same plot and neighbouring plots. There must be appropriate provisions for rescuing people and for fighting fires (source: http://bygningsreglementet.dk/).

- Energy requirements

BR18, Chapter 11 – Energy consumption, states that "buildings must be planned, established, converted and maintained in order to avoid unnecessary consumption of energy for heating, domestic hot water, cooling, ventilation and lighting with due respect of the use of the building and the scope of the building work" (source: http://bygningsreglementet.dk/).

- Moisture requirements

BR18, Chapter 14 – Moisture and wet rooms, requires that buildings be "planned, built and maintained to ensure that water and moisture do not result in health risk to persons or damage to the building" (source: http://bygningsreglementet.dk/).

- Acoustics requirements

BR18, Chapter 17 – Noise, states that buildings must have "the satisfactory requirements for noise conditions in terms of health and comfort in consideration of their use" (source: http://bygningsreglementet.dk/).

- Sustainable use of wood resources

Denmark has introduced FBK (Voluntary Sustainability Class), which sets the requirements for new buildings at kg. CO_2 eq per m^2. Therefore, special focus has been placed on the use of wood as well as recycled materials in order to meet the aforementioned requirements. Certified wood is recommended as the easiest way to document sustainable and legal wood. Sustainable wood is defined in the guidelines as wood from sustainably managed forests, recycled wood, or a combination mixed with legally harvested wood (source: https://dk.fsc.org/dk-dk/det-arbejder -vi-p/offentligt - indkbøb-og-lovgivning/goderaad). In addition, companies importing timber or timber products into the EU must establish a due diligence scheme and comply with EUTR (EU Timber Regulation) (Source: http://eutr.dk/). Furthermore, Denmark is part of the Program for the Endorsement of Forest Certification (PEFC), which is made up of national members from more than 50 countries who follow guidelines for sustainable forestry that are adapted to each country's climate and environment. Certified wood is recommended as the easiest way to document sustainable and legal wood. Sustainable wood is defined in the guidelines as wood from sustainable managed forests, recycled wood, or a combination mixed with legally harvested wood (source: https://dk.fsc.org/dk-dk/det-arbejder-vi-p/offentligt- indkb-og-lovgivning/goderaad). In addition, companies that import wood or wood products to the EU must establish a due diligence scheme and comply with EUTR

(source: http://eutr.dk/).

- Indoor air emissions

Indoor air quality and pollution from construction materials is not permitted to affect the indoor climate of buildings in any way that results in a risk to the health of people or provokes any comfort-related nuisance (BR18, Chapter 13 – Pollution) (source: http://bygningsreglementet.dk/)

- Safety systems

“DS/EN 1995-1-1 National Annex to Eurocode 5: Design of timber structures – Part 1-1: General – Common rules and rules for buildings.”

“DS/EN 1995-1-2 Eurocode 5: Design of timber structures – Part 1-2: General – Structural fire design.”

Lithuania

Wood is a traditional building material and, up until the 1940s, nearly 90% of all houses in Lithuania were built with wood. The trend has stopped until fairly recently. As the manufacturing of CLT and GLT is rapidly growing in Lithuania – in part to meet export demand – the volume of wood building projects should follow accordingly. In Lithuania, mid-rise buildings comprise any structure with a height of more than 8.5 m or that has between 4 and 12 storeys. High-rise buildings include any structure with a height of more than 35 m or that has more than 12 storeys. The following are some of the current building requirements in Lithuania.

- Mechanical resistance and stability

There are two technical regulations on mechanical resistance and stability:

1. The Lithuanian local document issued by the Ministry of the Environment: Technical regulations for construction. Design of timber structures (in Lithuanian: “Statybos techninis reglamentas. Medinių konstrukcijų projektavimas”).

2. European Standard Eurocode 5: Design of timber structures (with Lithuanian national annexes).

- Fire safety requirements

“There are general technical requirements for calculation of fire loading value for the buildings (Lithuanian technical regulation). The structural safety is ensured by structural calculations according to Eurocode 5 – Design of timber structures, Part 1-2: General rules – Structural fire design.”

- Energy efficiency

Building design and construction must comply with: STR 2.01.09:2012 Lithuanian technical regulation for construction. Energy efficiency of buildings. Energy efficiency certification.

- Sustainable use of wood resources

In Lithuania, there are no strict regulations, only recommendations for the use of natural resources.

Spain

Timber construction is a traditional construction method in Spain. However, the 1999 Spanish Building Act (Ley de Ordenación de la Edificación, known as LOE) established some requirements for the building process (source: https://www.forum-holzbau.com/pdf/ihf11_queipo.pdf).

The first requirements impose mandatory insurance on developers, with enforcement incumbent on the project and construction supervisors. In 2006, the new Spanish Building Code was approved. The Spanish Technical Building Code is the normative framework that establishes the safety and habitability requirements of buildings, as set out in the Building Act (LOE).

In Spain, the technical requirements for construction are the following:

- Mechanical resistance and stability

These requirements are regulated by CTE SE-M (the Spanish building code, in the annex about the structural security of wood) and Eurocode 5.
The methods used must ensure the mechanical resistance and stability of timber structures.

- Fire safety requirement

Compliance with fire safety requirements can be achieved by following CTE DB-SI or Eurocode 5.

- Energy efficiency

Compliance with energy efficiency must meet CTE HE, the Spanish building code annex on energy saving.

- Sustainable use of wood resources

Certification labels such as FSC and PEFC are used, but they are not mandatory. If the buildings are for the public administration, it is usually required that the wood be certified as having come from sustainable origins.

The UK

The UK timber construction market is dominated primarily by lightweight platform timber frames, which are typically manufactured from CLS (Canadian Lumber Standard) softwood and a mixture of engineered wood products such as OSB and glulam. Most timber products are imported from Europe and use the PEFC or FSC certification of sustainability. Timber frames are used in both the domestic and commercial sectors for low- to medium-rise buildings. UK timber frames use post and beam construction that incorporates studs and lintels as primary structural components, constructed in layers with independent floors.

Open panel prefabricated structurally load-bearing timber frames are manufactured off-site in a factory, with the internal face of the wall left unfinished for insulation. Services and linings are installed later on-site before closing with plasterboard.

Closed panel timber frames are load-bearing panels manufactured off-site with the insulation pre-installed and sometimes the windows, doors, and service channels also pre-installed. The external cladding for both systems is most commonly done in traditional masonry like concrete blocks or, less commonly, using lightweight render board with a siliconized render or sometimes timber panels.

CLT and mass timber have also taken on a widespread and growing presence in the UK for the last 20 years, and they are typically specified in commercial and high-end domestic projects.

In the UK, Eurocode 5 is still relevant while other countries follow various building regulations. The technical requirements for construction in England are the following:

- Mechanical resistance and stability

Building Regulations Approved Documents Part A

- Fire safety requirement

Building Regulations Approved Documents Part B

- Energy efficiency

Building Regulations Approved Documents Part L

- Sustainable use of wood resources

United Kingdom Forestry Standard (UKFS) – standard for sustainable forest management for locally grown timber

The UK Building regulations offer design guidance rather than prescriptive codes and, due to this fact, many companies that design and build in timber are members of the STA (Structural Timber Association) and TRADA (Timber Research and Development Association). Both organisations offer timber construction advice on detailing, construction, designing, and engineering to members. Furthermore, despite no longer being a member of the EU, UK designers still follow Eurocode 5 for structural design.

Finally, it should be noted that although the UK has seen a shift from traditional wood construction, with more CLT and mass timber being used in the last 20 years, the regulatory environment has changed after the fire at Grenfell Tower. For example, certain building types are now restricted to a height of 18 m in England/Wales and to 11 m in Scotland if they have timber or other combustible materials in the external walls. This effectively amounts to a ban on timber high-rise residential multi-occupied buildings of around 4 to 6 storeys (i.e., England, Scotland, Wales, or Northern Ireland). The office/commercial sector is different, but still subject to insurance restrictions. Most building regulations may also vary slightly, depending on where they are in the UK.

Additionally, the new Building Safety Act 2022 is intended to create an enhanced safety framework for high-rise residential buildings, namely by following the recommendations of the Hackitt report, *Building a Safer Future – Independent Review of the Building Regulations and Fire Safety*. This identified that the construction regulatory system was unfit for purpose, outlined proposals for regulatory reform, and indicated how industry needed to change its operating principles.

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4

ENGINEERED WOOD PRODUCTS AND BUILDING SYSTEMS

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4.1 Cross-laminated timber (CLT)

The origins of the product

CLT means cross-laminated timber, which, more precisely, is solid wood panels comprised of spruce slats laid in transverse and longitudinal directions (i.e., cross-laminated), often conjoined by finger joints. This results in very high strength, greater cargo capacity, and dimensional stability.

Areas of application in construction

An applied example is the 2018 housing project Lisbjerg Bakke, located a few kilometers north of Aarhus. Designed by Vandkunsten, this four-story structure is the highest wooden building in Denmark.

Lisbjerg Bakke comprises a total of 40 apartment blocks, all of which are built with a pillar beam system using glued laminated timber and facade cassettes in CLT. Concrete was used in the stairwells and elevator shafts, as well as in the glued laminated timber, where a concrete layer of 9 cm acts as sound insulation. The largest façade elements in solid CLT are 3.6 x 3 m and weigh 675 kg (see Figure 4.1).

Fig. 4.1 Lisbjerg Bakke. Construction in CLT and glulam (Photo: Helene Høyer Mikkelsen)

The façade elements are made of untreated spruce. Although the life expectancy of the outer façade is only 20–30 years, it will be easy to replace the wood. Inside the apartments are large quantities of visible wood treated with white lye, thus allowing the wood to retain its bright colour.

CLT can therefore be used in all kinds of construction for building walls, floors, ceilings, and roofs.

Properties

The material also produces less CO_2, is easy to recycle, and has good heat and sound insulating qualities. CLT also does well in relation to fire hazards, as it is difficult to ignite and burns slowly and predictably. The working conditions on the construction site are also better, as the noise and dust are not as bothersome as when constructing buildings in concrete.

Usage categories according to new CLT additions to Eurocode 5 are provided in Table 4.1.

Table 4.1. Usage categories (Eurocode 5)

Classification of usage	Level of humidity in wood	Usage area
Category group #2	Approx. 12%	Indoor, not exceeding a relative humidity of 65%
Category group #3	Approx. 20%	Exterior covered and ventilated constructions, not exceeding a relative humidity of 85% (unheated)
Category group #3	NOT approved for CLT panels	Exterior unprotected constructions exposed to weather

CLT has many applications that make the panels highly flexible for designs. It is a renewable, green, and sustainable material that is classified as eco-friendly. Its prefabrication qualities make CLT useful for many kinds of floor and wall components, which can be fully manufactured before reaching the job site. Being made from multiple layers of wood, CLT naturally has great thermal insulation properties.

Manufacturing principles

CLT is a further development of the glulam product (see Chapter 4.6), whereby boards are glued together in crossed layers, thus giving CLT greater strength than traditional glulam.

The slats are glued together end-to-end in finger-connected joints under pressure and hardened until the glue is completely free of volatile organic compounds. The structure and hardening also means that CLT virtually does not expand or shrink.

The price is roughly equivalent to concrete; but, on the other hand, CLT is significantly lighter and therefore faster to transport and assemble on the construction site. Because CLT is a relatively light building material, the foundations therefore do not need to be as large and the on-site machinery required can be smaller than what is needed for lifting heavier building materials.

Trade variants and dimensions

The typical (non-standard) dimensions of CLT panels are provided in Table 4.2 and variants in Table 4.3.

Table 4.2. The typical (non-standard) dimensions of CLT panels

Parameter	Typical	Rarer but existing
Thickness	20–45 mm	20–60 mm
Width	80–200 mm	40–300 mm
Classification	C24	C14–C30

Table 4.3. The typical (non-standard) variants of CLT panels

Parameter	Typical	Rarer but existing
Height	80–300 mm	60–500 mm
Width	1.2–3.0 m	> 4.8 m
Length	> 16.0 m	> 30.0 m
Number of layers	3–11	> 25

CLT slab with three layers made from spruce sample is provided in Figure 4.2.

Fig. 4.2
CLT slab with three layers made from spruce (www.wikipedia.org)

Risks due to different climatic conditions and thermal considerations

Due to the higher production costs from being a relatively new material, CLT is not produced in many locations. Thus, as a relatively new material, CLT has a limited track record and has not yet been used at a large scale in building projects. One drawback is that more CLT panels are required in order to achieve acceptable acoustic performance. Another is that wood is still inherently flammable, despite its advantages when used for thick beams.

Technology and BIM

Since the industrialized use of CLT is suitable to repetition, specifically as a modular system, it naturally fits in well with the digital design process.

The digital design process allows software programs to aid the designer and, later, the contractor who handles the implementation process. Using reliable information and data, the BIM model is passed directly into the manufacturing process of a highly standardized production facility or, alternatively, to the on-site work process, which are connected to the digital model.

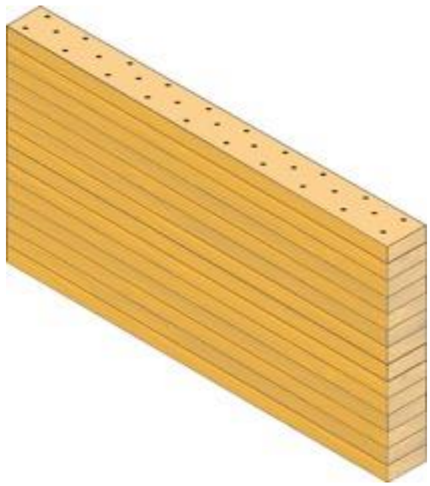
State-of-the-art computer-controlled fabrication (CNC) allows architects and designers to cut timber frame parts into unusual shapes with a high degree of precision. CNC machine tools can utilize the principles of building information modeling (BIM) in, for example, Revit, so any imaginable type of information and data can be transferred directly to the next step in processing the materials or CLT elements, in any shape or form, and on any production line dedicated to prefabricated construction parts like crossed laminated timber.

4.2 Nailed laminated timber (NLT)

Introduction

Nailed laminated timber (NLT) is an historic building construction material made of dimensional lumber stacked on edge and fastened together with nails or sometimes screws to form a solid structural element. This monolithic slab of wood has off-the-shelf dimensions and supports a broad range of architectural constructions (see Figure 4.3). It is produced and used mostly in North America.

Fig. 4.3
NLT image (BM TRADA)



Areas of application

Nailed laminated timber (NLT) is most utilized as an interior element for floors and roof systems, though it can also be used for walls, elevator shafts, stairways, and enclosures. Creating simple curves with NLT is not a problem for the interior design of walls, ceilings, and roofs. In flat or curved building elements, the NLT components remain distinguishable in the final product, thus allowing the designer considerable flexibility and freedom in designing the surface features.

Plywood or OSB boards can be added to one face to provide plane shear strength while functioning as a diaphragm.

Classification and types

The International Building Code (IBC) recognizes NLT as code-compliant for buildings with varying heights, areas, and occupancies, thus allowing for Type III, Type IV, and Type V constructions.

The boards are nominal 2x, 3x, and 4x inches thick (respectively, 50 mm, 75 mm, and 100 mm). The width is typically 4 to12 inches (100 mm to 300 mm). NLT obtains its strength and durability from the nails or screws that fasten the individual pieces of dimensioned lumber into a single structural element.

NLT connections must also be protected to the appropriate fire rating of the elements they are connecting. Protection can be provided by additional wood (for charring), gypsum board, other approved materials, or a combination of approved materials.

Manufacturing principles

NLT lumber boards are mechanically nailed together side by side with steel nails. NLT fabrication is best done using jigs to help ensure straight, square panels. Jigs also help speed up fabrication. The exposed surface of individual laminations can have smooth or ribbed edges, depending on the desired aesthetic effect. The cross-section depth can be made constant or varied by using different sizes of lumber in alternating laminations. The types of lumber used are Douglas fir, fir, pine, larch, and spruce.

North American dimension lumber is machined with slightly rounded corners at the cross sections, giving NLT a distinctive grooved or ribbed texture. To achieve a smooth face, the entire surface is planned. To comply with acoustic and fire specifications, among others, it may be necessary to lay individual layers of OSB or fix plywood to one side. The cross-section depth can be made constant or varied by using different sizes of lumber in alternating laminations. Size differentials are kept to within 2-inch (50 mm) dimensions in order to maximize structural efficiency, for example2 x 6 (50 mm x 150 mm) and 2 x 8 (50 mm x 200 mm).

If the NLT panels are assembled first and then planed or sanded to smooth the gaps between the boards, then the grooves will become more visible. The grooves tend to hide the imperfections. Nailed laminated timber pertains to the non-adhesive group of engineered timber systems because adhesives are not used in the manufacturing process.

Trade variants

Structurally, NLT is a system that spans in only one direction, which has implications for the layout of the structural grid. NLT requires linear support and cannot be supported on columns alone. NLT standard panel conversion dimensions are provided in Table 4.4.

Table 4.4. NLT standard panel conversion dimensions

NLT panel thickness	NLT maximum panel spans
4 inches ≈ (10 cm)	12 feet ≈ (3.6 m)
6 inches ≈ (15 cm)	17 feet ≈ (5.2 m)
8 inches ≈ (20 cm)	21 feet ≈ (6.4 m)
10 inches ≈ (25 cm)	24 feet ≈ (7.3 m)
12 inches ≈ (30 cm)	26 feet ≈ (7.9 m)

Climatic conditions

As a hygroscopic material, NLT absorbs moisture from the surrounding environment. When running and maintaining a building, the content will differ from the moisture content seen during the construction process and, as such, NLT will experience dimensional changes in the same way that untreated timber does.

Project specifications need to address the handling of wood during construction in order to manage exposure to moisture. Strategies can include moisture control planning. Panels must be covered when stored on site.

For larger NLT areas, it is recommended to include a 1.5-inch (35 mm) gap approximately every 20 feet (7 meters) to account for swelling due to changing moisture content during construction.

Due to the nature of their construction, nailed laminated panels are not airtight and need additional layers to create an airtight, smoke proof assembly that also meets acoustic standards. For lateral loads, a layer of plywood is added on top of the NLT elements.

Closing words

NLT is a historical construction method that is regaining popularity with designers due to several factors. It is easy to manufacture and lightweight compared to similar floor and roof systems based on concrete and steel. It can be used to create aesthetic features such as optional surface finishes (rough or sanded), lamination depths, and curved or straight forms. NLT can be used for both residential and commercial structures

A life cycle assessment (LCA) measures the environmental impacts of materials, assemblies, and buildings over their entire lives. Wood products that include NLT consistently outperform their counterparts in LCA assessments. What is more, NLT panels can be re-used or recycled the end of a building's life.

4.3 Dowel laminated timber (DLT)

Introduction

The resurgence of DLT (also known as Brettstapel) in Europe during the 1970s and 1980s provided an efficient method for quickly and easily constructing low carbon, healthy buildings. In the early 1990s, a Swiss company developed a DLT system called dübelholz. The product was superior to nailed laminated timber (NLT) because it used only wood and no glue, steel nails, or metal fasteners (see Figure 4.4). DLT panels can be easily processed using CNC machinery to create a high-tolerance panel that can also contain pre-integrated acoustic materials, electrical conduits, and other service interfaces. Several other companies in Germany, Austria, and Switzerland adopted this idea and started manufacturing DLT commercially, using automated systems for drilling and inserting the dowels. DLT panels are the only all-wood mass timber product on the market. Dowel-laminated timber (DLT) panels are a mass timber product commonly used in Europe, and they are gaining popularity in North America.

The types of wood used are Douglas fir, fir, pine, larch, and spruce and beechwood dowels.

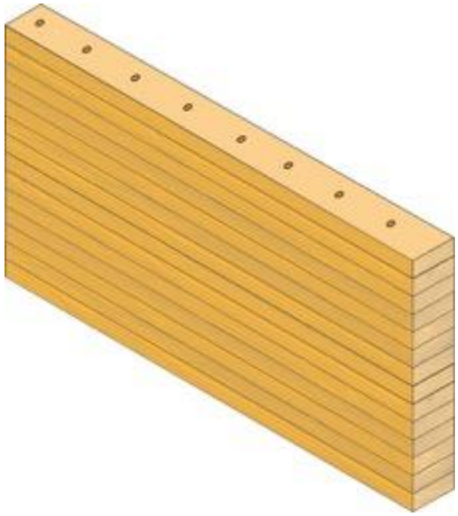


Fig. 4.4
DLT image (BM TRADA)

Areas of application

DLT panels are made for walls, floors, roof constructions, stairways, and elevator shafts. DLT can be curved and assembled to create curved structures.

DLT timber structures were initially developed as slab elements, which consisted of low-cost, inferior quality boards that are joined together to make high quality, loadbearing solid wood structural elements (see Figure 4.5).

Fig. 4.5
On-site DLT assembly (Rothoschool)

Dowel laminated timber, cross-laminated and stacked elements

Cross-laminated DLT are large elements manufactured by cross-laminating 3 to 7 layers of softwood lumber. The elements are made by layering wood on top of each other along their wide edges at alternating angles and pegging them together with beech dowels. Cross-laminated DLT has higher structural values for shear walls and in seismic zones.

Stacked DLT elements are manufactured by stacking the wood layers on top of or next to each other along their edges in the same direction and pegging them together with beech dowels. The elements are made from softwood timber boards stacked end to end in dimensions of 50 x 100 mm (2 by 4 inches), 50 x 150 mm (2 by 6 inches), and 50 x 200 mm (2 by 8 inches), among others. Stacked DLT provides higher structural values for ceilings and roofs.

Manufacturing principles and regulations

Dowel-laminated elements can be either stacked on edge or cross-laminated. Cross-laminated doweled timber elements are similar to CLT but use wooden dowels in place of adhesives. Solid wood doweled elements generally consist of one vertically oriented central layer and several layers oriented either horizontally or diagonally. Generally, DLT wall elements can also be used for floor and roof constructions with panels that are from 12 to 40 cm thick.

DLT products have a wide range of profiles that can be integrated inexpensively into the bottom surface of the element. Each finger-jointed board goes through a molder, thus allowing a limitless range of different profiles to be implemented and exposed at the bottom of a panel. An acoustic profile can be produced to achieve noise reduction objectives while keeping the wood exposed and allowing for a range of surface finishes. Fibrous insulation can be placed inside acoustic grooves to absorb sound.

Eurocodes on general structures provide a set of documents that will enable the design of buildings and civil engineering structures using different structural materials in accordance with common standards across the European Union. The documents are structured according to a hierarchy, at the top of which is EN 1990 – Basis of structural design, which defines the basis of structural design. Below that is EN 1991 – Eurocode 1: Actions on structures, which comprises ten parts that define the actions to be followed. These documents are supported by a number of Eurocodes detailing the particular design methods that must be followed for using the structural materials, i.e., structural timber, steel, concrete, etc.

Eurocode 5 (EN 1995 2004) gives simple design guidelines for evaluating the stiffness of connections, guidelines demand that the stiffness be proportional to the numbers of dowels and shear planes.

Eurocode 5 (EN 1995-1-2 2004, CEN 1995 2004) concerns structural fire design and the cross-section methods that determine the effective residual cross-sections after charring (EN 1995-1-2 2 2004).

US and Canadian building codes. DLT qualifies as a heavy timber element and therefore meets the fire rating requirements of heavy timber buildings.

ASTM E119 / CAN / ULC S101 fire testing has been completed to demonstrate a 2-hour fire resistance rating for a 2 x 6 DLT panel (including a spacing gap between panels).

Trade variants

DLT elements can be topped with concrete to form timber concrete composite (TCC) panels, which is a hybrid system used to reduce cross sections, increase spans, and reduce noise as well as vibrations. Alternating patterns of wood can be used to create aesthetic appearances.

There are many options for creating structural composite action between a DLT element and the concrete topping by means of acoustic layers or insulation separating the two materials. Robust design methodologies have been developed in Europe and used in many buildings over the past 10–15 years.

Climatic conditions

Cross-laminated DLT elements can offer some degree of airtightness, whereas elements stacked on edge cannot.

In terms of building physics, cross-laminated DLT walls consist of just one thick block of layered wood: a wood-only mono-material. Therefore, no changes occur in the vapor permeability in the wall, and no moisture can condense as in the case of the vapor barrier foils or insulation materials that are often used in conventional construction methods. 100% wood DLT regulates the indoor climate much better because moisture can be transferred freely between entire wall systems. In DLT, the moisture flow is not blocked by layers of glue, which can reduce the breathability of the construction by up to 80%. Such reduced breathability can cause condensation and poor air quality in the building.

Closing words

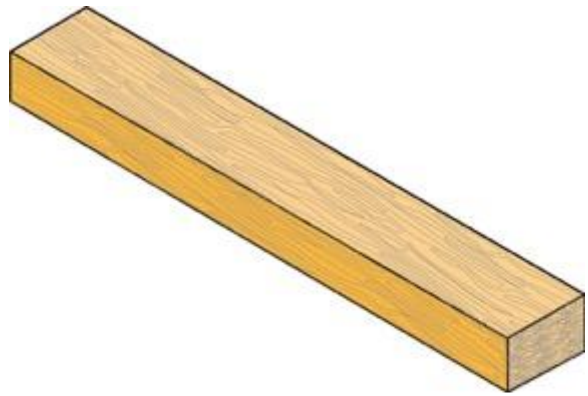
DLT is a safe product that is easy to produce and mill, lathe, and route, as well as for other general uses in CNC machines, because it does not use nails or screws. The absence of nails or screws in DLT means that other on-site trades can safely and easily use saws, drills, and other standard equipment to make changes at later stages in the construction process, such as for building services and electrical conduits. It contains no glues or other chemicals, thus making it 100% uncontaminated and therefore 100% recyclable wood. The elements can be disassembled, recycled, and reused at the end of the building’s life.

4.4 Parallel strand lumber (PSL)

Introduction

Parallel strand lumber (PSL) is part of a family of products known as structural composite lumber (SCL), which are made of dried and graded wood veneers, strands, or flakes that are layered upon each other and bonded together with a moisture-resistant adhesive into large blocks known as billets (see Figure 4.6).

Fig. 4.6
PSL image (BM TRADA)



PSL is part of a family of products known as structural composite lumber (SCL), which are made of dried and graded wood veneers, strands, or flakes that are layered upon each other and bonded together with a moisture-resistant adhesive into large blocks known as billets.

Areas of application

Common applications of PSL in construction include headers, beams, and lintels in light-frame construction; and beams and columns in post and beam construction. PSL is an attractive structural material that is suited to applications for which the finished appearance is important.

Parallel strand lumber is used primarily as structural framing for residential, commercial, and industrial construction.

Classifications and types

The PSL beams are manufactured as 12-by-12-inch (300 mm × 300 mm) or 12-by-18-inch (300 mm × 460 mm) rectangular cross-sections, which are then sawn and trimmed into smaller cross-sectional sizes. The beams are continuously formed and thus the length of the beam is limited only to the maximum length that can be handled and transported. Typical widths are 31⁄2, 51⁄4, and 7 inches (89, 133, and 178 mm); typical depths are 91⁄2, 117⁄8, 14, 16, and 18 inches (240, 300, 360, 410, and 460 mm). The maximum length of beams is 60 feet (18 m).

Manufacturing principles

Parallel strand lumber is manufactured from individual strips of veneer measuring approximately 3 mm in thickness, 15 mm in width, and bonded together. The strips can be up to 2.6 m long before they are bundled together with individual ends offset and the fibers oriented primarily parallel to the major axis of the beam. The veneer strands are bonded together in a continuous press using waterproof adhesives with a phenol-formaldehyde base and resin bonds. The beams can be produced using waste materials from plywood and LVL production, in which the most common species are Douglas fir, pine, western hemlock, poplar, and southern yellow pine. PSL exhibits a rich texture and retains numerous dark glue lines.

PSL can be stained to enhance the warmth and texture of the wood. It is sanded at the end of the production process to ensure precise dimensions and to provide a high-quality surface for appearance.

It is an excellent product. Because its specific engineering properties are unique to each manufacturer, it does not have a common standard of production nor any common design values.

The design values are derived from test results analyzed in accordance with CSA O86 and ASTM D5456, and they are reviewed and approved by the Canadian Construction Materials Centre (CCMC).

PSL has similar fire performance to a comparably sized solid sawn lumber or glued-laminated beam.

In fire testing PSL and other composite lumber products, the char rates are comparable to those of solid sawn lumber and within the range previously found for different species.

Trade variants

PSL is manufactured from veneers laid into long, parallel strands and bonded together. One variant is laminated strand lumber (LSL), which is manufactured from flaked wood strands and resembles oriented strand board (OSB) in appearance, though the strands are arranged parallel to the longitudinal axis.

Parallam is the brand name for the product that was invented, developed, commercialized, and patented by MacMillan Bloedel (now Weyerhaeuser). It is the world's only commercially manufactured and marketed parallel-strand lumber product.

Climatic conditions

Manufactured at a moisture content of 11%, PSL resists shrinking, warping, cupping, bowing, and splitting. Similar to other wood products, PSL will not rot or grow mold when designed and installed correctly.

Relatively large porous voids in PSL mean preservatives are able to saturate and penetrate into the element. PSL can be used in both exterior and interior constructions. Treated PSL can also be applied in high humidity areas. It is important to protect it during transport to the building site in order to avoid moisture absorption. Protecting the ends and edges by sealing them will prevent moisture penetration. Following best practices for managing moisture in wood construction will safeguard the product from damage or decay.

Closing words

Parallel strand lumber (PSL) has attributes such as high strength, high stiffness, and dimensional stability. The manufacturing process enables making large pieces from relatively small trees, thus providing efficient utilization of forest resources.

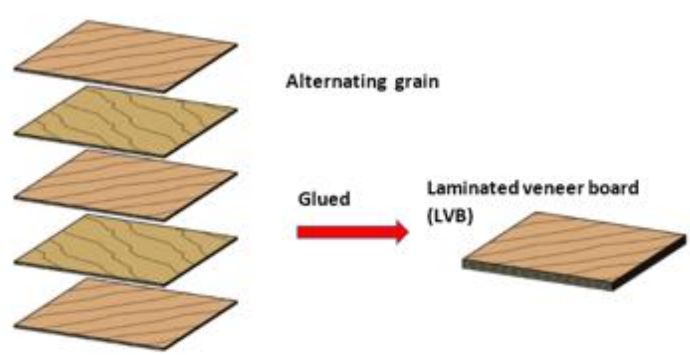
Because of its highly predictable, uniform timber characteristics and its efficient use of wood fiber, PSL is an eco-friendly, attractive alternative to more carbon intensive materials. Like most wood products, it is well suited to prefabrication and is an attractive structural material, which is why PSL is a good choice when the finished appearance is important. What is more, as an engineered product, PSL offers high bending strength and is well suited to long-span designs.

4.5 Laminated veneer lumber (LVL)

Introduction

LVL is an engineered type of timber. Unlike traditional engineered wood (GL types), LVL is composed of veneers bonded together with glue. The thickness of each veneer is about 3 mm. As with other engineered woods, the physical dimensions can be designed independently of the natural wood's dimensions, thus allowing for the manufacture of almost any size and shape (see Figures 4.7–4.9).

Fig. 4.7
Laminated veneer board



The poor parts of the natural wood are discarded and only the top-quality parts are selected and glued into the final component, a process that ensures very high strength properties and very small tolerances and deformations.

However, as with other engineered woods, this comes at a cost: The engineered woods are more expensive than natural timber.

LVL is divided mainly into three types: beams and columns; stabilizing panels for light timber constructions; and hybrid pieces.

The beam and column types of LVL have the veneers arranged all in the same direction and the sheet types have the veneers arranged in alternating directions.

LVL is a highly reliable building material that provides many of the same attributes associated with large-sized timbers. LVL can also be used in combination with glulam to increase the strength of the glulam beam.

Due to the fact that the assembly adhesives limit the penetration of chemicals typically used to treat outdoor-rated lumber, LVL may not be easily treated for outdoor use.

Fig. 4.8
Laminated veneer lumber

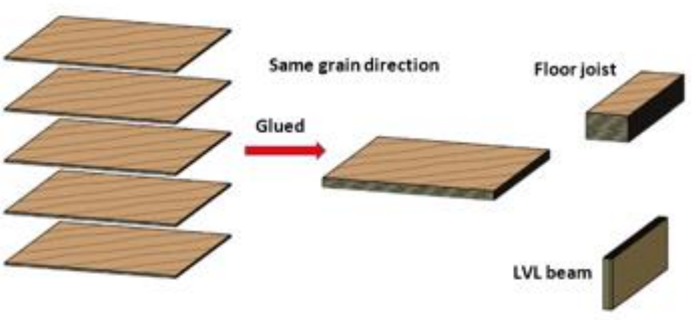


Fig. 4.9
LVL as a stabilizing component in a box wall construction

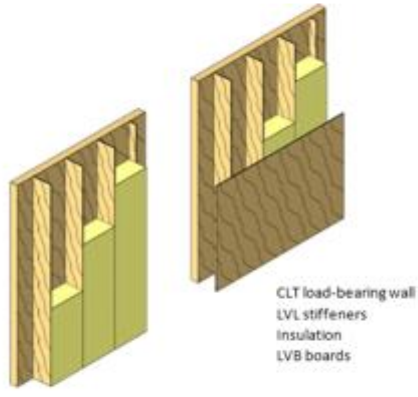
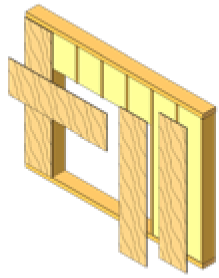


Fig. 4.10
LVB as bracing for light stud walls



Structural properties

In EN 1995-1-1 (EC5), the structural design calculations are made in the ultimate limit state (ULS) for: bending moment; shear; tension and compression resistance; stability; connections; and the stress concentrations in notches, holes, and tapered beams. Serviceability limit state (SLS) design calculations are made for deformations and floor vibrations. In addition, one is required to use EN 14374: Timber structures - Structural laminated veneer lumber – Requirements.

For further information, the LVL Handbook from Metsä Wood is a very extensive source of information.

4.6 Glulam

Introduction

Glulam is the abbreviation for glued laminated timber, which is different from plywood in that it is made by gluing thin wooden lamellas parallel to the grain. The lamella thickness varies from a few mm (e.g., in furniture) to 2–4 cm in building constructions. The elements can easily be formed into curves, so they are suitable for frames and arches, to name but two examples. The strength properties of a glulam beam are significantly higher than for solid timber made of a similar wood type and dimensions (see Figure 4.11).

Fig. 4.11
Glulam (Træsamlingen Teknologisk Institut)

Beginning with the first industrial patented use in Weimar, Germany, in 1872, glulam constructions have been used since the end of the 19th century. Glulam constructions really took off in the 1960s, and the technology has seen rapid development in the past decade.

Glulam optimizes the structural strength of wood and is an alternative to more traditional materials such as steel and I-beams.

Areas of application in construction

The possibility of manufacturing beams in tailor-made sizes offers great freedom to the design of glulam constructions. Glulam is malleable and can be used to make arches, frames and other exciting constructions. The beams retain the aesthetic characteristics of the wood and are an environmentally and resource-friendly building material.

One application example is the Aalborg University School for Architecture and Design's Utzon Center, completed in 2008 and located on the Aalborg city waterfront (see Figure 4.12). The building was designed by Jørn Utzon and his son Kim Utzon. With its three main building units, the sculptural glulam roof structures show the great scale of wooden curves that are made possible by glulam, whose potential is limited only by one's imagination.

Fig. 4.12 Utzon Center. Construction of the sculptural glulam roof structure. Photo: Michael Rønnow Jørgensen

Glulam is used for the framework of houses, as well as in larger structures such as bridges, airports, and any other construction where the wood is visible.

It can be used for vertical columns, horizontal beams, and curved arches. The joints usually comprise bolts and steel fittings.

Properties

Fire safety is generally very good for glulam. The powerful beams burn slowly and with a well-defined burning rate. After the fire, the strength and stiffness of the remaining cross sections remain largely unchanged. Glulam can survive fires that would have easily destroyed lighter wood structures or melted steel structures to the point of collapse.

Manufacturing principles

Glulam is a type of laminated wood product that consists of many layers of timber joined together with durable, moisture-resistant glue.

Glulam beams can be made from many smaller trees that are harvested after a few years of growth, thus making it possible to more quickly produce large, long beams than to wait for one tree to grow large enough to provide similar sized beams.

The material for making glulam is mostly softwood, which in Europe is usually spruce. The actual production involves taking dried boards sorted by strength and gluing them together into long slats by means of finger joints. The slats are cut to the desired length and planed to the final slat thickness, which is typically 33⅓ mm or 45 mm. Then glue is applied and the slats are laid with their wider longitudinal sides and pressed together. The adhesive joints are then cured under maintained pressure. After curing, the beam is planned.

Trade variants and dimensions

Glulam is produced in many sizes and made from different types of timber, depending on the requirements of the final product. Glulam beans come in four standard widths: 65, 90, 115, and 140 mm.

Every beam variant comes with an incremental height of one layer, determined by a slat of 33⅓ mm (see Table 4.5).

Table 4.5. Beam variants

Height in mm												
100	133	166	200	233	266	300	333	366	400	433	466	500

Risks due to different climatic conditions and thermal considerations

In moisture-affected constructions, poor spruce durability can be a problem. Such cases therefore require pressure-impregnated glulam. As spruce is difficult to impregnate, lamellae of pressure-impregnated pine are used. This solution is not without problems, partly because gluing makes it difficult and partly because the final planing of the glulam can expose inadequately impregnated areas. In such cases, one solution is to take special efforts for constructive wood protection instead of impregnation.

Technology and BIM

Since the industrialized use of glulam is suitable to repetition and specifically modular systems, it automatically fits in well with the digital design process.

The digital design process allows software programs to aid the designer and, later, the contractor who handles the implementation process. Using reliable information and data, the BIM model is passed directly into the manufacturing process of a highly standardized production facility or, alternatively, to the on-site work process, which are connected to the digital model.

State-of-the-art computer-controlled fabrication (CNC) allows architects and designers to cut glued laminated timber into unusual shapes with a high degree of precision. CNC machine tools can utilize the principles of building information modeling (BIM) in, for example, Revit, so any imaginable type of information and data can be transferred directly to the next step in processing the materials or CLT elements, in any shape or form, and on any production line dedicated to prefabricated construction parts like glulam.

4.7 Timber frame

Introduction

Timber frames were historically made in a half-timbered style, a building construction method that was common from ancient times to around 1920. The style involved timber beams being joined together in a framework, then filled with masonry, clay, bulwark, or some other similar material. The spaces between the pieces of timber are called a panel.

Modern timber frame constructions are carried out as simple open plan constructions either on-site or in a workshop. Walls may be beveled or braced with cladding on one side, or insulated with cladding on both sides.

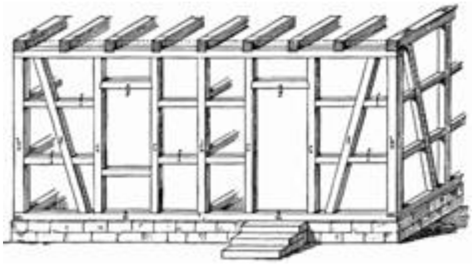
The parts are easy to transport, erect, and assemble on the construction site. Timber framing is a basic construction principle that forms the basis for other construction methods that use ribbed slabs, deck and roof elements, cassette panels, and façades.

Areas of application in construction

This construction method is used for light buildings whose load-bearing skeleton is often a wooden frame, which is typical for smaller construction projects such as single-family houses, terraced houses, and smaller multi-story residential buildings of up to 1½ stories. This construction method is inherently applicable where many repetitions are needed with a very high degree of uniformity among the individual components.

Some examples in which the principles can be applied are external walls, internal partition walls, floor partitions, decks, and roofs (see Figure 4.13).

Fig. 4.13
Typical example of the old Danish half-timber system
(www.wikipedia.org)



The wooden skeleton requires a layer that will stabilize the frame construction, obtain the shear forces, and keep the frame in a fixed shape. Alternatively, wooden frames can also be combined with other stabilizing construction materials, such as load-bearing concrete interior walls or exterior non-load-bearing walls made with brickwork. The two constructions will, in this instance, be tied together with special features that join the properties as a whole.

Properties

The skeleton that is comprised of a wooden frame construction is commonly made from 45-mm studs placed incrementally at a distance of c/c 600 mm, which generally adheres to the standard dimensions of other products like gypsum boards, plywood sheets, and other common industry materials.

Protection against fire and heat loss are properties that need to be analyzed and documented.

In cases where dwellings are separated by a partition wall or deck, the sound insulation between habitable sections must be especially analyzed, designed, and documented. In Denmark, the authorities must always approve all properties of the building components before implementation takes place.

Manufacturing principles

The skeleton of a wooden frame construction is made by squaring the frame to its required width and height, and dividing that with incrementally placed load-bearing studs.

In the interior, an additional layer of mostly horizontal wooden studs can provide extra space for insulation and a damp-proof membrane to make the construction air tight. The cavity for this layer is also very often used as space to install electrical and communications cables. which can be routed and hidden behind the final visible outer layer.

On the exterior, an additional layer (or more) of horizontal or vertical wooden studs can be installed to provide extra space for insulation and other finishings, such as outer visible cladding and ventilation gaps for protection from humid weather conditions.

Trade variants and dimensions

No standardized properties apply to the basic principles underlying wooden frame construction. The fundamental properties required of the frames themselves are that they be used in situ and are therefore very flexible and specific to the design, whether built in a workshop or on-site. Furthermore, they must be easy to transport and erect when the building is assembled and completed.

Risks due to different climatic conditions and thermal considerations

Any time that wood is used for a construction project, consideration must be given to moisture entering from below the foundation, humidity from the inside air, and water from the weather outside. What is more, all of these anticipated factors and protection against them must be detailed in the design. In Denmark, wood is a common building material within the industry and is subject to many codes of practice that guide and support the design process.

Other vital risk considerations are safety against fire, which must follow the Eurocodes.

Technology and BIM

Since the industrialized use of timber frames is suitable to repetition, specifically as a modular system, it naturally fits in well with the digital design process.

The digital design process allows software programs to aid the designer and, later, the contractor who handles the implementation process. Using reliable information and data, the BIM model is passed directly into the manufacturing process of a highly standardized production facility or, alternatively, to the on-site work process, which are connected to the digital model.

Combining today's technology with the historical method of half-timbering could potentially revitalize much more sustainable methods for cleverly joining timber together into frames without using any steel fixtures.

State-of-the-art computer-controlled fabrication (CNC) allows architects and designers to cut timber frame parts into unusual shapes with a high degree of precision. CNC machine tools can utilize the principles of building information modeling (BIM) in, for example, Revit, so any imaginable type of information and data can be transferred directly to the next step in processing the materials or elements, in any shape or form, and on any production line dedicated to prefabricated construction parts like timber frames.

4.8 Timber-concrete composite

Introduction

CLT constructions are often enhanced with other materials such as steel or concrete. Steel is most commonly used for connectors and concrete for the foundation, basement, and elevator and stair shafts. Shafts are installed in concrete mostly to improve stabilization and fire protection (see Fugures 4.14 and 4.15).

Fig. 4.14
Centrally installed concrete elevator and stair shaft

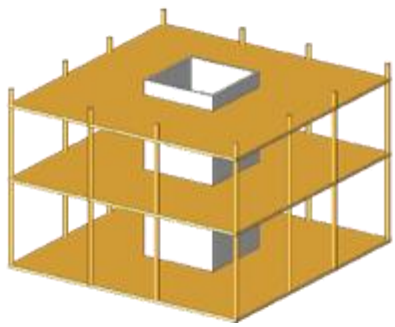
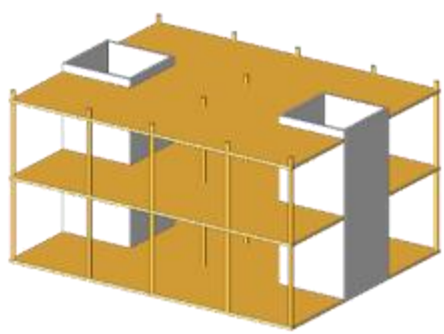


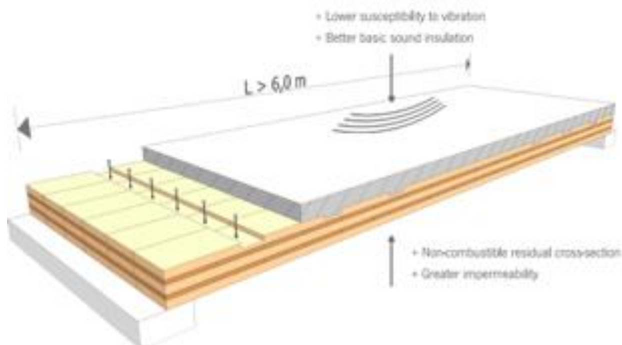
Fig. 4.15
Dual concrete access shafts for stabilization



However, CLT elevator and stair shafts work fine. The Mjøstårnet in Norway is an all-wood construction. The Brock Commons Tallwood House in Vancouver is a hybrid with elevator shafts and ground floor made of concrete and then CLT is used for the rest of the building.

Individual structural components can be composed as hybrids using glulam or CLT in combination with concrete, a method known as timber concrete composite (TCC). This is commonly used for floor constructions, where it improves structural performance by providing higher bending stiffness and strength, better shear performance, and improved vibration characteristics. In addition, the building physics will be improved in terms of fire resistance, sound insulation, and thermal mass (see Figure 4.16).

Fig. 4.16
Composite floor TCC
(KLH Massivholz
GmbH)

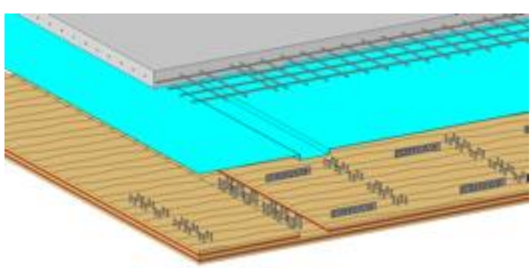


The improved strength performance is achieved from the higher compression strength of concrete compared to wood. Furthermore, the concrete can be reinforced for additional strength.

The increased mass from the layer of concrete increases the sound insulation and also the thermal performance. In case of fire, the increased mass will absorb extensive amounts of heat and thus reduce the temperature in the compartment fire. The concrete layer furthermore adds a non-combustible surface to the structure.

To benefit from the composition of concrete with great compressive strength and timber with high tension strength, it is necessary to establish a good connection between the two materials. Several different shear connection methods have been proposed by Collins (2020), who asserts that the structural performance of inter-connected concrete-timber floors is four times greater than standard concrete cast on timber floors (see Figure 4.17).

Fig. 4.17
Example of TCC
element with various
shear connector
systems



The notched or grooved system is the least expensive, while a dovetail layout adds resistance to uplift delamination. This system can be improved by adding bolts or screws (see Figures 4.18–4.20).

Fig. 4.18
Dovetail notch shear connector

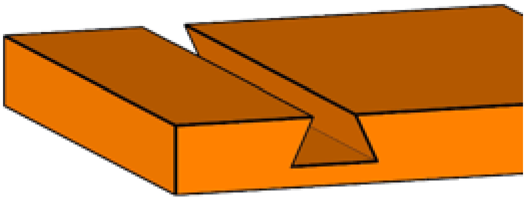


Fig. 4.19
Inclined bolt or screw shear connectors

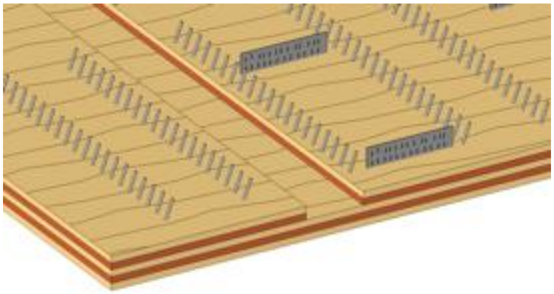
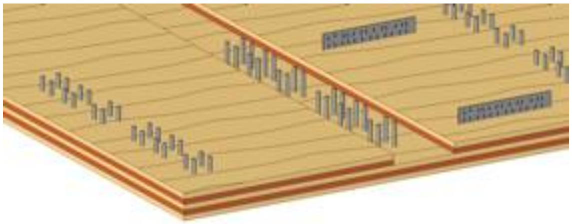


Fig. 4.20
Straight shear connectors from glued perforated plate



Which type of connection performs the best? According to tests by the American Institute of Architects (AIA), adhesive connections outperform mechanical connections.

Code EC5 in Appendix B] gives the method for mechanically designing joined beams in CLT and for concrete connections.

4.9 Timber-concrete composite

Introduction

The first I-joists/beams were invented over 50 years ago. I-joists and I-beams, also referred to as double T-profiles, are wood-based composite elements consisting of two flanges glued to an intermediate web. The top and bottom flanges are made mainly of either finger-jointed structural timber, glued laminated timber, laminated veneer lumber (LVL), or structural plywood. The webs are made mostly of either oriented strand board (OSB), plywood, or cold rolled steel struts that are better known as metal-webbed joists (see Figures 4.21–4.22).

Fig. 4.21
I-joist/beam (BM TRADA)

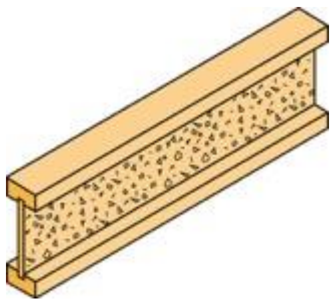


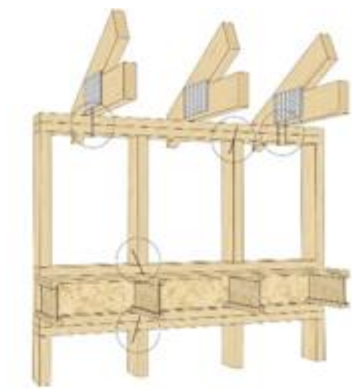
Fig. 4.22
I Left: I-joist section made of LVL flanges and OSB web. Right: transport assembly. (Photos by Roger Taylor)

Areas of application

These joists and beams are used as the loadbearing parts of building constructions, but their utilization is limited to small loads like floor partitions and certain parts of roofs. Their advantage is their low weight and low thermal conductivity due to their geometry and, therefore, they serve as suitable low-energy components with reduced thermal bridges (see Figures 4.23–4.24).

Fig. 4.23
Rothoblaas wood connectors

Fig. 4.24
Timber-framed buildings (Rothoblaas)



Classification and types

I-joists and I-beams can obtain third-party accreditation and certification through BM Trada Q-Mark, European technical approval (ETA), and be CE marked. For the dimensions and span tables of I-joists and I-beams, the normal practice is to refer to the manufacturer.

Manufacturing principles

I-joists and I-beams are manufactured from oriented strand board webs, and the flanges are normally made from laminated veneer lumber (LVL).

The flanges are manufactured from rotary peeled softwood veneers that are dried, bonded, and heat-pressed together to form continuous 1.8- to 2.8-meter-wide boards with thicknesses of between 38 and 97 mm and depths of 20 to 60 cm; then they are further machined to the finished dimensions.

The veneers are bonded together with the wood grain in the same direction or with small portions laid crossways to produce greater compressive strength.

Climatic conditions

Like any wood product, I-joists can be at risk for fungal decay or rot when repeatedly exposed to dampness or high moisture environments if not properly ventilated or provided with proper drainage. Therefore, the design of the building and on-site construction must include protecting joists from exposure to precipitation and moisture by means of accepted construction practices and adherence to applicable building codes.

Technology and BIM

Since April 2016, suppliers that wish to bid for public sector building contracts must use BIM tools and techniques. Organized into categories, the key engineered BIM timber product systems and solutions are available online. The key driver of the BIM strategy is to facilitate wider specifications of EWP systems. Launched by Revit, BIM components can be downloaded from suppliers.

Closing words

I-joists and I-beams are extremely strong, dimensionally stable, and they do not shrink or become distorted. They derive their high strength from the homogeneous bonded structure and flange material.

Engineered timber I-joists and I-beams deliver strength and rigidity, thus eradicating floor movement and thereby resulting in greater floor performance. They are also lightweight, which results in quick and reliable installation.

4.10 Ribbed slabs

Introduction

Ribbed slabs are deck and roof elements that, when made in wood, will mostly be simple open plank constructions carried out at a factory or in a large workshop. In the case of slabs, they are beveled or braced with cladding on one side, or insulated with cladding on both sides.

The systematic prefabrication approach originally began as early as 2,000 years ago, when Mongolian yurts – just as they are today – were designed to be dismantled for transport to new locations to be raised again within an hour. The simple construction offered a wide range of strong benefits for families constantly on the move seeking food and to trade their wares.

In 1908, the production techniques of the Ford automobile company generated fascination among state-of-the-art architects, leading them to systematize construction work by means of machine power. Later in that century, wood was sold abundantly during the USA housing boom and rapidly fueled an industry that later spread to

Europe, such as Great Britain, where new systems to build housing were needed due to destruction from the Second World War. Among other industrial events, this developed into modern innovative methods that we see today with prefabricated building components such as slabs that are lifted by crane into buildings whose sum of their parts result in very cost efficient and high-quality constructions.

Slabs are easy to transport, erect, and assemble on-site. The basic methods used for building timber frames (see Chapter 4.9) have been further developed for slabs because they are efficient, cost-effective, high quality, and productive. By applying mass production principles and modular systems to industrializing construction, these methods have become highly standardized.

Areas of application in construction

This construction method is used for light building components that often have a loadbearing ribbed slab as a wooden frame construction, and mostly in larger construction projects.

The principles can be applied to a floor partition, deck, or roofs.

The wooden ribbed slab will require a layer that will stabilize the frame construction, obtain the shear forces, and keep the frame in a fixed shape.

One application example is the Aalborg University School for Architecture and Design's Utzon Center, completed in 2008 and located on the Aalborg city waterfront. The building was designed by Jørn Utzon and his son Kim Utzon. With its three main building units, the sculptural ribbed slab roof structures show the great scale of wooden curves that are made possible by prefabricated elements, whose potential is limited only by one's imagination.

Fig. 4.25 Utzon Center. Construction of the roof with prefabricated ribbed slabs. Photo: Michael Rønnow Jørgensen

Ribbed slabs are efficient, reliable, and provide high quality in constructions such as wide-span production facilities and tall multi-story residential buildings. The construction method is inherently applicable where many repetitions are required, as well as a very high degree of uniformity for the individual components.

When designing the elements to be produced, the design process must be able to commit to the concept at a rather early stage.

Modular tolerances, connections to other constructions, design features, and other factors must be prepared and produced long before the on-site work begins. This means that no changes should be expected once the components are shipped off to the construction site. This is the benefit of industrializing every step of the process, from conceiving the idea to handing over the building to the client. Complex projects can be carried out using this concept, as was done with the Utzon Center (see Figure 4.25), where a very complex roof was fitted on site within a week.

Properties

The supporting part of the elements consists of wood ribs. Cross-sectional dimensions and rib distances are optimized, depending on the requirements for span, load, element geometry, and insulation thickness. The ribs are made mostly of Nordic spruce sorted according to its strength and usually classified as C24, always planed on all four sides and oven-dried to a humidity of max. 18%.

Larger spans use compound structurally glued ribs of glulam wood.

Modular tolerances are considered when designing the elements. Tolerances to allow wood expansion and contraction. Tolerances for fitting the ribbed slabs are also considered. Because a fair amount of movement is to be expected on site when handling and mounting the pieces, the crew will need to be flexible when sealing the elements with secure joints.

Protection against fire and heat loss are properties that need to be analysed and documented.

In Denmark, the authorities must always approve all properties of the building components before implementation takes place.

Manufacturing principles

The ribbed slabs in a wooden frame construction are made by squaring the frame to a modular width and variable height (or even curving it like in the Utzon Center; see Figure 4.26), then dividing that with incrementally placed load-bearing studs.

Just as with the fabrication of a car, the production facility processes the slabs by applying each layer of the construction in work stations that add material and check for quality before the slab moves on to the next workstation, where the subsequent material is added to the ribbed slab construction.

Fig. 4.26
Utzon Center.
Construction of the roof
with prefabricated
ribbed slabs. Photo:
Michael Rønnow
Jørgensen

Once the production line develops the slab into a complete piece that is ready to ship, the product is wrapped in plastic and stacked for temporary storage before being shipped by truck to the building site.

Trade variants and dimensions

As such, no standardized and fixed properties are applied to the basic principles behind ribbed slab construction, although typical standards of modular sizes do apply. The slabs are easy to transport and erect.

Typical standard modular grid dimensions for a ribbed slab (horizontal deck): 2.4 m; variations occur (see Table 4.6).

Table 4.6. Deck variants

Deck variants	
Slab within the same multi-story dwelling	Slab for multi-story dwellings

Typical standard modular grid dimensions for a ribbed slab (sloped/inclined roof): 2.4 m; variations occur (see Table 4.7).

Table 4.7. Roof variants

Roof variants			
Roof ventilation	Exposure to moisture	Pitch of the roof	Roofing materials
Non-ventilated	Warm roof	1.4° – 15°	Bitumen felt Foil
Non-ventilated	Cold roof (tight diffusion)	1.4° – 30°	Bitumen felt Foil
Non-ventilated	Cold roof (open diffusion)	15° – 45°	Corrugated plates Trapezoid sheet metal
Ventilated	Cold roof (tight diffusion)	15° – 45°	Pentiles Zink sheet profiles Steel sheet profiles
Ventilated	Cold roof (tight diffusion)	1.4° – 15°	Bitumen felt Foil

Risks due to different climatic conditions and thermal considerations

Any time that wood is used for a construction project, consideration must be given to moisture entering from below the foundation, humidity from the inside air, and water from the weather outside. What is more, all of these anticipated factors and protection against them must be detailed in the design. In Denmark, wood is a common building material within the industry and is subject to many codes of practice that guide and support the design process.

Other vital risk considerations are safety against fire, which must follow the Eurocodes.

Technology and BIM

Since the industrialized use of ribbed slabs is suitable to repetition, specifically as a modular system, it naturally fits in well with the digital design process.

The digital design process allows software programs to aid the designer and, later, the contractor who handles the implementation process. Using reliable information and data, the BIM model is passed directly into the manufacturing process of a highly standardized production facility or, alternatively, to the on-site work process, which are connected to the digital model.

State-of-the-art computer-controlled fabrication (CNC) allows architects and designers to cut timber frame parts into unusual ribbed slab shapes with a high degree of precision. CNC machine tools can utilize the principles of building information modeling (BIM) in, for example, Revit, so any imaginable type of information and data can be transferred directly to the next step in processing the materials or elements, in any shape or form, and on any production line dedicated to prefabricated construction parts like ribbed slabs.

4.11 Cassette panels

Introduction

Cassette panels are façade elements made of wood that are manufactured mostly in factories or large workshops as simple open plank constructions. In the case of panels, they may be beveled or braced with cladding on one side, or insulated with cladding on both sides.

The systematic prefabrication approach originally began as early as 2,000 years ago, when Mongolian yurts – just as they are today – were designed to be dismantled for transport to new locations to be raised again within an hour. The simple construction offered a wide range of strong benefits for families constantly on the move seeking food and to trade their wares.

In 1908, the production techniques of the Ford automobile company generated fascination among state-of-the-art architects, leading them to systematize construction work by means of machine power. Later in that century, wood was sold abundantly during the USA housing boom and rapidly fueled an industry that later spread to Europe, such as Great Britain, where new systems to build housing were needed due to destruction from the Second World War. Among other industrial events, this developed into modern innovative methods that we see today with prefabricated building components such as panels that are lifted by crane into buildings whose sum of their parts result in very cost efficient and high-quality constructions.

The panels are easy to transport, erect, and assemble on-site. The basic methods used for building timber frames have been further developed for panels because they are efficient, cost-effective, high quality, and productive. By applying mass production principles and modular systems to industrializing construction, these methods have become highly standardized.

Areas of application in construction

This construction method is used for light building components that often have a loadbearing cassette panel as a wooden frame construction, and mostly in larger construction projects.

The principles can be applied to external walls like façades or gables, as well as to internal partition walls.

The wooden cassette panel requires a layer that will stabilize the frame construction, obtain the shear forces, and keep the frame in a fixed shape.

One application example is the Aalborg University School for Architecture and Design's Utzon Center, completed in 2008 and located on the Aalborg city waterfront. The building was designed by Jørn Utzon and his son Kim Utzon. With its three main building units, the sculptural gable structures made of cassette panels show the great scale of wooden curves that are made possible by prefabricated façade elements, whose potential is limited only by one's imagination.

Fig. 4.27 Utzon Center. Construction of the gables with prefabricated elements as cassette panels. Photo: Michael Rønnow Jørgensen

Cassette panels are efficient, reliable, and provide high quality in constructions such as wide-span production facilities and tall multi-story residential buildings. The construction method is inherently applicable where many repetitions are required, as well as a very high degree of uniformity for the individual components.

When designing the elements to be produced, the design process must be able to commit to the concept at a rather early stage.

Modular tolerances, connections to other constructions, design features, and other factors must be prepared and produced long before the on-site work begins. This means that no changes should be expected once the components are shipped off to the construction site. This is the benefit of industrializing every step of the process, from conceiving the idea to handing over the building to the client. Complex projects can be carried out using this concept, as was done with the Utzon Center (Figure 4.27), where a very complex roof was fitted on site within a week and the subsequent work on interior cladding and exterior roofing could be completed.

Manufacturing principles

The cassette panels in a wooden frame construction are made by squaring the frame to a modular width and variable height (or even a circular shape like in the Utzon Center; see Figure 4.28), then dividing that with incrementally placed load-bearing studs.

Just as with the fabrication of a car, the production facility processes the panels by applying each layer of the construction in work stations that add material and check for quality before the slab moves on to the next workstation, where the subsequent material is added to the ribbed slab construction.

Once the production line develops the panel into a complete piece that is ready to ship, the product is wrapped in plastic and stacked for temporary storage before being shipped by truck to the building site.

Fig. 4.28 Utzon Center. Constructing the gables with prefabricated cassette panels. Photo: Michael Rønnow Jørgensen

Trade variants and dimensions

As such, no standardized and fixed properties are applied to the basic principles behind cassette panel construction, although typical standards of modular sizes do apply. The panels are easy to transport and erect.

Typical standard modular grid dimensions for a cassette panel: 2.4 m are provided in Table 4.8.

Table 4.8. Typical standard modular grid dimensions

Variants		
Application of wooden elements	Flexibility	Notes
Element used as frame-filling (column & beam system)		Ventilated vertical cavity
Façade wall-element (load bearing & non-load-bearing)	Length < 10 m	Ventilated vertical cavity
Secondary wall-element (e.g., concrete inner wall or brickwork outer wall)	Height < 3.6 m	Ventilated vertical cavity
Apartment wall-gap between dwellings		Two-part wall construction
Single partition-wall between dwellings		

Risks due to different climatic conditions and thermal considerations

Any time that wood is used for a construction project, consideration must be given to moisture entering from below the foundation, humidity from the inside air, and water from the weather outside. What is more, all of these anticipated factors and protection against them must be detailed in the design. In Denmark, wood is a common building material within the industry and is subject to many codes of practice that guide and support the design process.

Other vital risk considerations are safety against fire, which must follow the Eurocodes.

Technology and BIM

Since the industrialized use of cassette panels is suitable to repetition, specifically as a modular system, it naturally fits in well with the digital design process.

The digital design process allows software programs to aid the designer and, later, the contractor who handles the implementation process. Using reliable information and data, the BIM model is passed directly into the manufacturing process of a highly standardized production facility or, alternatively, to the on-site work process, which are connected to the digital model.

State-of-the-art computer-controlled fabrication (CNC) allows architects and designers to cut timber frame parts into unusual cassette panel shapes with a high degree of precision. CNC machine tools can utilize the principles of building information modeling (BIM) in, for example, Revit, so any imaginable type of information and data can be transferred directly to the next step in processing the materials or elements, in any shape or form, and on any production line dedicated to prefabricated construction parts like cassette panels.

4.12 Oriented strand boards (OSB)

Introduction

Oriented strand boards were developed in the mid-1970s in order to make use of smaller logs that are not suitable for plywood production. OSB production in Europe started in 1985. OSB is made of strands that are normally about 75mm long, often laid out in three layers with the surface strands oriented roughly in line with the length of the panel. This gives the panel higher mechanical properties in that direction. OSB was developed from the earlier wafer board or flake-board, which had random particle orientation.

OSB is a widely used versatile engineered wood panel made by using waterproof heat cured adhesives and rectangular shaped wood strands that are arranged in cross-oriented layers. It is similar in strength and performance to plywood and also resists deflection, warping, and distortion (see Figure 4.29).

Fig. 4.29
OSB Image (BM TRADA)

Areas of application

OSB is used for structural and non-structural construction. It is a lightweight, strong, and versatile wooden material used as the mounting panels for roofs, walls, and floors. It is also used as the web material for prefabricated I-joists and cladding for structural insulated panels. It is strong stable material that resists wind and seismic loads. Other uses of OSB include secondary roofs, prefabricated box units, industrial panels, pallets, containers, marine applications, furniture manufacturing, and concrete formwork. OSB can be cut by hand or power saw and machined (routed, spindled, planed, and bored) with common woodworking machinery. Tungsten carbide cutting edges are recommended for use with powered tools. Where smooth surfaces are required, panels can be pre-sanded (see Figures 4.30–4.31).

Fig. 4.30
Rothoblaas OSB timber frame construction systems

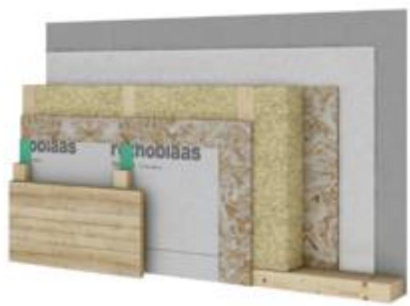


Fig. 4.31
Rothoblaas membranes and tapes

Classification and tables

National building regulations require that manufacturers demonstrate compliance with all legal requirements by showing that their OSB complies with the harmonized standard EN 13986: Wood-based panels for use in construction – Characteristics, evaluation of conformity and marking. It draws on EN 300: Oriented strand boards (OSB) – Definitions, classification and specifications, which must be used when specifying OSB.

When a European standard is drafted based on an ISO and then adopted as a DIN ISO standard (e.g. DIN ISO 2424), this indicates that the ISO standard was adopted unchanged as a national standard. Four grades of OSB are defined in EN 300 in terms of their mechanical performance and relative resistance to moisture. They are:

OSB/1 – General purpose boards and boards for interior fitments (including furniture) for use in dry conditions.

OSB/2 – Load-bearing boards for use in dry conditions.

OSB/3 – Load-bearing boards for use in humid conditions

OSB/4 – Heavy-duty load-bearing boards for use in humid conditions.

In Canada, OSB panels are manufactured to meet the requirements of the Canadian Standards Association. This standard sets performance ratings (grades) for specific end uses such as floor, roof and wall sheathing in light-frame wood construction. In addition, design values for OSB construction sheathing are listed in CSA O86, which allows for the engineering design of roof sheathing, wall sheathing, and floor sheathing using OSB that conforms to CSA O325.

Manufacturing principles

OSB is made from wood strands that are 8 to 15 centimeters long. It uses the whole tree and makes use of crooked, knotty, and deformed trees that would otherwise go unused. OSB is made from small diameter poplar and aspen trees. As strands, they are mixed with either waterproof phenol foraldehyde (PF) resin, melamine-urea-formaldehyde (MUF) resin, or polymeric diphenylmethane (PMDI) resin, then interleaved together into thick mats that are glued together under heat and pressure. Manufacturers use a variety of different fabrication processes to deliver a spectrum of OSB products. The result is solid building panels that are uniform and have enhanced features, high strength, and water resistance. The types of timber used are alder, Aleppo pine, Douglas fir, pine, and poplar.

Climatic conditions

Careful storage and handling are important for maintaining panels in proper condition for their use. OSB must be protected from rain and accidental soaking. During transport, it is important to keep the edges well covered. Panels should be stored flat in an enclosed, dry building. When handling boards, the edges and corners should be protected against damage.

Four grades of OSB are defined in EN 300 in terms of their mechanical performance and relative resistance to moisture. OSB can be chemically treated to improve resistance to decay or fire. It is water-resistant when assembled correctly with resins. OSB products are tested to determine the effects of fire retardants or any other chemicals.

Closing words

Similar to plywood, OSB is often a go-to product and preferred for its many common uses. It can be fabricated into panels that are larger than plywood. Compared to plywood, OSB is heavier and swells more when wet (especially at the panel edges), and thus it retains water longer than plywood. Regardless of their differences, OSB and plywood are comparable products fabricated to meet the same standards of strength and structural performance. OSB provides exceptional light-weight strength and durability, and it is more cost effective.

4.13 Oriented strand boards (OSB)

Introduction

One typology applied in modular construction principles is the column and beam system, which is also called post and beam construction. This combines a number of methods in building projects in which the load bearing system relies on a skeletal framework, such as a wooden structure. The light-weight frames and slabs are combined into a system of modular construction.

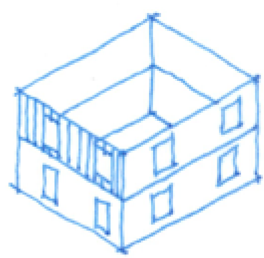
Areas of application in construction

Timber frame
The principles can be applied to:

- External walls
- Internal partition walls
- Floor partition decks
- Roofs

Timber frame construction is used in buildings such as single-family houses, terraced houses, and smaller multi-story residential buildings up to 1½ stories (see Figure 4.32). See more about timber frame construction in Chapter 4.7.

Fig. 4.32
Timber frame

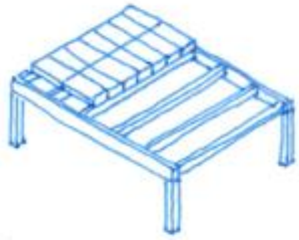


Ribbed slabs
The principles can be applied to:

- Floor partition decks
- Roofs

Ribbed slabs are used mostly for larger construction projects such as wide-span production facilities, tall multi-story residential buildings, or anywhere that requires efficiency and reliable quality (see Figure 4.33). See more about ribbed slabs in Chapter 4.10.

Fig. 4.33
Ribbed slabs

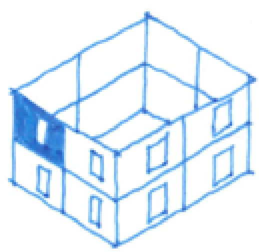


Cassette panels
The principles can be applied to:

- External walls (façades or gables)
- Internal partition walls.

Cassette panels are used in buildings such as wide span production facilities, tall multi-story residential buildings, or anywhere that requires efficiency and reliable quality (see Figure 4.34). See more about cassette panels in Chapter 4.11.

Fig. 4.34
Cassette panels



Properties

This construction method is inherently applicable where many repetitions are required, as in the case of light wooden columns and timber beam structures that often have a very high degree of uniformity within the individual components (see Table 4.9).

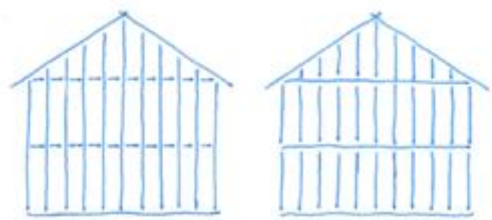
Table 4.9. Properties

Construction method:	Typology:	System:
Timber frame	On-site building, prefabrication, or flat-pack	Modular or non-modular
Ribbed slabs		
Cassette panels		

Manufacturing principles

In a wooden frame construction, the skeleton for a column and beam system is made by squaring the frame according to the specific dimensions of parallel linear elements or studs, then dividing that with incrementally placed load-bearing studs (see Figure 4.35).

Fig. 4.35
Diagram of construction types (showing parallel linear elements, or studs)



Technology and BIM

Since the industrialized use of ribbed slabs is suitable to repetition, specifically as a modular system, it naturally fits in well with the digital design process.

The digital design process allows software programs to aid the designer and, later, the contractor who handles the implementation process. Using reliable information and data, the BIM model is passed directly into the manufacturing process of a highly standardized production facility or, alternatively, to the on-site work process, which are connected to the digital model.

State-of-the-art computer-controlled fabrication (CNC) allows architects and designers to cut timber frame parts into unusual ribbed slab shapes with a high degree of precision. CNC machine tools can utilize the principles of building information modeling (BIM) in, for example, Revit, so any imaginable type of information and data can be transferred directly to the next step in processing the materials or elements, in any shape or form, and on any production line dedicated to prefabricated construction parts like those used in a column and beam system.

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WOOD WORKS. http://www.woodworks.org

→ 5

THERMAL AND ACOUSTIC PERFORMANCE OF WOOD AND TIMBER BUILDINGS

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In recent years, improving comfort and energy savings in buildings has become a priority. Timber buildings can offer interesting solutions to meet these requirements, which include thermal and acoustic aspects. As explained in the previous chapters, wood is a highly sustainable material because it is recyclable, reusable and naturally renewable. In addition, its excellent strength-to-density ratio makes it useful for different types of building applications. In this chapter we will focus on its thermal and acoustic properties.

After introducing some basic theory, we will analyse the thermal and acoustic characteristics of wood and wood-based products in comparison with other types of materials and will focus on their performance as part of building elements. Regarding thermal aspects, we will see that the relatively low thermal conductivity values make wood a good performance material that allows the achievement of low thermal transmittances in both Timber Frame (TF) and Cross Laminated Timber (CLT) systems. Regarding acoustics, we will deal with the aspects of absorption and insulation. We will see that wood cannot be considered a good noise insulator due to its lightness, although CLT panels can increase the acoustic performance of timber buildings. We will consider constructive details and the importance of the connection elements. Floor impact noise will also be briefly discussed.

5.1 Thermal behaviour of wood and its derived products

5.1.1 Thermal conductivity

Among other considerations, the current building regulations establishes the minimum requirements for the thermal transmittance U [W/m^{2}K], which is the steady state heat flux passing through a unit of a surface area induced by a temperature difference of 1 Kelvin (K) between the indoor and outdoor environments. The thermal resistance R is the inverse of the thermal transmittance: R=1/U. The U-value takes in account the heat through the different layers of the wall and also convective and radiative heat transfer.

The thermal conductivity, λ [W/mK], is characteristic of each material. It is defined as the steady state heat flux passing through a 1m thick material, when a temperature difference of 1 K is maintained between the two faces. For the same thickness of material, the smaller the thermal conductivity, the higher the thermal resistance and the lower the energy losses.

Although the thermal conductivity of wood depends on the type of wood and its density (see **Error! Reference source not found.**), in general it is relatively low, being about 4 times lower than that of perforated bricks, 10 times lower than that of concrete and 2000 times lower than that of aluminium (see **Error! Reference source not found.**).

Table 5.1. Values of thermal conductivity for wood of two types, depending on its density. Table prepared from the data of constructive elements of the Spanish Building Regulation Code (CTE).		ρ (kg / m^3)	λ (W / m · K)
hardwood	Very heavy	$\rho > 870$	0.29
	Heavy	$750 < \rho \leq 870$	0.23
	Medium weight	$565 < \rho \leq 750$	0.18
	Light	$435 < \rho \leq 565$	0.15
	Very light	$200 < \rho \leq 435$	0.13
softwood	Very heavy	$\rho > 610$	0.23
	Heavy	$520 < \rho \leq 610$	0.18
	Medium weight	$435 < \rho \leq 520$	0.15
	Light	$\rho \leq 435$	0.13

Low conductivities are also maintained in the case of wood-derived products, such as plywood board or particleboard. According to the values compiled by M.R. Cabral and P. Blanchet (2021) in their review and shown in **Error! Reference source not found.**, their conductivity ranges from 0,11 to 0.17 W / mK depending on their density, while oriented strand boards (OSB) and hardboards have a slightly higher value. For comparison, the table also shows the thermal conductivities of other common non-wooden panels, which clearly have higher values. Finally, it is worth mentioning that cork and wood wool panels have thermal conductivities similar to those of other thermal insulators such as mineral wool or polystyrene foams.

Table 5.2. Density and thermal conductivity for some wooden-based products. Cement-bonded board and gypsum board vàlues are also inroduced for comparison. Source: M.R. Cabral & P. Blanchet (2021) and references therein	ρ (kg / m^3)	λ (W / m · K)
Particleboard	600	0.12–0.17
Medium density fiberboards (MDF)	600	0.11–0.14
Plywood	700	0.12–0.15
Oriented strand boards (OSB)	650	0.13–0.24
Hardboard	1000	0.12–0.29
Cement-bonded board	1200	0.23–0.80
Gypsum board	900	0.25–0.80

5.1.2 Thermal inertia

Although U-transmittance is the most commonly used parameter to evaluate the thermal behaviour of a building and to comply with regulatory requirements, to design energy-efficient buildings it is necessary to take into account its dynamic behaviour (thermal inertia). There are numerous studies showing that the use of high thermal inertia walls in buildings, in addition to improving interior comfort, can lead to a very significant reduction in energy needs, both for heating and for cooling. In fact, the best energy efficiency is given by a combination of the two factors (transmittance and inertia), appropriate to the situation and type of use of the building.

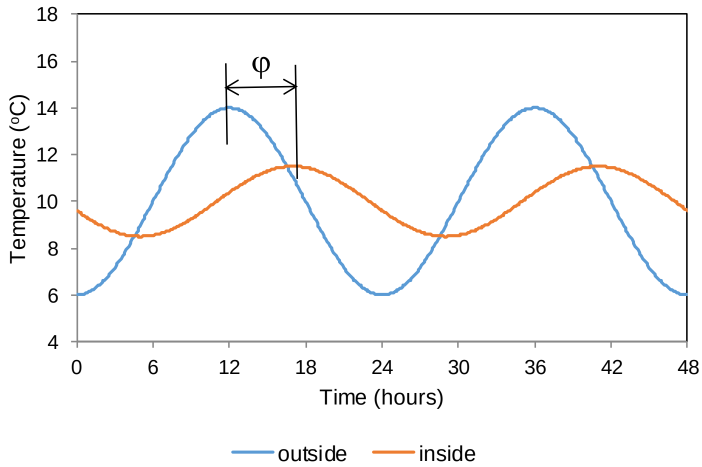

Figure 5.1. Diagram showing the outdoor and indoor temperature variations over two days, as well as the delay expressed in hours.

The temperature of the outside environment in a building varies over time, throughout the daily cycle. If the temperature variation in the indoor environment occurs with a large delay and a small magnitude with respect to the outdoor variations, the building is said to have a high thermal inertia. **Error! Reference source not found.** shows, schematically, the delay (φ), measured as the difference, in hours, between the time when the maximum temperature occurs outside and the time when it occurs inside.

For a wall of a certain material, delay and damping are more important when the thickness of the wall is greater and the thermal diffusivity of the material is lower. Thermal diffusivity α [m^2/s] is defined as the ratio of thermal conductivity and the product of specific heat and density

$$\alpha = \frac{\lambda}{c\ \rho} \ .$$

The specific heat capacity (c) is the amount of heat, measured in Joules, required to increase in 1K the temperature of 1 kg of a material. Wood is characterized by very high values of specific heat, from 1600 to 2900 J/(kg K). Materials with low thermal conductivity also have low densities so that, in general, thermal diffusivity is usually relatively high. However, interestingly, materials such us wood, with high specific heat, have low diffusivity values even with low density.

Table 5.3. Values of the thermal conductivity and diffusivity of different materials and the corresponding delay to 10 cm in thickness.	Conductivity λ (W / mK)	Diffusivity α (m2 / h)	Delay φ (hours)
Aluminum	230	0.3485	0.2
Air	0.026	0.0755	0.5
EPS insulation	0.035	0.0076	1.6
Wood fiber insulation	0.04	0.0025	2.8
Concrete	1.35	0.0024	2.8
Glass	1	0.0019	3.2
Perforated brick	0.49	0.0018	3.3
Cork	0.049	0.0009	4.5
Wood	0.13	0.0004	7.3

Error! Reference source not found. shows a comparison of the values of thermal conductivity and diffusivity of different materials, as well as the delay corresponding to the same material thickness of 10 cm. It is very remarkable the good result of the wood for which, typically, a delay of 7 hours by a thickness of 10cm is obtained. It is also very interesting to note that wood fiber thermal insulators show a thermal conductivity similar to other insulators such as EPS, but a much lower diffusivity and therefore give a longer delay. This is even more outstanding in the case of cork insulators, which produce a delay almost 3 times greater than EPS.

5.1.3 Thermic behaviour in timber construction systems

Timber Frame. Enclosures in a TF construction can be solved in different ways, such as plywood or OSB. It is a system that can be built on site, but also supports a high degree of prefabrication. In the prefabricated systems of construction with wood these insulators can be incorporated directly in the factory, what facilitates the setting and reduces the times of execution. On the other hand, in order to reach the environmental benefits of wood and other lignocellulosic materials, insulators made of wood fibers or cellulose can be used.

Kosny et al. (2014) analysed different types of wall frame assemblies in which the use of wood, together with traditional and innovative thermal insulation materials, achieve a low U-value. For the analysed systems, transmittances between 0.11 W/m^2K and 0.3 W/m^2K where obtained.

Wooden constructions incorporating the adequate level of thermal insulation and other measures of energy efficiency can achieve energy classifications as demanding in passivhaus certification. As an example, we present a project by House Habitat located in the municipality of Castelldefels (Barcelona) and certified as a Passive House. This is a light timber frame house made of Nordic pine wood from sustainably managed forests. The façade enclosures consist of a low-density wood fiber thermal insulation, interspersed between the light wood framework (see Figure 5.2), 22mm OSB panels, and an external thermal insulation composite system (ETICS), composed by high density wood fiber panels and silicate mortar render, as illustrated in Figure 5.3.

Figure 5.2. Assembly of the structure with light wood framework (left) and thermal insulation of the facade (right). Source: House Habitat (with permission)

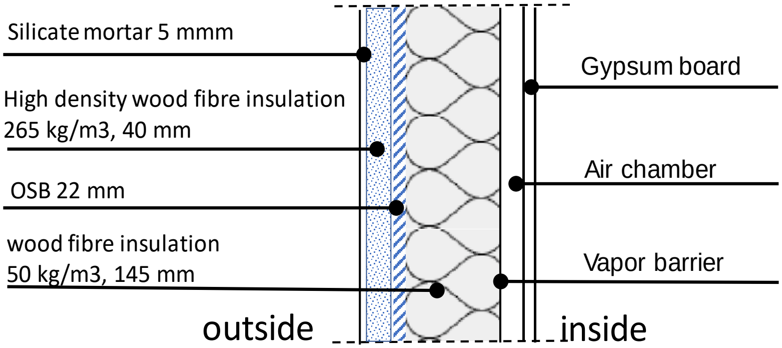

Figure 5.3. Section of the house façade.

Mass Timber buildings. The use of Cross Laminate Timber as an envelope material has a potential benefit, given its natural massiveness and increased airtightness (L. Setter et al, 2019). Although wood (and hence CLT) is relatively insulating compared to, for example, concrete or brick, it is often not enough to meet the energy saving standards currently required and needs, as in other conventional building systems, the incorporation of thermal insulation panels. G.Nunez et al. (2020) conducted an extensive study, based on 72 simulations, and concluded that CLT panels have a significant potential for thermo-energetic improvement in various types of dwellings under different climatic conditions. They found that, in some climatic zones in Brazil, it is necessary to combine 5-layer CLT panels with 10 cm of thermal insulation while, in other situations, the envelope should be provided with low solar absorption and 5-layer CLT panels without thermal insulation.

5.2 Acoustics in timber buildings

5.2.1 Acoustic fundamentals

A sound wave is a vibration, in the form of pressure variations, that propagates in an elastic medium (gas, liquid or solid) and that the ear can detect. Its main characteristics are the magnitude and the frequency.

Magnitude of a sound: the sound pressure level

The sound pressure is the local pressure deviation from the atmospheric one, caused by a sound wave. It is measured in Pascal (Pa).

- hearing threshold: $Po = 2{\cdot}10^{-5}$ Pa
- pain threshold: Po = 20 Pa

The sound pressure level, denoted Lp, is a logarithmic measure of the effective pressure of a sound relative to a reference value. It is measured in dB (decibels) and is defined by

$$L_p = 20 \log \frac{p}{p_0} \quad (dB)$$

where P is the root mean square sound pressure and Po is the reference sound pressure ($Po=2{\cdot}10^{-5}$ Pa).

Frequency of a sound: spectrum

The acoustic frequency is a measure of the pitch of a sound, expressed in Hertz (Hz) or cycles per second. According to its frequency, a sound can be infrasonic, audible or ultrasonic. The audio range falls between 20 Hz and 20.000 Hz (**Error! Reference source not found.**).

Table 5.4 Acoustic classification according to frequency	
< 20 Hz	Infrasound
20 Hz – 20 kHz	Audible sound
> 20 kHz	Ultrasound

Noises are sounds formed by the superposition of infinite pure tones, with infinitely close frequencies. To analyze a sound or a noise it is essential to know its spectrum, that is, the distribution for each frequency.

Spectrum can be divided into consecutive bands, each one between frequencies f1 y f2, and characterized by the central frequency. In architectural acoustics, two kinds of bands are used: octave bands and third octave bands.

Importance of the frequency:

- the sound perception depends on the frequency (dBA).
- The acoustic behaviour of materials and constructive solutions depends on the frequency. Low-frequency sounds, such as traffic's, are more difficult to isolate.

5.2.2 Architectural acoustic

Architectural acoustics is the study of sound in buildings (indoor spaces) and their design, including control of sound transmission throughout the building, achievement of sound isolation for speech privacy (sound isolation, protect a room from external noises) and maintenance of conditions for good speech intelligibility (sound conditioning, controlling the characteristics of sound transmission within the room).

There are two main parameters for evaluating the acoustic performance in a building: acoustical absorption and sound transmission loss (TL). Acoustical absorption is the capacity of a material or system to absorbs sound and thus avoid reflection. Sound transmission loss (or acoustical insulation) refers to the ability to reduce sound transfer from one space to another. It is important to know the difference between the two (Fig. 5.4)

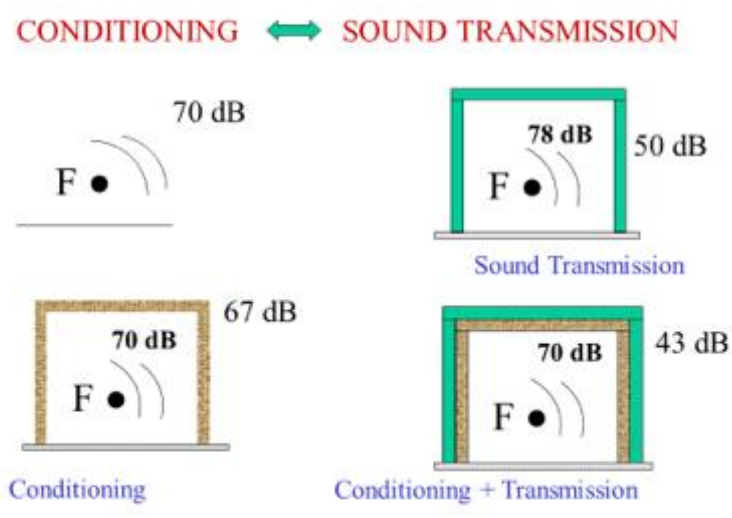

Figure 5.4 Differences between acoustical conditioning and sound transmission

Increasing acoustic absorption decreases reverberation and echoes in a room, and this can be achieved by using porous materials. However, in order to reduce the transmission of sound, a denser material is needed. Materials with high sound absorption are not adequate in reducing sound transmission. For example, mineral wool panel is great for sound absorption but not for sound transmission loss. And the opposite, concrete is great for sound transmission loss but not for sound absorption.

When referring to sound transmission loss or acoustical insulation, we distinguish between airborne sound insulation and impact noise insulation. Airborne sound insulation is important for both walls and floors. It can be measured on-site by generating a sound in one room (the source room) and comparing it with sound in a second adjacent room (the receiving room). These measurements are made as a function of the frequency spectrum.

Impact insulation is generally only relevant to floors. It is also measured on-site. A standard impact sound source (a tapping machine consisting of automated hammers) is used to strike the floor repeatedly at a standard rate. The resulting sound in the receiving (downstairs) room is measured and this value is termed the impact sound pressure level L.

The most important physical property controlling the airborne sound transmission loss through an assembly is the mass per unit area of its component layers and the nature of the joints between elements. The "mass law" is a theoretical rule that applies to most materials in certain frequency ranges. It can be approximated as

$$TL = 20 \log 10\,(ms \cdot f) - 48 \quad (dB)$$

where TL is the incidence sound transmission loss of the layer; ms is the mass per unit area, kg/m²; and f is the frequency of the sound wave, Hz. The mass per unit area, ms, is the product of the material density and its thickness. In principle, this law suggests that the sound insulation of a solid element will increase by approximately 6 dB when doubling the mass. The same happens with frequency, higher frequencies implies better sound insulation and the transmission is higher for low frequency.

In real buildings, sound travels between suites indirectly by way of the surrounding constructions as well as directly through the common wall or floor assembly. These less obvious paths for the sound are called flanking paths and, in a poor design, they can transmit more sound energy than the direct path through the common wall or floor. Floors are particularly prone to increased impact sound transmission because of flanking transmission through the supporting structure. The flanking transmission of sound represents the sound that is transmitted between spaces indirectly, going over or around, rather than directly through the main separating element between rooms. All the possible flanking transmissions add up to the direct sound transmission and return to a lower value of the characteristic sound insulation of the separating element between rooms.

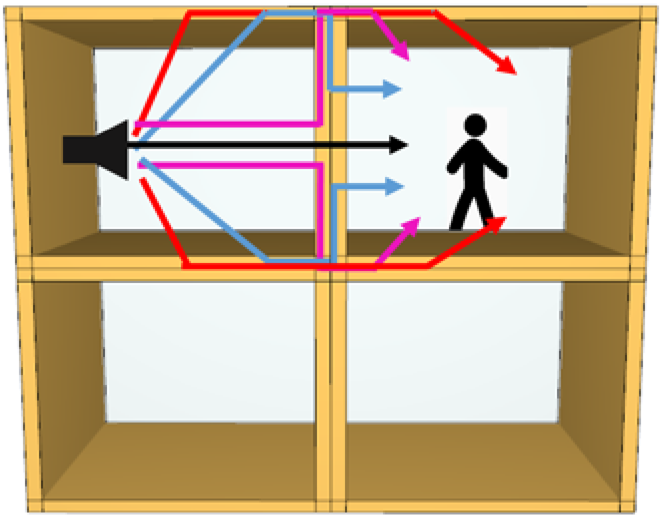

Figure 5.5. The picture shows the possible direct and indirect sound transmission paths

Flanking transmission is relevant not only in interior building elements but also in low weight wooden facades and curtain walls, where it can represent the main sound transmission between adjacent rooms. The design details between floors at the contact with the facade must be carefully considered. Fire insulation systems commonly used in such facades can also provide acoustic insulation and are often designed to perform this double function.

Due to flanking transmission, the acoustic design of buildings must be evaluated in two steps: a first one in which each building component (wall, floor, facade...) is designed individually; and a second step in which the global solution is evaluated jointly.

The first step relies on laboratory measurements. In the European context, databases of commonly used wooden assemblies are available to help in the choice of the most suitable building system for each design. The second step is more complex as it requires either the use of specific software for predictive calculations or the use of solutions already validated by means of on-site measurements in existing buildings.

5.2.3 Acoustical characteristics of wood and wooden products

The acoustic absorption coefficient is defined as the quotient between the energy absorbed or transmitted (that is, that which is not reflected) and the incident energy. Thus, a perfect absorbent would have a value of 1. An absorbent material is considered to be a material with a coefficient of 0.6 or higher. According to this definition, wood cannot be considered an absorbent material, since its values are around 0.03, however a wide range of sound-absorbing products are made with wood. It is rather their design than the intrinsic material properties which confers them their acoustic properties. They are normally used for acoustic conditioning purposes in rooms where reverberation control is required to provide good acoustics. Wood panels (figure below) are an example of sound-absorbing products made with wood. They offer sound-absorbing properties, capturing the sound and they also have special aesthetic value.

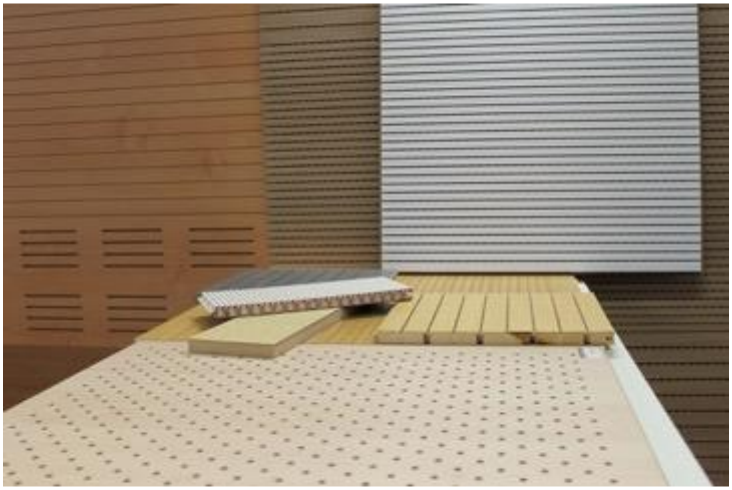

Figure 5.6. Examples of wooden sound absorbing panels. Source: Spigo Groupc

5.2.4 Airborne sound insulation in wooden buildings

d This reduces building mass, which is beneficial in many aspects, but not in terms of acoustic insulation. According to Mass Law, more mass means better noise control. In that way wood is not a good insulator of sound due to its lack of mass. However, construction systems with wood allow the creation of insulating elements.

Acoustic performance can be improved in three ways:

1. Adding mass

2. Adding noise barriers

3. Adding decouplers

In the timber frame systems, denser materials such as ceramic, concrete or gypsum are used together with wood to achieve acoustically well insulated assemblies. In some cases, these denser materials act as coating or pavement while in other cases, such as in mixed wooden-concrete wood floors, they have a structural function. In the case of CLT panels, although their high surface density is adequate in terms of sound insulation, they have a weakness caused by the panel connection elements (nails, screws, dowels, …). This type of connectors, whose function is the transmission of structural stresses, does not allow the application of many of the soundproofing systems based on the decoupling of the components of the building elements.

Decouplers are products that break (decouple) the direct connections between elements of an assembly. This reduces the sound that is transmitted from one side to the other. In timber-frame construction, the most common decouplers are resilient channels and air gaps. In mass timber floor/ceiling systems, elastic underlay and mats are often used between the solid wood panel and the concrete or gypsum layer. In this way, the direct connection between the solid wood panel and the finish on top (the floor covering and/or the finish floor) is broken. Several examples of underlayment products are shown in Figure 5.7. In timber frame construction is common to add acoustic barriers, such as batt insulation in floor cavities. This method is much less common in solid wood floor/ceiling assemblies, although systems that include wood sleepers over CLT panels and batt insulation or sand between the sleepers have been successfully tested (see Figure 5.8).

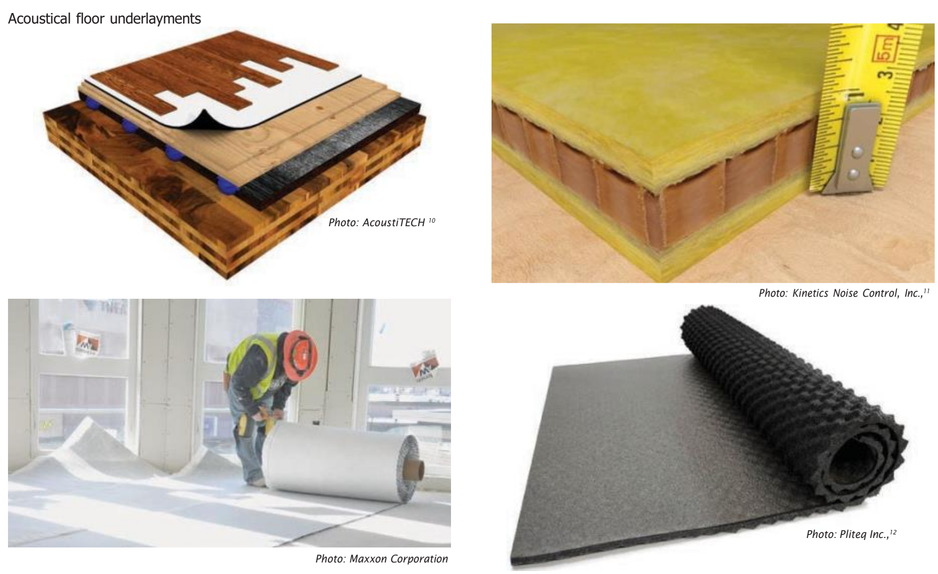

Figure 5.7 Acoustical floor underlayment, Source: McLine (2018)

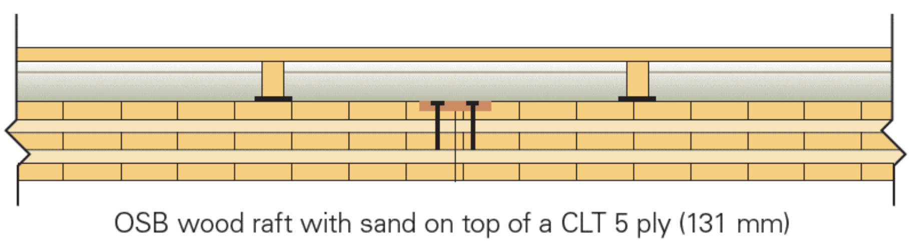

Figure 5.8 CLT floor assembly with wood sleepers and sand topping. Source: McLine (2018)

5.2.5 Impact noise in wooden floors

Some studies of impact noise show that wood-based structures work worse than the concrete-based ones at low frequencies, but better at higher frequencies (see Figure 5.9). Similarly, X. Zhang et al. (2019) compared a cross laminated timber (CLT) floor with a timber concrete composite (TCC) floor. They obtained poor sound insulation performance at low frequencies for the CLT floor and poor sound insulation performance at medium and high frequencies for the TCC floor, concluding that neither of them meets European building codes.

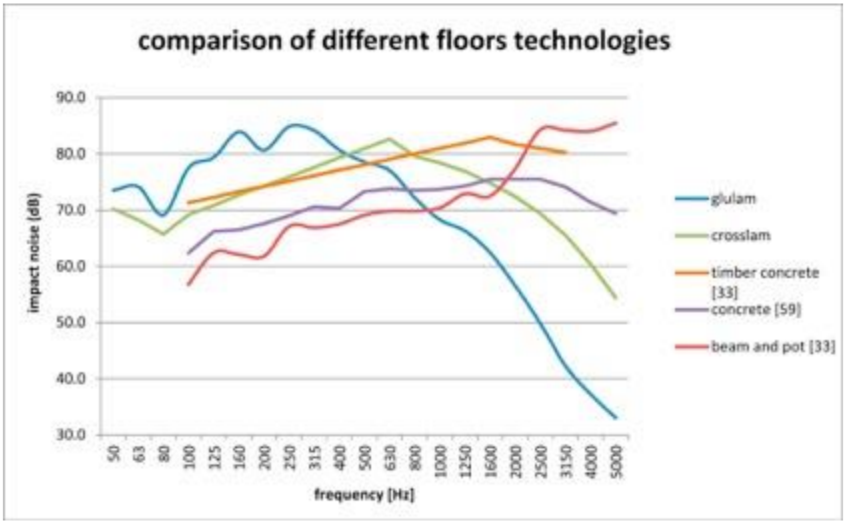

Figure 5.9. Comparison of impact noise for different bare floor technologies. Source: M. Caniato et al.(2017).

The addition of layers to the wooden floor allows the reduction of the impact sound pressure level. The resulting impact noise Ln can be expressed as

$$Ln = Ln,o - \ L \ (dB)$$

where *Ln,o* is the impact noise of the bare floor (dB) and ΔL is the impact sound pressure level reduction (dB). Thus, from the starting point of the bare floor, a reduction of the impact sound pressure level can be achieved by adding, on top or below the floor, floating pavements, air cavities filled with absorbent materials or pending ceilings (see Figure 5.10 by Caniato et al. (2017)).

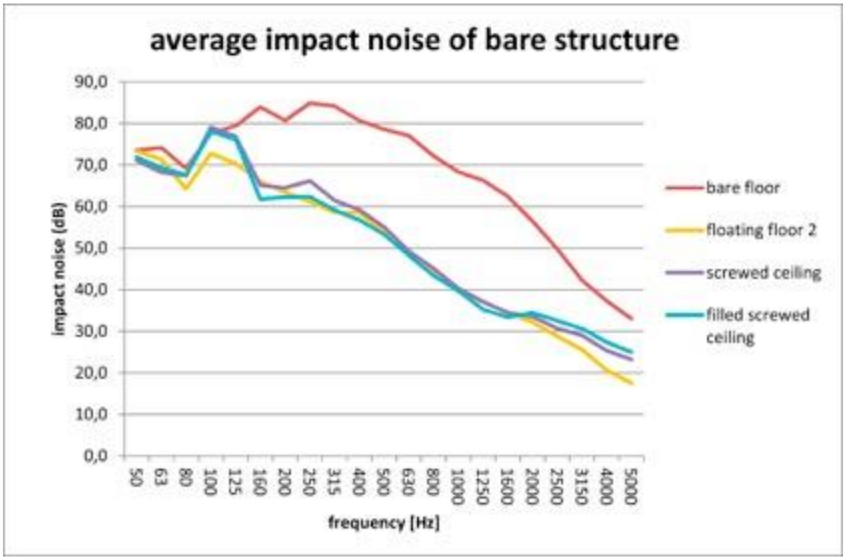

Figure 5.10. Laboratory measurements in a CLT floor. Source: M. Caniato et al.(2017).

Tests on CLT and CCT floors, considering different floating floor and suspended ceiling systems were conducted by X. Zhang et al. (2019). The test results showed significant improvements in the acoustic insulation of the floors in all cases, being more important for suspended ceilings.

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6

FIRE PERFORMANCE OF WOOD AND FIRE SAFETY IN TIMBER BUILDINGS

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In recent years wood has once again gained importance in the construction sector. The development of new wood products which have an excellent performance and the growing awareness in relation to the environmental impact have contributed to its progressive use in all types of buildings. Wood is no longer a material with limitations due to its size, dimensional variability, or the uncertainty of its properties, but an exponential technological leap has been made that equates it in all its benefits to any construction material. Since 2008 many wooden-framed buildings have been built around the world, many of them are tall buildings. However, some reluctance persists, such as the negative perception of its behaviour in font of fire because it is a combustible material, furthermore, here are still restrictions in terms of fire regulations in many countries, especially for tall buildings.

While it is true that wood and its by-products are combustible materials due to their anatomy and chemical composition, it is also true that in a fire situation wooden structure can achieve equivalent fire resistance times and even superior to concrete or steel structures (Fig. 6.1).

Fig. 6.1
Fire in Saldos Arias building (Madrid – 1987)
Part of the old wooden structure of the building had been replaced by steel frame structure. The timber frame structure was maintained but steel structure collapsed during the fire.
Wood and fire. University of Navarra.

6.1 Fire reaction of materials and fire resistance of construction elements

There are two main stages in a fire scenario to be considered for the design of fire safety measures. Especially for defining materials and structural and non-structural construction elements in buildings. These are the initial fire stage and the fully developed fire stage after a flashover in an enclosure (Fig.6.2). In **the initial fire**, the content of the building e.g., furniture and the surface lining materials have significant importance in both the growth of the fire and its development. However, while furniture is not regulated by national building codes, fire limitations of **reaction to fire** of surface linings are required by most national regulations, especially in escape routes and public environments.
On the other hand, in a **fully developed fire**, i.e. after a flashover in a compartment, the performance of load-bearing, and separation structures is important to limit the fire to the room or compartment of fire origin. Here we talk about the **fire resistance** of the building structure and construction elements. Which is a fundamental aspect for the evacuation of occupants of the building and the intervention of the firefighters.

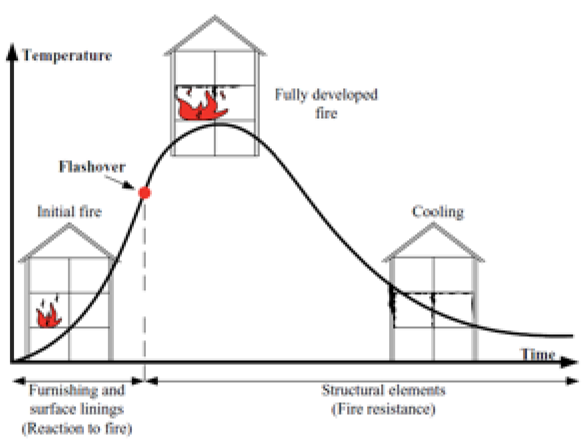


Fig. 6.2
These two stages in a fire scenario determine requirements levels in most national fire regulations:
- the initial fire (reaction to fire performance of surfaces)
- the fully developed fire (fire resistance of structural elements).
Östman, B. et al.

The fire performance of materials, products, and construction elements is understood from these two fundamental concepts. Reaction to fire refers to the ability of a material to promote the development of fire. While fire resistance defines the ability of a building element (pillar, beam, wall, etc.) to maintain for a certain period the bearing function (R), the integrity (E), and/or the thermal insulation (I) that is required of it, in a time scale that goes from 15 to 240 minutes.

Wood structural elements can obtain high performance for fire resistance and high levels for the separating and load-bearing capacity of wall and floor structures can be achieved, while the surface properties of wooden linings in the initial fire may be less favourable.

According to the common framework established by the European Commission (Euroclasses) the reaction to the fire class of wood and all its derived products is D-s2, d0. This indicates that it is a combustible material with an average contribution to the fire, that it produces a moderate amount of smoke, and that it does not produce drops or incandescent particles (Fig.6.3). The combustibility of wood is one of the main reasons why many building regulations strongly restrict the use of wood as a building material.

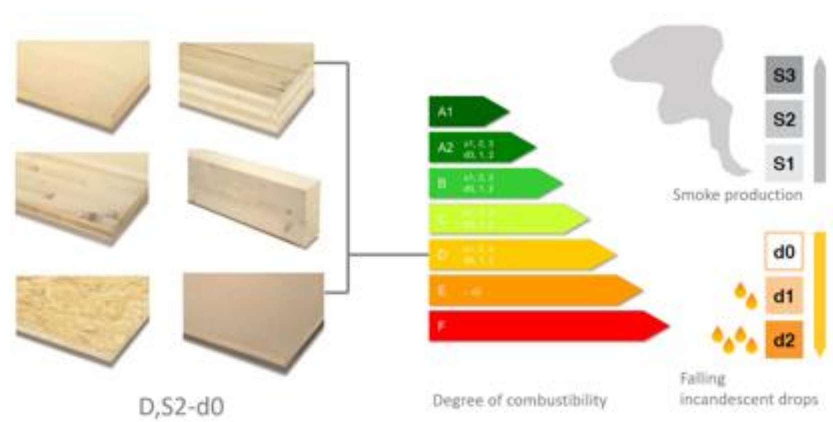


Fig. 6.3
Classification of reaction to fire of wood and its derived products

6.2 Fire performance of wood

Wood consists mainly of cellulose, hemicellulose, and lignin. Contains hydrogen, oxygen, and a percentage close to 50% carbon. It is therefore a combustible and flammable (which produces flame) material.

When a timber element is exposed to fire, the outer layer burns and turns to char. This occurs at a temperature of approximately 300°C (572°F). This creates a protective charring layer, something like a natural intumescent that acts as insulation and delays the onset of heating for the unheated, or cold, inner layer (White R., 2004). This process of charring allows timber elements to resist for long periods (Fig.6.4).

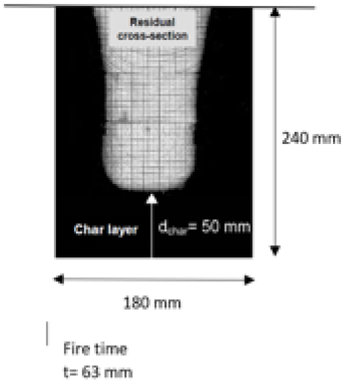
Wood burns, but mainly on the surface. Mass is a key factor in defining the fire resistance of a wooden structural element. In massive structural elements, the flame front does not easily advance inwards due to charring. Coal is 6 times more insulating than wood. Furthermore, a temperature of around 270 - 300 ºC is required for a certain period before the material starts to produce vapours due to the loss of moisture and to start burning.

The burning process of a structural member of wood with a typical cross-section happens at a slow rate, this phenomenon is technically known as Smouldering. During the combustion process or degradation by the action of fire, a chemical process called pyrolysis takes place, producing combustible gases and accompanied by a loss in mass. The pyrolysis process, in turn, is what gives rise to carbonization.

The char layer grows with constant exposure to fire, slowing down the burning rate, and reducing the cross-section. The inner part of the structural member remains virtually intact, with its physical and mechanical properties unchanged (Fig.6.4). Therefore, the loss of bearing capacity that occurs in a piece of wood in these conditions occurs by a reduction of the section, but not by a decrease in the strength of the material. Testing of this charring process has shown that timber demonstrates a constant, predictable charring rate (Buchanan, 2001). The charring rate, section size, and the required fire duration can be used to calculate the fire resistance time for a timber element (White R., 2002).

Fig. 6.4
(left) The char layer, pyrolysis zone and cold/unheated timber. (right) Comparison of the section reduction of a piece of laminated wood expose to fire.

The rate of carbonization is estimated to be around 0.7 - 0.55 millimetres per minute depending on the density and hardness of the species, this data is essential to calculate the sizing of structures. The char layer depth can be estimated by multiplying the charring rate by the fire exposure time to determine the reduced section properties (Frangi, A. et al., 2008) (Fig.6.5). So, a wooden structure is oversized to improve its resistance to fire. In other words, wood is protected by more wood.



$$\beta = \frac{d_{char}}{t} = \frac{50mm}{63min} = 0.8\,mm/min$$

Fig. 6.5
Charring rate β: Ratio between charring depth d_{char} and fire time t (in mm/min).

Therefore, the good fire performance of mass timber elements is due to its degradation process (pyrolysis), but also to other thermal properties such as its low emissivity and low thermal conductivity. On the other hand, the wooden structures have a very low thermal expansion, so they do not cause stress between elements or thrusts in the walls. This is very important in a fire situation because it minimizes the chances of the structure collapsing. All this allows us to state that wooden structures are an excellent option for building fire-resistant structures (Fig.6.6).

Fig. 6.6
Fire station of Moià (Barcelona).
https://www.arquitectes.cat/

The fire resistance calculation is particularly applicable to heavy timber frame members compared to light timber frame members. The larger cross-section size results in significantly greater fire resistance. This fire resistance can be incorporated as part of the building structural fire strategy. In light timber, frame systems are essential to establish protection measures through boards and plates of non-combustible insulating material.

6.3 Fire regulations

The regulatory framework for fire safety consists of a set of general regulations and local regulations applicable to building and product and system testing standards, some of them are harmonized at the European level. Each country has national and regional codes related to fire safety for buildings and Industrial Establishments. The regulations set the limit of requirements that buildings must meet to achieve the permissible safety levels depending on the height of evacuation and use.

The protection measures could vary depending on the characteristics of the project. They can be aimed at strictly complying with the requirements of prescriptive regulations or applying performance-enhancing fire protection engineering strategies by combining passive and active protection measures. Some experts point out that the latter is more appropriate for addressing fire safety in wooden-framed buildings given the uniqueness of their fire behaviour. Fire safety performance codes and methods are based on the PBD (Performance-Based Design) concept, which has been widely used for years in northern European countries, New Zealand, the USA, and Canada, among others. All these are distinguished by a significant presence of wood in the field of construction. Whatever safety strategy is used, prevention and control measures are based on the aspects listed in Table 1

Today is possible to build all types of buildings with a wooden structure capable of complying with the fire safety requirements required in any regulatory framework. There are many examples of nationally and internationally constructed buildings that confirm this.

<table>
<tr><th colspan="2">Mesura</th><th>Requisit</th><th>Tipus de protecció</th></tr>
<tr><td colspan="2">Disseny i dimensionament d'elements estructurals</td><td>(R)</td><td>Passiva</td></tr>
<tr><td colspan="2">Disseny d'elements de compartimentació</td><td rowspan="2">(EI) (REI)</td><td rowspan="2">Passiva</td></tr>
<tr><td>Horitzontals: forjats i sostres.
Verticals: murs i façanes</td><td>Sistemes d'entramats
Sistemes de taulers fusta massissa (CLT)</td></tr>
<tr><td colspan="2">Ruixadors automàtics</td><td>Justificació d'estratègies de protecció alternatives a la norma.</td><td>Activa</td></tr>
<tr><td colspan="2">Vies d'evacuació i elements de detecció, alarma i extinció</td><td>Evacuació, control de la propagació interior del foc / justificació d'estratègies de protecció alternatives a la norma.</td><td>Passiva/Activa</td></tr>
<tr><td colspan="2">Detalls constructius, segells i barreres tallafocs</td><td>Control de la propagació interior i exterior del foc</td><td>Passiva</td></tr>
</table>

The fire resistance of structures and compartment elements (with the function of separating sectors of fire) can be determined by the calculation basis contained in Annex SI E of the CTE and Eurocode 5. The load-bearing elements they are designed and dimensioned according to the strength required in each case. Partitioning elements can be made up of several layers of boards that make up a system. The number of layers depends on the required resistance value. In some cases, boards of non-combustible materials are used which, in addition to the protection they provide to the system, allow it to meet the fire reaction requirements of the surfaces. These boards are usually made of gypsum board, fibro-silicates or wood cement whose reaction to fire rating is A1 or A2. This type of board with protection capacity is called class k boards, and the complete system that protects encapsulated. The effectiveness of the proposed constructive solutions in each case is usually supported by large-scale laboratory tests.

Technical wood products such as Glulam structural elements and CLT (Cross Laminated Timber) panels have a behaviour equivalent to that of solid wood in a fire situation. Thus, they can reach high fire resistance times. In Canada, as part of a technology transformation project, CLT structural panels (under load) were subjected to fire resistance tests reaching maximum strength values of 113 minutes in wall panels (5 layers) without protection boards and 178 minutes in slabs (7 layers) without protection boards. Data such as these reflect the structural reliability of solid wood in a fire situation (Fig.6.7).

Fig. 6.7
Brock Commons Tallwood House. UBC, Vancouver campus. Acton Ostry Architects Inc. It is currently the tallest building in the world with a wooden structure (18 floors). Source: maisons-bois.com

Fire retardants

Current regulations limit the use of wood siding in certain applications (walls, ceilings, or floors in occupiable spaces, escape routes, facades, etc.) due to their fire reaction characteristics. The effect of carbonization, which decisively favours wooden structures, is not significant in thin elements such as cladding panels, slats, panels, slats, etc.

Flame retardant treatments are a good option for obtaining a better classification of reaction to fire in wood elements and products. Wood treated with retardant products can achieve C or B ratings and S1 smoke production rates. However, we must not lose sight of the fact that wood is a combustible material, so with the application of retardants it is possible to improve its reaction to fire characteristics, but not change the nature of the material. In this sense, to speak of firewood may be an inaccurate term.

There are several retardant products on the market that act differently on the surface to slow down the processes of ignition and combustion. Some retardants act by promoting carbonization (catalytic effect), others form a film that prevents contact of the surface with oxygen, others release non-flammable gases (water vapor, ammonia, and CO2) that dilute combustible gases. There are also those that form a layer that inflates and insulates the surface excluding oxygen and preventing the escape of combustible gases, as is the case with intumescent paints and varnishes (Fig.8).

→ 7

DESIGNING CONNECTIONS WITH METAL FASTENERS IN ACCORDANCE WITH EUROCODE 5

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7.1 General data

Timber structures are one of the fastest growing sectors in the modern construction industry. The demand for timber structure buildings arises mostly from environmental concerns and efforts to minimize CO2 emissions during the construction process and production of construction materials. Over the last several decades, typical attitudes toward timber buildings have changed and, nowadays, we can find a really wide range of timber buildings, from one-floor single family houses up to 18-storey high-rise buildings. High-rise and wide-span timber structures have become more common in recent years, due to an increase in production and the improved performance of wood-based timber products. When increasing the size of timber structures, the behaviour of connections becomes a decisive factor in dimensioning the load-bearing elements.

Metal fasteners are one of the most popular types of connections in timber structures. Figure 7.1 shows some examples of timber connections implemented with metal fasteners.

The load-carrying capacity and stiffness parameters of the connection can be determined according to Eurocode 5. The main types of metal fasteners in timber structures are shown in Figure 7.2.

All the design rules in the current version of Eurocode 5 are developed according to the Johansen yield theory. Later in this chapter, the main design principles of timber connections with metal fasteners will be provided, according to Eurocode 5.

Fig. 7.1
Connections with metal fasteners in timber structures (Photo: Tomas Gecys)

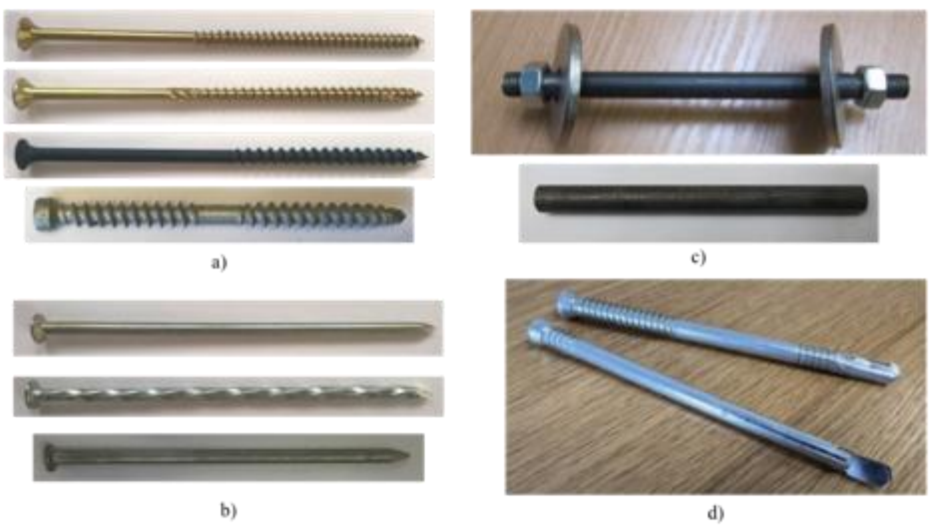


Fig. 7.2
The main types of metal fasteners in timber connections: a) screws; b) nails; c) bolts with nuts, washers and dowels; d) self-tapping dowels (Photo: Tomas Gecys)

7.2 The load-carrying capacity of steel fasteners according to EN 1995-1-1

According to EN 1995-1-1, one must choose the arrangement and sizes of fasteners in connections, spacings, and the edge and end distances so that the expected strength and stiffness can be obtained. One must take into account that the load-carrying capacity of a multiple fastener connection (consisting of fasteners of the same type and dimension) may be lower than the sum of all individual load-carrying capacities for each fastener. When a connection comprises different types of fasteners or when the stiffness of the connection in respective shear planes of a multiple shear plane connection is different, their compatibility should be verified. To summarize, it is not recommended to use different diameters for different types of threads in the same connection.

To determine the load-carrying capacity of the connection, both the service and the load-duration classes should be evaluated, together with a partial safety factor for the connection. The design for the load-carrying capacity of the connection in accordance with Eurocode 5 is thus determined by:

$$F_d = k_{mod} \frac{F_k}{\gamma_M}, \quad (1)$$

where k_{mod} is the modification factor that takes into account the moisture content in timber and the load duration class. The factor value is directly related to the service class of timber structures. The value for solid, glued laminated timber or LVL varies in range 0.5 … 1.10.

F_k is the characteristic load-carrying capacity of the connection. The main rules for determining this value for different types of fasteners will be provided later in this chapter.

γ_M is the partial factor for a material property. For metal type fasteners, this value is equal to 1.30, according to Eurocode 5.

For one row of fasteners parallel to the grain direction, the effective characteristic load-carrying capacity parallel to the row, $F_{v,ef,Rk}$, should be determined according to EN 1995-1-1:

$$F_{v,ef,Rk} = n_{ef} F_{v,Rk}, \quad (2)$$

where $F_{v,ef,Rk}$ is the effective characteristic load-carrying capacity of one row of fasteners parallel to the grain; n_{ef} is the affective number of fasteners in line parallel to the grain; and $F_{v,Rk}$ is the characteristic load-carrying capacity of each fastener parallel to the grain.

For a force acting at an angle to the direction of the row, it should be verified that the force component parallel to the row is less than or equal to the load-carrying capacity calculated according to expression (2).

7.3 The load-carrying capacity of metal dowel-type fasteners in timber-to-timber and panel-to-timber connections, according to EN 1995-1-1

According to Eurocode 5, when determining the characteristic load-carrying capacity of connections with metal dowel-type fasteners, it is necessary to consider the contributions of the yield strength, the embedment strength, and the withdrawal strength of the fasteners.

The characteristic load-carrying capacity for nails, staples, bolts, dowels, and screws per shear plane per fastener should be taken as the minimum value found from the following expressions, according to Eurocode 5:

For fasteners in single shear connections:

$$F_{v,Rk} = \min \begin{cases} f_{h,1,k} \cdot t_1 \cdot d \quad (a) \\ f_{h,2,k} \cdot t_2 \cdot d \quad (b) \\ \frac{f_{h,1,k} \cdot t_1 \cdot d}{1+\beta}\left[\sqrt{\beta + 2\beta^2\left[1+\frac{t_2}{t_1}+\left(\frac{t_2}{t_1}\right)^2\right]+\beta^3\left(\frac{t_2}{t_1}\right)} - \beta\left(1+\frac{t_2}{t_1}\right)\right] + \frac{F_{ax,Rk}}{4} \quad (c) \\ 1.05\frac{f_{h,1,k} \cdot t_1 \cdot d}{2+\beta}\left[\sqrt{2\beta(1+\beta)+\frac{4\beta(2+\beta)\cdot M_{y,Rk}}{f_{h,1,k}\cdot d \cdot t_1^2}} - \beta\right] + \frac{F_{ax,Rk}}{4} \quad (d), \\ 1.05\frac{f_{h,1,k} \cdot t_2 \cdot d}{1+2\beta}\left[\sqrt{2\beta^2(1+\beta)+\frac{4\beta(1+2\beta)\cdot M_{y,Rk}}{f_{h,1,k}\cdot d \cdot t_2^2}} - \beta\right] + \frac{F_{ax,Rk}}{4} \quad (e) \\ 1.15\sqrt{\frac{2\beta}{1+\beta}}\sqrt{2 \cdot M_{y,Rk} \cdot f_{h,1,k} \cdot d} + \frac{F_{ax,Rk}}{4} \quad (f) \end{cases}$$

(3)

For fasteners in double shear connections:

$$F_{v,Rk} = \min \begin{cases} f_{h,1,k} \cdot t_1 \cdot d \quad (g) \\ 0.5 f_{h,2,k} \cdot t_2 \cdot d \quad (h) \\ 1.05\frac{f_{h,1,k} \cdot t_1 \cdot d}{2+\beta}\left[\sqrt{2\beta(1+\beta)+\frac{4\beta(2+\beta)\cdot M_{y,Rk}}{f_{h,1,k}\cdot d \cdot t_1^2}} - \beta\right] + \frac{F_{ax,Rk}}{4} \quad (j), \\ 1.15\sqrt{\frac{2\beta}{1+\beta}}\sqrt{2 \cdot M_{y,Rk} \cdot f_{h,1,k} \cdot d} + \frac{F_{ax,Rk}}{4} \quad (k) \end{cases}$$

(4)

where $F_{v,Rk}$ is the characteristic load-carrying capacity per shear plane per fastener; t_i is the timber element thickness or penetration depth, with either 1 or 2, according to Figure 7.3; $f_{h,l,k}$ is the characteristic embedment strength in timber member *l*; *d* is the fastener diameter; $M_{v,Rk}$ is the characteristic fastener yield moment; *β* is the ratio between the embedment strength of the members; and $F_{ax,Rk}$ is the characteristic axial withdrawal capacity of the fastener.

In the expressions (a)–(k), the first term on the left-hand side is the load-carrying capacity according to the Johansen yield theory, whilst the second term $F_{ax,Rk}/4$ is the contribution from the rope effect. According to Eurocode 5, the contribution to the load-carrying capacity due to the rope effect should be limited to the following percentages of the Johansen part for different types of fasteners:

- Round nails: 15%;
- Square and grooved nails: 25%;
- Other nails: 50%;
- Screws: 100%;
- Bolts : 25 %;
- Dowels: 0%.

In the previously provided equations, if $F_{ax,Rk}$ is not known then the contribution from the rope effect should be taken as zero. For single shear fasteners, the characteristic withdrawal capacity, $F_{ax,Rk}$, is taken as the lower of the capacities in the two members. The different modes of failure are provided in Figure 7.3. For the withdrawal capacity $F_{ax,Rk}$ of bolts, the resistance provided by the washers may be taken into account.

If no design rules are given in Eurocode 5, the characteristic embedment strength $f_{h,k}$ and the characteristic yield moment $M_{y,Rk}$ should be determined in accordance with the actual EN standards.

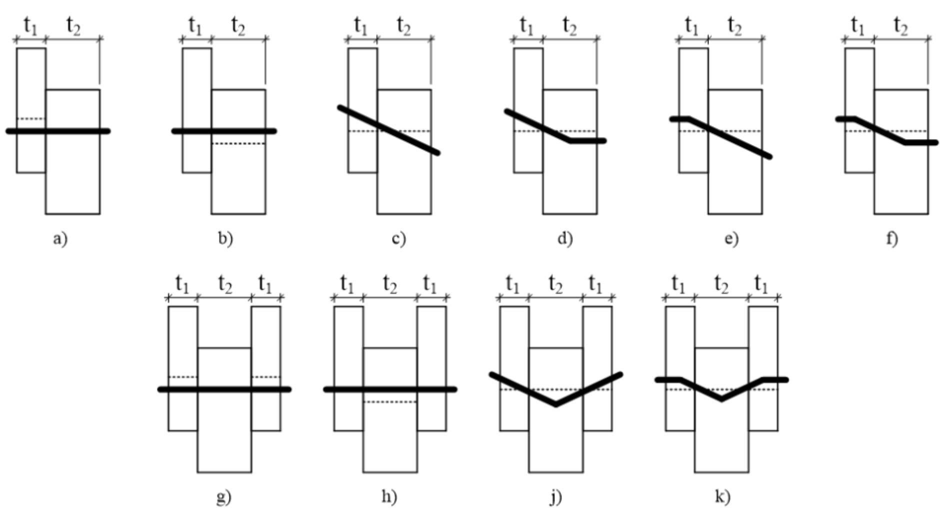


Fig. 7.3
Failure modes for timber-to-timber and panel-to-timber connections (created by Tomas Gecys)

7.4 The load-carrying capacity of steel-to-timber connections in accordance with EN 1995-1-1

According to Eurocode 5, the characteristic load-carrying capacity of a steel-to-timber connection depends on the thickness of the steel plate. Steel plates of thickness less than or equal to 0.5*d* are classified as thin plates, and steel plates are classified as thick plates if their thickness is greater than or equal to *d* and the tolerance on hole diameters is less than 0.1*d*. The characteristic load-carrying capacity of connections where the steel plate thickness is between thin and thick should be calculated by linear interpolation between the limiting thin and thick plate values. The strength of the steel plate shall also be checked.

During the design of timber-to-steel connections, it shall be taken into account that the load-carrying capacity of steel-to-timber connections with a loaded end may be reduced by failure along the perimeter of the fastener group.

The characteristic load-carrying capacity of nails, bolts, dowels, and screws per shear plane per fastener should be taken as the minimum value found from the following expressions, according to Eurocode 5.

For a thin steel plate in single shear connections:

$$F_{v,Rk} = min\begin{cases} 0.4 f_{h,k} \cdot t_1 \cdot d \quad (a) \\ 1.15\sqrt{2 \cdot M_{y,Rk} \cdot f_{h,k} \cdot d} + \frac{F_{ax,Rk}}{4} \quad (b). \end{cases} \quad (5)$$

For a thick steel plate in single shear connections:

$$F_{v,Rk} = min\begin{cases} f_{h,k} \cdot t_1 \cdot d \quad (c) \\ f_{h,k} \cdot t_1 \cdot d \left[\sqrt{2 + \frac{4 \cdot M_{y,Rk}}{f_{h,k} \cdot d \cdot t_1^2}} - 1\right] + \frac{F_{ax,Rk}}{4} \quad (d). \\ 2.3\sqrt{M_{y,Rk} \cdot f_{h,k} \cdot d} + \frac{F_{ax,Rk}}{4} \quad (e) \end{cases} \quad (6)$$

For a steel plate of any thickness as the central member of a double shear connection:

$$F_{v,Rk} = min\begin{cases} f_{h,1,k} \cdot t_1 \cdot d \quad (f) \\ f_{h,1,k} \cdot t_1 \cdot d \left[\sqrt{2 + \frac{4 \cdot M_{y,Rk}}{f_{h,1,k} \cdot d \cdot t_1^2}} - 1\right] + \frac{F_{ax,Rk}}{4} \quad (g). \\ 2.3\sqrt{M_{y,Rk} \cdot f_{h,1,k} \cdot d} + \frac{F_{ax,Rk}}{4} \quad (h) \end{cases} \quad (7)$$

For thin steel plates as the outer members of a double shear connection:

$$F_{v,Rk} = min\begin{cases} 0{,}5 f_{h,2,k} \cdot t_2 \cdot d \quad (j) \\ 1.15\sqrt{2 \cdot M_{y,Rk} \cdot f_{h,2,k} \cdot d} + \frac{F_{ax,Rk}}{4} \quad (k) \end{cases} \quad (8)$$

For thick steel plates as the outer members of a double shear connection:

$$F_{v,Rk} = min\begin{cases} 0{,}5 f_{h,2,k} \cdot t_2 \cdot d \quad (l) \\ 2.3\sqrt{M_{y,Rk} \cdot f_{h,2,k} \cdot d} + \frac{F_{ax,Rk}}{4} \quad (m) \end{cases}, \quad (9)$$

where $F_{v,Rk}$ is the characteristic load-carrying capacity per shear plane per fastener; $f_{h,k}$ is the characteristic embedment strength in the timber member; t_1 is the smaller thickness of the timber side member or the penetration depth; t_2 is the thickness of the timber middle member; *d* is the fastener diameter; $M_{v,Rk}$ is the characteristic fastener yield moment; and $F_{ax,Rk}$ is the characteristic axial withdrawal capacity of the fastener.

Figure 7.4 shows different failure modes of timber-to-steel connections.

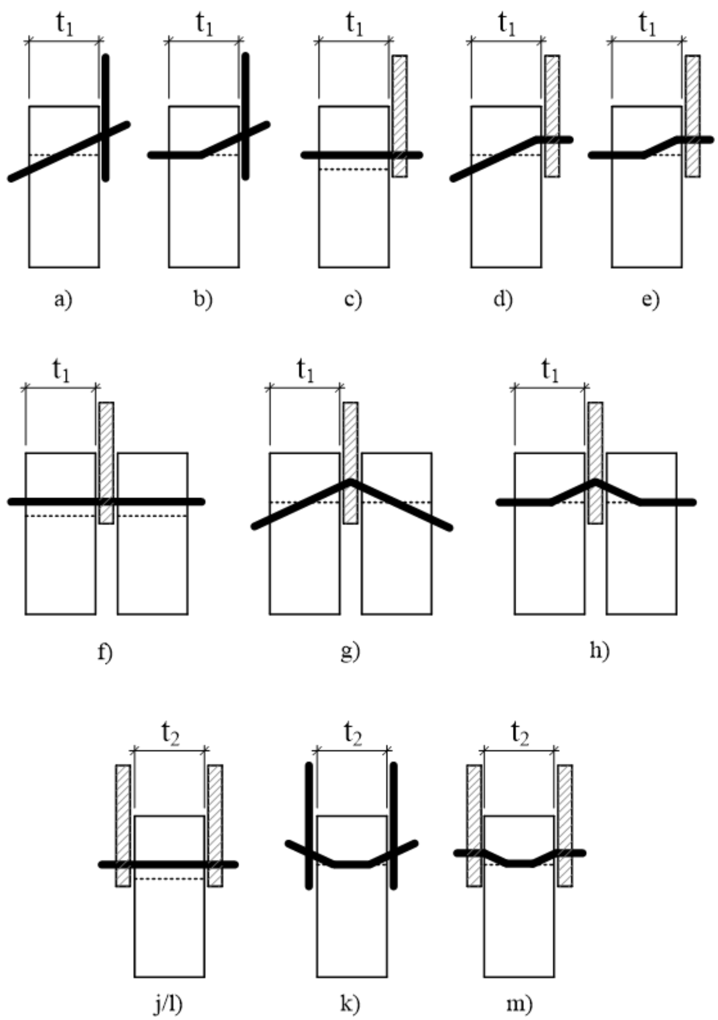


Fig. 7.4
Failure modes for steel-to-timber connections (created by Tomas Gecys)

7.5 Designing nailed connections in accordance with EN 1995-1-1

Further on, this sub-chapter will provide the main design assumptions and principles of nailed connections based on Eurocode 5. Timber should be pre-drilled when the characteristic density of the timber is greater than 500 kg/m^3 or the diameter *d* of the nail exceeds 6 mm. For square and grooved nails, the diameter *d* should be taken as the side dimension.

For smooth nails produced from wire with a minimum tensile strength of 600 N/mm^2, the following characteristic values for yield moment should be used in accordance with Eurocode 5:

$$M_{y,Rk} = \begin{cases} 0.3 f_u \cdot d^{2,6} & \text{for round nails} \\ 0.45 f_u \cdot d^{2,6} & \text{for square and grooved nails} \end{cases} \qquad (10)$$

where $M_{y,Rk}$ is the characteristic value for the yield moment, in Nmm; d is the nail diameter as defined in EN 14592, in mm; and f_u is the tensile strength of the wire, in N/mm^2.

For nails with diameters of up to 8 mm, the following characteristic embedment strengths in timber and LVL should be used in accordance with Eurocode 5:

Without pre-drilled holes $f_{h,k} = 0.082\rho_k \cdot d^{-0,3}$, N/mm^2; (11)

With pre-drilled holes $f_{h,k} = 0.082(1 - 0.01d)\rho_k$, N/mm^2, (12)

where ρ_k is the characteristic timber density, in kg/m^3; and d is the nail diameter, in mm.

For nails with diameters greater than 8 mm, the characteristic embedment strength values should be determined according to the methods provided for bolted connections.

According to Eurocode 5, for one row of n nails parallel to the grain, unless the nails of that row are staggered perpendicular to the grain by at least 1d, the load-carrying capacity parallel to the grain should be calculated using the effective number of fasteners n_{ef}:

$$n_{ef} = n^{k_{ef}}, \qquad (13)$$

where n_{ef} is the effective number of nails in the row; n is the number of nails in a row; and k_{ef} is the coefficient that evaluates the spacing between nails and type of installation, provided in Table 7.1.

Table 7.1. k_{ef} values for nailed connections

Spacing*	k_{ef}	
	Not pre-drilled	Pre-drilled
$a_1 \geq 14d$	1.0	1.0
$a_1 = 10d$	0.85	0.85
$a_1 = 7d$	0.7	0.7
$a_1 = 4d$	–	0.5

*For intermediate spacings, linear interpolation is permitted.

Designing nailed timber-to-timber connections in accordance with EN 1995-1-1

Later on, the main design assumptions will be provided. For smooth nails, the point-side penetration length should be at least 8*d*. For nails other than smooth nails, the point-side penetration length should be at least 6*d*, as defined in EN 145292. Nails in end grain should not be considered capable of transmitting lateral forces. Smooth nails in end grain may be used in secondary structures. The design values of the load-carrying capacity should be taken as 1/3 of the values for nails installed at right angles to the grain.

Nails other than smooth nails may be used in structures other than secondary structures, as defined in EN 14592. The design values of the load-carrying capacity should be taken as 1/3 of the values for smooth nails of equivalent diameter installed at right angles to the grain, thus ensuring the following conditions:

– The nails are only laterally loaded.

– There are at least three nails per connection.

– The point-side penetration is at least 10*d.*

– The connection is not exposed to service class 3 conditions.

– The prescribed spacings and edge distances given in Table 7.2 are satisfied.

Table 7.2. Minimum spacings and edge and end distances for nails

Spacings or distance (according to Figure 5)	Angle α	Minimum spacing or end/edge distance		
		Without pre-drilled holes		With pre-drilled holes
		$\rho_k \leq 420$ kg/m^3	420 kg/m^3 < $\rho_k \leq$ 500 kg/m^3	–
Spacing a_1 (parallel to grain)	0° ≤ α ≤ 360°	*d* < 5 mm: (5+5lcos αl)*d* *d* ≥ 5 mm: (5+7lcos αl)*d*	(7+8lcos αl)*d*	(4+lcos αl)*d*
Spacing a_2 (perpendicular to grain)	0° ≤ α ≤ 360°	5*d*	7*d*	(3+lsin αl)*d*
Distance $a_{3,t}$ (loaded end)	–90° ≤ α ≤ 90°	(10+5cos α)*d*	(15+5cos α)*d*	(7+5cos α)*d*
Distance $a_{3,c}$ (unloaded end)	90° ≤ α ≤ 270°	10*d*	15*d*	7*d*
Distance $a_{4,t}$ (loaded edge)	0° ≤ α ≤ 180°	*d* < 5 mm: (5+2sin α)*d* *d* ≥ 5 mm: (5+5sin α)*d*	*d* < 5 mm: (7+2sin α)*d* *d* ≥ 5 mm: (7+5sin α)*d*	*d* < 5 mm: (3+2sin α)*d* *d* ≥ 5 mm: (3+4sin α)*d*
Distance $a_{4,c}$ (unloaded edge)	180° ≤ α ≤ 360°	5*d*	7*d*	3*d*

In Table 7.2, the minimum spacings and edge and end distances (according to Figure 7.5) are the following:

- a_1 is the spacing of nails within one row parallel to grain.
- a_2 is the spacing of rows of nails perpendicular to grain.
- $a_{3,c}$ is the distance between nails and unloaded end.
- $a_{3,t}$ is the distance between nails and loaded end.
- $a_{4,c}$ is the distance between nails and unloaded edge.
- $a_{4,t}$ is the distance between nails and loaded edge.
- α is the angle between the force and the grain direction.

Timber should be pre-drilled when the thickness of the timber members is smaller than:

$$\mathrm{t} = \max\begin{cases} 7d \\ (13d - 30)\,\rho_k/400 \end{cases}, \qquad (14)$$

where t is the minimum thickness of a timber member necessary to avoid pre-drilling, in mm; ρ_k is the characteristic timber density, in kg/m^3; and d is the nail diameter, in mm.

Timber species especially sensitive to splitting should be pre-drilled when the thickness of the timber members is smaller than:

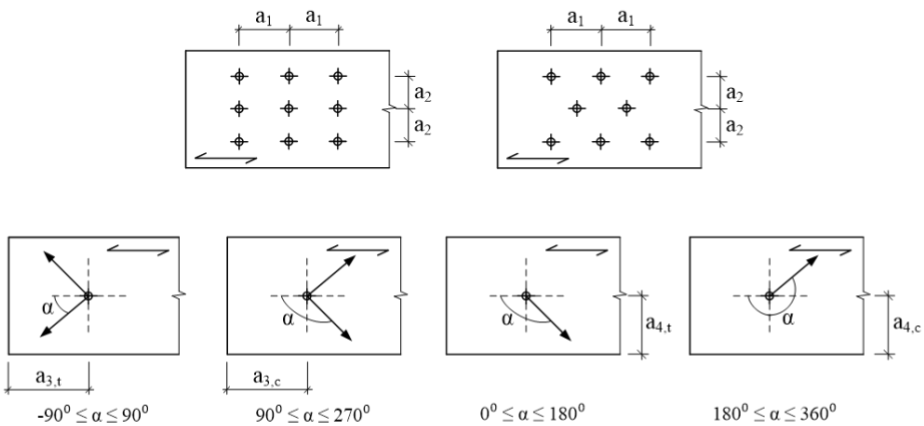
$$\mathrm{t} = \max\begin{cases} 14d \\ (13d - 30)\,\rho_k/200 \end{cases}. \qquad (15)$$

Expressions (15) may be replaced by expression (14) for edge distances given by:

$a_4 \geq 10d$ for $\rho_k \leq 420$ kg/m^3;

$a_4 \geq 14d$ 420 kg/m$^3 < \rho_k \leq 500$ kg/m^3.

Fig. 7.5
Spacings and end and edge distances for nails (created by Tomas Gecys)



Designing nailed panel-to-timber connections in accordance with EN 1995-1-1

In lightweight timber frames, one of the most efficient ways to connect timber elements with panel-based elements is to use nails. Below, the main principles of nailed panel-to-timber connections are provided.

Minimum nail spacings for all nailed panel-to-timber connections are those provided in Table 7.2, multiplied by a factor of 0.85. The end/edge distances for nails remain unchanged unless otherwise stated. Minimum edge and end distances in plywood members should be taken as 3*d* for an unloaded edge/end and (3+4 sinα)*d* for a loaded edge/end, where α is the angle between the direction of the load and the loaded edge/end.

For nails with a head diameter of at least 2*d*, the characteristic embedment strengths are as follows.

For plywood: $f_{h,k} = 0{,}11\rho_k \cdot d^{-0{,}3}$, (16)

For hardwood in accordance with EN 622-2: $f_{h,k} = 30d^{-0{,}3}t^{0{,}6}$, (17)

For particle board and OSB: $f_{h,k} = 65d^{-0{,}7}t^{0{,}1}$, (18)

where $f_{h,k}$ is the characteristic embedment strength, in N/mm^2; ρ_k is the characteristic plywood density, in kg/m^3; *d* is the nail diameter, in mm; and *t* is the panel thickness, in mm.

Designing axially loaded nails in accordance with EN 1995-1-1

Nails used to resist permanent or long-term axial loading shall be threaded. The definition of the minimum withdrawal parameter is provided in EN 14592. For threaded nails, only the threaded part should be considered capable of transmitting axial load. Nails in end grain should be considered incapable of transmitting axial load.

The characteristic withdrawal capacity of nails, $F_{ax,Rk}$, for nailing perpendicular to the grain and for slant nailing, should be taken as the smaller of the values found from the expressions according to Eurocode 5:

For nails other than smooth nails, as defined in EN 14592:

$$F_{ax,Rk} = \begin{cases} f_{ax,k} d \cdot t_{pen} \\ f_{head,k} \cdot d_h^2 \end{cases} . \quad (19)$$

For smooth nails:

$$F_{ax,Rk} = \begin{cases} f_{ax,k} d \cdot t_{pen} \\ f_{ax,k} d \cdot t + f_{head,k} \cdot d_h^2 \end{cases} , \quad (20)$$

where $f_{ax,k}$ is the characteristic point-side withdrawal strength; $f_{head,k}$ is the characteristic head-side pull-through strength; d is the nail diameter; t_{pen} is the point-side penetration length or the length of the treaded part in the point-side member; t is the thickness of the head-side member; and d_h is the nail head diameter.

For smooth nails with a point-side penetration of at least 12d, the characteristic values of the withdrawal and pull-through strengths should be found from the following expressions:

$$f_{ax,k} = 20 \cdot 10^{-6} \rho_k^2, \quad (21)$$

$$f_{head,k} = 70 \cdot 10^{-6} \rho_k^2. \quad (22)$$

For smooth nails, the point-side penetration t_{pen} should be at least 8d. For nails with a point-side penetration smaller than 12d, the withdrawal capacity should be multiplied by (t_{pen}/4d–2). For threaded nails, the point-side penetration should be at least 6d. For nails with a point-side penetration smaller than 8d, the withdrawal capacity should be multiplied by (t_{pen}/2d–3). For structural timber that is installed at or near the fibre saturation point and which is likely to dry under load, the values of $f_{ax,k}$ and $f_{head,k}$ should be multiplied by 2/3. The spacings and the end and edge distances for laterally loaded nails apply to axially loaded nails.

For nailed connections subjected to a combination of axial load $F_{ax,Ed}$ and shear load $F_{v,Ed}$, the following expressions should be fulfilled, in accordance with Eurocode 5.

For smooth nails:

$$\frac{F_{ax,Ed}}{F_{ax,Rd}} + \frac{F_{v,Ed}}{F_{v,Rd}} \leq 1. \quad (23)$$

For nails other than smooth nails, as defined in EN 14592:

$$\left(\frac{F_{ax,Ed}}{F_{ax,Rd}}\right)^2 + \left(\frac{F_{v,Ed}}{F_{v,Rd}}\right)^2 \leq 1, \quad (24)$$

where $F_{ax,Rd}$ and $F_{v,Rd}$ are the design load-carrying capacities of the connection loaded with axial and shear load, respectively.

7.6 Designing bolted connections in accordance with EN 1995-1-1

Later on, this sub-chapter provides the main design assumptions and principles of bolted connections based on Eurocode 5. For bolts, the characteristic value for the yield moment should be used:

$$M_{y,Rk} = 0.3 f_{u,k} \cdot d^{2.6}, \qquad (25)$$

where $M_{y,Rk}$ is the characteristic value for the yield moment, in Nmm; $f_{u,k}$ is the characteristic tensile strength of steel, in N/mm^2; and d is the bolt diameter, in mm.

For bolts up to 30 mm diameter, the following characteristic embedment strength values in timber and LVL should be used, at an angle α to the grain:

$$f_{h,\alpha,k} = \frac{f_{h,0,k}}{k_{90} \cdot sin^2\alpha + cos^2\alpha}, \qquad (26)$$

$$f_{h,0,k} = 0{,}082(1 - 0{,}01d)\rho_k, \qquad (27)$$

$$k_{90} = \begin{cases} 1.35 + 0{,}015d & for\ softwoods \\ 1.30 + 0{,}015d & for\ LVL \\ 0.90 + 0{,}015d & for\ hardwoods \end{cases}, \qquad (28)$$

where $f_{h,0,k}$ is the characteristic embedment strength parallel to the grain, in N/mm^2; ρ_k is the characteristic timber density, in kg/m^3; α is the angle of the load to the grain; and d is the bolt diameter, in mm.

Minimum spacings and edge and end distances are provided in Table 7.3.

Table 7.3. Minimum spacings and edge and end distances for bolts

Spacings or distance (according to Figure 7.5)	Angle α	Minimum spacing or end/edge distance
Spacing a_1 (parallel to grain)	$0^o \le \alpha \le 360^o$	(4+Icos αI)*d*
Spacing a_2 (perpendicular to grain)	$0^o \le \alpha \le 360^o$	4*d*
Distance $a_{3,t}$ (loaded end)	$-90^o \le \alpha \le 90^o$	max (7*d*; 80 mm)
Distance $a_{3,c}$ (unloaded end)	$90^o \le \alpha < 150^o$ $150^o \le \alpha < 210^o$ $210^o \le \alpha \le 270^o$	(1+6sin α)*d* 4*d* (1+6Isin αI)*d*
Distance $a_{4,t}$ (loaded edge)	$0^o \le \alpha \le 180^o$	max [(2+2sin α)*d*; 3*d*]
Distance $a_{4,c}$ (unloaded edge)	$180^o \le \alpha \le 360^o$	3*d*

For one row of n bolts parallel to the grain direction, the load-carrying capacity parallel to the grain should be calculated using the effective number of bolts n_{ef}, as:

$$n_{ef} = min\begin{cases} n \\ n^{0.9} \cdot \sqrt[4]{a_1/13d} \end{cases} \qquad (29)$$

where a_1 is the spacing between bolts in the grain direction; d is the bolt diameter; and n is the number of bolts in the row.

For loads perpendicular to the grain, the effective number of fasteners should be assumed to be $n_{ef} = n$, the actual number of bolts. For angles $0^o < \alpha < 90^o$ between the load and grain direction, n_{ef} may be determined by linear interpolation.

In bolted panel-to-timber connections, the embedment strength value should be technically approved.

In timber connections, bolts could be subjected to direct axial force. The axial load-bearing capacity and withdrawal capacity of a bolt should be taken as the smaller value: the bolt tensile capacity or the load-bearing capacity of either the washer or the steel plate. The bearing capacity of a washer should be determined assuming a characteristic compressive strength on the contact area of $3.0f_{c,90,k}$. It is assumed that the local compressive stresses are transferred to a rather large area around the washer. The bearing capacity per bolt should not exceed that of a circular washer with a minimum diameter of $12t$ (where t is the plate thickness) or $4d$ (where d is the bolt diameter).

7.7 Designing screwed connections in accordance with EN 1995-1-1

Laterally loaded screwed connections are efficient connections, given that the rope effect contribution can be up to 100% of the Johansen part of the load-carrying capacity. The effect of the threaded part of the screw shall be taken into account in determining the load-carrying capacity by using an effective diameter d_{ef}. For smooth shank screws where the outer diameter is equal to the shank diameter, the rules given in Sections 7.3 and 7.4 apply, provided that the effective diameter d_{ef} is taken as the smooth shank diameter and that the smooth shank penetrates no less than $4d$ into the timber member containing the point of the screw. If the previous conditions are not satisfied, the screw load-carrying capacity should be calculated using an effective diameter d_{ef}, taken as 1.1 times the threaded root diameter. For smooth shank screws with a diameter $d > 6$ mm, the rules used for bolts apply; while for smooth screws with a diameter of 6 mm and less, the rules for nails apply.

Axially loaded screws can be used as reinforcement for elements or to transfer large tension forces. To verify the resistance of axially loaded screws, the following failure modes shall be taken into account.

– The withdrawal failure of the threaded part of the screw.

– The tear-off failure of the screw head of the screws used in combination with steel plates. The tear-off resistance of the screw head should be greater than the tensile strength of the screw.

– The pull-through failure of the screw head.

– The tensile failure of the screw.

– The buckling failure of the screw when loaded in compression.

– Failure along the circumference of a group of screws used in conjunction with steel plates (block shear or plug shear).

The equations for determining the characteristic withdrawal capacity of screws depend on geometrical parameters. Eurocode 5 and EN 14592 provide the detailed ranges for the geometry that determines which equations should be used to ascertain the characteristic withdrawal capacity.

7.8 Stiffness of the connections in accordance with EN 1995-1-1

In the design of timber connections, it is significantly important to evaluate not only the load-carrying capacity, but also the actual stiffness and deformations of the connections. Because most timber connections are semi-rigid, evaluating the stiffness is extremely important for the final design and dimensioning the rational cross-section. Eurocode 5 provides the stiffness coefficient values and slip values of most connections in timber structures. For joints made with dowel-type fasteners, the slip modulus K_{ser} per shear plane per fastener under service load should be taken according to Table 7.4, with ρ_m in kg/m^3 and d or d_c in mm.

Table 7.4. Values of K_{ser} for fasteners and connectors in N/mm in timber-to-timber and wood-based panel-to-timber connections

Fastener type	K_{ser}
Dowels Bolts with or without clearance Screws Nails (with pre-drilling)	$\rho_m^{1.5}d/23$
Nails (without pre-drilling)	$\rho_m^{1.5}d^{0.8}/30$
Staples	$\rho_m^{1.5}d^{0.8}/80$
Split-ring connectors type A according to EN 912 Shear-plate connectors type B according to EN 912	$\rho_m d_c/2$
Toothed-plate connectors: Connectors types C1 to C9 according to EN 912 Connectors type C10 and C11 according to EN 912	 $1.5\rho_m d_c/4$ $\rho_m d_c/2$

In cases where the mean densities $\rho_{m,1}$ and $\rho_{m,2}$ of two jointed wood-based members are different than ρ_m in the Table 7.4 expressions, they should be determined according to the following equation:

$$\rho_m = \sqrt{\rho_{m,1} \cdot \rho_{m,2}}\,. \quad (30)$$

For steel-to-timber or concrete-to-timber connections, K_{ser} should be based on ρ_m for the timber member and may be multiplied by 2.0.

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EN 1995-1-1: Eurocode 5: Design of timber structures.

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8

Construction considerations for mass timber building projects

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Driven largely by wood's light carbon footprint and a desire to build sustainably, mass timber design for new buildings has seen a sharp increase in North America since 2015. In Canada, timber has disrupted the built environment in part due to resurgence of tall wood buildings since 2009.

Achieving the highest level of cost efficiency with mass timber requires an understanding of both material properties, manufacturing capabilities and constructability constraints. This chapter will focus on addressing the following learning outcomes:

- Identifying construction management practices in mass timber projects
- Defining the roles of technology in mass timber projects
- Recognizing the steps to off-site construction management
- Defining site organization and project delivery of mass timber projects

8.1 Construction management practices for mass timber projects

Before reviewing the specific practices for mass timber projects, it is important to define and review the general practices for construction project management.

It is accepted that in construction project management that the several phases are clearly outlined to ensure the success of project deliverables.

The broad definition of a project according to the Project Management Institute, PMI usually refers to it as “a temporary endeavour undertaken to create a unique project service or good” (Weaver, P.2010)

Accepting the temporary and uniqueness attributes of a project implies a start and end point to a project dissimilar to any other projects.

Project Management is often about ensuring the success of a project according to three measurable factors and constraints: cost, time, and scope or quality. However, with increasing environmental and climate change constraints, it has become increasingly critical to add sustainability considerations as part of project goals and deliverables.

A project can have a different definition pending on the organization. However, one good practice of project management is to start understanding a project by identifying the operational constraints derived from the project.

It is common as shown in Figure 8.1, to breakdown project management into 4 active phases: define, develop, analyse and evaluate.

Figure .8.1 The 4 phases of Project Management

The consideration of a proj3ct around 4 phases is quite simplistic. In construction practices, it is critical to also have a wholistic approach to the infrastructure being constructed. This is becoming more critical as sustainability constraints require the consideration of not just the construction but also the operation and maintenance of a project after it has been built.

Figure 8.2 The life cycle of a project

One way to consider the life cycle of projects would be a gate to gate approach where a project can be broken down into 5 processes as shown in Figure 8.2 to include: initiation; planning; execution; controlling; and close out. Using a whole life cycle for building projects much more aligned with sustainable design and construction practices, one could include: operation and decommission process to follow the close out or commissioning is complete. In construction project management practices, similarly to the description of figure 8.2, it is most common practice to consider the following phases:

- The Initiation phase:

The first phase of any construction project must define the business case to determine if the project is feasible and viable given the specific constraints of the project. This phase often consists in the feasibility and programming of the project and can be supported by some schematic design renderings and

worth undertaking. Once all stakeholders engaged at this stage agree to proceed with the project, the project manager writes a project charter or project initiation document (PID), which includes both the project need, risks, constraints and the business or planning case.

- The Pre-construction phase

The pre-construction phase serves to develop the project management plan also setting the baseline for cost and schedule and sanctioned by the following deliverables:

  - the project’s goals
  - the business case
  - the scope of work
  - the project budget
  - the project’s organizational chart
  - the project’s risks and corresponding management strategy
  - quality management strategy
  - change management plan
  - construction documents
- The procurement phase

During this phase, the project team orders and procures all , purchases all the materials, tools, equipment and services necessary to complete the project.

The procurement phase is very critical in the life cycle of a project as it defines and finalized the project delivery method and all contractual agreements necessary to complete the project.

- The construction phase

The execution phase of the project management lifecycle is where the project team constructs its deliverables. It is typically incumbent on the project manager to oversee this stage to ensure that compliance with the plans developed during the planning stage. At this stage all project tasks and activities must have been identified and whilst deliverables are being completed, the project team manages any changes and measures progress against the performance baseline set during the planning. Quality control testing and monitoring are also undertaken in accordance with the quality management plan in compliance with the client's needs. The change management protocol and plan to include change orders, change directives, and substitution requests, should help minimize the financial and schedule impact of change always inevitable during construction. The project manager should ensure

- The close out and post construction phase

This phase of a construction project which typically signifies the completion of the construction and May be referred to as post-construction, tends to focus primarily on: correcting any deficiencies;

obtaining the Certificate of Occupancy or other jurisdictional approvals,

delivering: the final project budget, as-built schedule, and as-built drawings.

There is a substantial period of time that allows for proper handoff and turnover to the building owner. Pending on th3 complexity of the project, this assures that the owner is comfortable operating every facet of the newly completed project. In construction this phase is often accompanied and supported by the Builder, and should always be planned in the early phase of the project to support quality control of the deliverable.

During close out, the project is handed over to the owner, whilst the project team performs a final review to ensure the relevant files are stored accordingly. Holding a learning session is of good practice.

The post-construction phase should ensure that the building owner is fully prepared to take over operation of the building. It should be a collaboration between all the stakeholders (owner, contractor, engineer, architect).

Mass timber building projects may follow the best practices for project management outlined this far. Nevertheless, in order to achieve optimum project performances mass timber projects, require specific considerations. The fact that the majority of mass timber products are prefabricated using computer-controlled CNC tools requires an extensive integration within the project management team to include input from the contract and detailed design drawings for the prefabrication.

Amongst the key considerations that should take place during the pre-construction phase, best practices for mass timber project management should encompass:

  - Early and continued integration between the project management team
  - Coordination of mass timber with other building materials
  - Integration between mass timber and other subcontractors—e.g., MEP mechanical, electrical and plumbing and FP fire protection
  - A responsibility matrix including: Designer, General Contractor, Supplier, sub-contractors.

As described below, the integration of technology plays an important role in mass timber projects in order to coordinate smoothly between the design, manufacturing and assembly or construction.

8.2 The roles of technology in mass timber construction projects

Mass timber construction has emerged during the innovative transformation of the (AEC) Architecture, Engineering and Construction sector. In addition, over the past decade and certainly during the COVID years, the Construction sector has also seen an acceleration of the digital transformation with the integration of Building Information Modelling (BIM).

In construction projects, BIM is a modelling system that condenses

and coordinates all project details in one location. Building information models are therefore used to enable the followings:

- Visualization: 3D renderings can be easily generated in house with little additional effort.
- Fabrication/shop drawings: It is easy to generate shop drawings for various building systems. For example, the sheet metal ductwork shop drawings can be quickly produced once the model is complete.
- Code reviews: Fire departments and other officials may use these models for their review of building projects.
- Cost estimating: BIM software has built-in cost estimating features. Material quantities are automatically extracted and updated when any changes are made in the model.
- Construction sequencing: A building information model can be effectively used to coordinate material ordering, fabrication, and delivery schedules for all building components.
- Conflict, interference, and collision detection: Because building information models are created to scale in 3D space, all major systems can be instantly and automatically checked for interferences. For example, this process can verify that piping does not intersect with steel beams, ducts, or walls.
- Forensic analysis: A building information model can be easily adapted to graphically illustrate potential failures, leaks, evacuation plans, and so forth.
- Facilities management: Facilities management departments can use it for renovations, space planning, and maintenance operations.

For mass timber construction, BIM is quite critical because with BIM, architects, engineers, contractors and subcontractors can interface within the model and share information. Mass timber manufacturers or producers may use BIM to extract data and communicate with the CNC manufacturing equipment to create customized panels.

BIM is a digital database extension of 2D project drawings into 3D project models and animations, or 4D schedule sequencing and 5D cost estimate. BIM 6D and 7D are extension to respectively sustainability and facility management of a construction project.

It allows for a visual simulation of a construction project and a "digital twin building model during the pre-construction phase and thereby requires significant coordination and communication between the Project team including the contractor, mass timber fabricator, installers and other specialty contractors. As we shall discuss below, the digital transformation of a construction project is key to the successful management of off-site construction of mass timber buildings.

8.3 Off-site management for mass timber buildings

Prefabrication or Off-site construction should be the recommendation for mass timber construction in order to achieve a successful project. Off-site construction has increasingly been promoted to mitigate issues of productivity and labour shortage in construction, and has been on the rise.

In off-site construction projects, elements or components of the construction project are fabricated or manufactured at a different location to where they will be permanently installed. Project management in such projects involves planning, design, fabrication and assembly. Therefore, off-site construction is often referred to as Design for manufacturing and assembly (DfmA).

Mass timber construction has disrupted the construction sector because it highlights the significance of the prefabrication phase on which relies successful assembly of the building items transported to site

Off site management of mass timber projects is best practiced when supported by technology like BIM to enable full integration and collaboration between the designer, contractor and mass timber manufacturer.

Whilst the life cycle of mass timber projects resembles that of other building projects, due to the high level of prefabrication associated with mass timber project, a big emphasis must be put towards the pre-construction phase of such projects. The design phase during the pre-construction phase is typically broken down into 3 steps:

- Conceptual or Schematic design

At this stage all the information about the building project and models of all structural components are often volumetric with no specific details.

- Design development

At this step of the architectural design, all elements and components of the structure "as designed" can be identified, quantified and sized, directly from the building model. For mass timber project, this is the phase where the pre-fabrication model and shop drawings are developed with input from the builder to enable optimum manufacturing, assembly and installation during the construction phase. The shop drawings needed for CNC machining of mass timber products must include location of opening, cuts, connections.

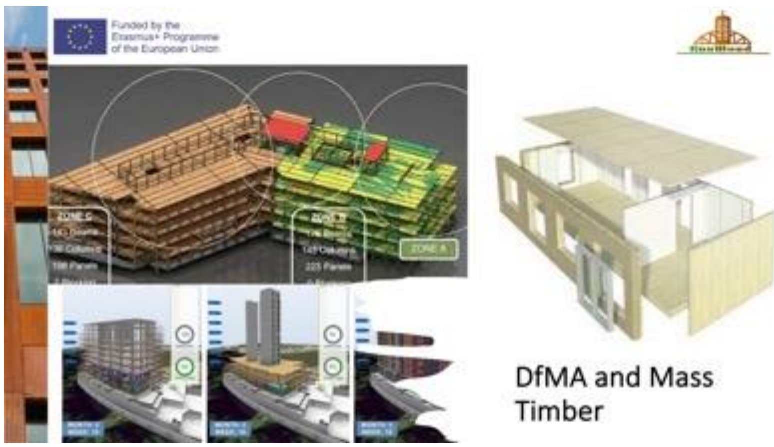

Figure 8.3 Virtual building model and assembly sequencing

- Construction documents

The phase typically produces detailed "as designed" drawings or models to be used for construction. These drawings also include specifications for construction details and materials. CDs – construction documents are often used at this stage to issue procurement for specialty sub-contractors and building products, and therefore all complete sets of drawings and full building models are complete. The as-design benchmark is set to serve for project control.

For mass timber projects, CDs or digital twin models should encompass the sequencing assembly of the mass timber elements like CLT or Glulam, including connection details. To accommodate dimensional variations for some mass timber elements and products like shrinkage and swelling until the building is fully closed in, construction tolerances should be clearly indicated to include all the gaps required during assembly.

Building tolerances should be considered in the design phases, based on normal needs and common construction practices, and managed during the assembly. The prefabrication of mass timber elements in a controlled environment can enable quality control for tolerances typically governed by building codes and controlled through construction inspection. This is particularly significant for hybrid construction where timber is connected to steel or concrete. A visualization of the design and the specifics of the various connections can be helpful for designers, contractors, manufacturers and installers in identifying the constructability impacts of the diverse assembly connections.

According to WoodWorks, “the key to fast construction is designing and coordinating all systems during the design stage”. As described above and illustrated in the chart below, mass timber project best practices include a greater integration during the various stages of the design phase.

The project management of construction projects including mass timber is not necessarily linear and sequential in time. Best practices suggest a collaborative and more integrated delivery method with all the stakeholders involved at an early stage of the pre-construction phase. Coordination with mass timber suppliers, sub-contractors and installers enables achieving the significant advantages of mass timber construction over traditional practices.

Mass timber projects may allow for speedy completion and savings to labor costs. The charts below indicate an aggregate of costs breakdown of mass timber projects built using a turnkey process.

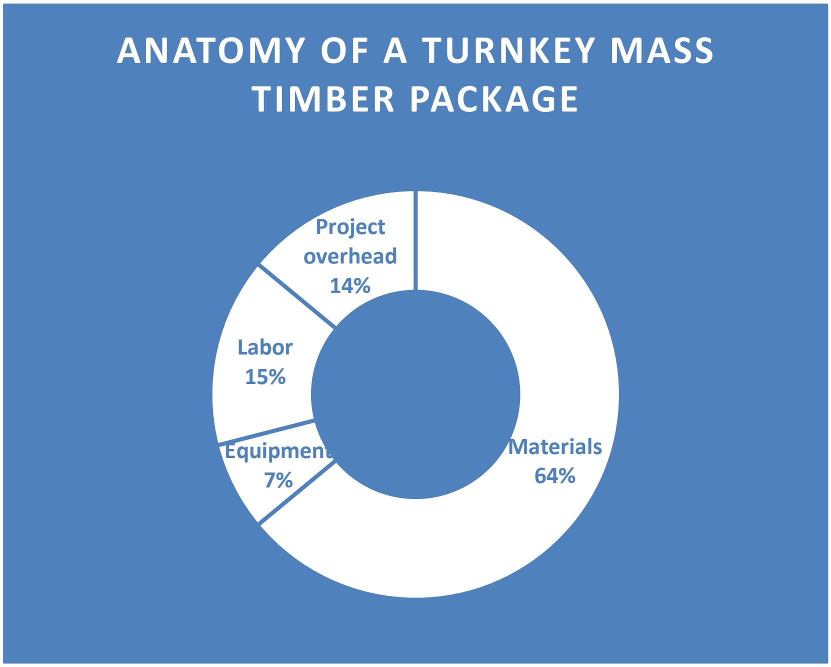

Figure 8.4 Cost breakdown of a turnkey mass timber project

In a turnkey mass timber project, involves all of the steps from the design to construction and close out: from the selection, negotiations, space planning, construction coordination and complete installation, all are completed under one contract. A similar construction delivery method to Design Build.

Most commonly, as shown below, three procurement methods are commonly used in mass timber projects.

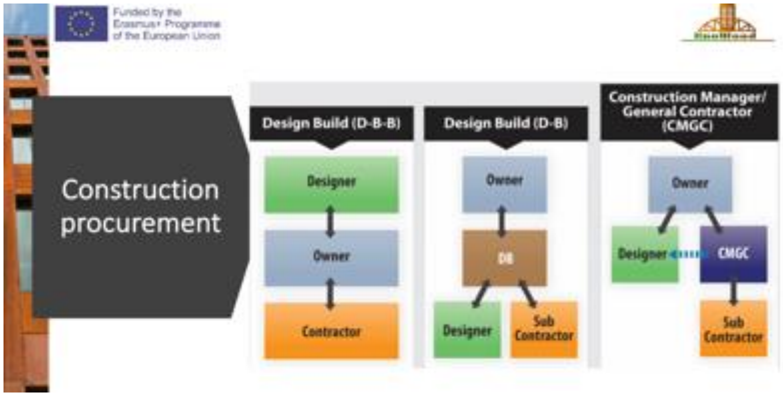

Figure 8.5 construction procurement of mass timber projects

IPD – or Integrated Project Delivery could potentially be recommended for mass timber projects due to the early integration of all stakeholders including supplier and installers.

Once all construction documents and procurement are complete, the focus shifts to construction site. Site management of mass timber project will resemble traditional projects especially given that all ground work is normally going to be with concrete.

8.4 Construction site control and management

Prefabrication and design for manufacturing assembly also known as DfmA or Off-site construction should be the recommendation for mass timber construction in order to achieve a successful project. A successful project is primarily one that aligns with the pre-determined scope, schedule and budget. Additional quality or performance criteria may also be required by the building project stakeholders. Thereby, as described in the practices for design and planning mass timber construction projects, full integration of the manufacturing details is key to the success of the project.
Given the assembly characteristics of mass timber projects, it is critical to develop a delivery, loading and handling planning and schedule
in conjunction with the engineered wood products manufacturer.
Safety, moisture and fire are three key site factors that need a particular attention during mass timber construction in addition to the typical risk, cost and schedule control management incumbent on the project manager.
Site planning is a key consideration for mass timber building projects and can encompass: mass timber logistics, on-site delivery, road access, site
conditions, overhead clearance and equipment. Theses aspects ought to be discussed and reviewed as early as possible and can be integrated in the right sequencing of the project execution.

- Mass timber supply and site delivery

Mass timber presents a few additional areas for site planning key to efficient mass timber installation.

Hence, pending on the supplier, mass timber components may be delivered:

- on flatbed trailers,
- in shipping containers

In both cases, optimum efficiency by a careful coordination between the supplier and the contractor on site. JIT – just in time is often recommended for mass timber projects.

JIT helps accommodate for an inventory management in which building materials are only shipped when needed for an immediate assembly or installation on site. Yet again, the use of BIM 4D in the design with construction scheduling and sequencing should allow the contractor, supplier and installer to have the sequential order in which elements such as CLY floor plates or GLT posts or beams ought to be assembled. An optimum delivery and logistic will ensure that trailers or containers are loaded to their maximum capacity to reduce the number of trips. This may be particularly important if the hauling is over long distances or overseas cargo. From the perspective of the contractor or installer, maximum efficiency for on-site assembly, no site storage and minimum crane time would mean that shipments of mass timber components are loaded in a reverse order to the assembly sequencing.

Site access is certainly key to ensuring an efficient assembly in mass timber projects. On the other hand, safety management does not differ from that of traditional construction projects unlike the construction management of moisture always very critical. Pending on the project specifics, it could also start from the storage of wood building material as they get delivered to site.

- Construction moisture management

The management of moisture for mass timber construction should start from the earliest stage of the project, influencing everything from siting to the selection of assemblies, enclosure design and detailing, and protection measures on site.

Techniques to control and mange moisture during construction of mass timber projects will largely depend on the local climate and weather.

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→ 9

Case studies

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9.1. Housing on Lisbjerg Hill

Location: Lisbjerg, Denmark

Functional type: Residential (40 social housing units) and a communal space

Architects: Vandkunsten Architects

Client: AL2Bolig

Year: 2014–2018

Number of floors: 2–4

Cost: € 1,500/m^2 excl. VAT

Photo: Social housing on Lisbjerg Hill (by Helene Høyer Mikkelsen)

Description of the building

This building project won the Sustainable Non-profit Housing of the Future competition, which was launched in 2014 by the Ministry of Cities, Housing, and Rural Areas, the city of Aarhus, and the non-profit housing administrator AL2bolig. For this project, Vandkunsten Architects proposed a future-proof and sustainable housing scheme that applies a new hybrid wood-based construction system (Vandkunsten Architects, n.d.).

The complex is located on Lisbjerg Hill on the outskirts of Aarhus, the second biggest city in Denmark. Forty social housing units and communal spaces were designed as a small village with dense housing clusters of 2–4 storeys. The buildings were completed in 2018 (Vandkunsten Architects, n.d.).

The project focused mainly on using a new hybrid wooden building system to create flexibility in the multi-storey buildings while guaranteeing their suitability for the local market and local building codes (Vandkunsten Architects, n.d.).

Photo: Social housing on Lisbjerg Hill (by Helene Høyer Mikkelsen)

Photo: Social housing on Lisbjerg Hill (by Helene Høyer Mikkelsen)

Photo: Inside one apartment (by Helene Høyer Mikkelsen)

Drawing: Site plan (by Vandkunsten Architects)

Drawing: Floor plan (by Vandkunsten Architects)

Drawing: Façade (by Vandkunsten Architects)

Drawing: Section (by Vandkunsten Architects)

Design and structural principles

The architecture of Lisbjerg Hill uses wood and takes advantage of the benefits of prefabrication.

Vandkunsten Architects and engineers at the company MOE developed the hybrid system, whose main material is solid wood, which is combined with the secondary materials concrete and steel. Concrete is especially excellent for fulfilling regulations on fire protection and soundproofing in multi-storey buildings. Combining the advantages of wood with concrete and/or steel can improve the performance of a building's components (Vandkunsten har tegnet et moderne træhus på Libjerg Bakke).

Laminated wood was used for the columns, beams, long-span decks, and façade; concrete in the staircases and elevator shafts; and steel beams in specific places to support the load-bearing system of the entire building. The floor decks are composed of solid wooden elements with a layer of concrete, which assists fire resistance and soundproofing while keeping the decks slender (Vandkunsten har tegnet et moderne træhus på Libjerg Bakke).

The column and beam system, with its long-span deck elements, offers freedom in floor planning as well as flexibility for future changes in user needs. Additionally, the solid wooden elements can be reused and disassembled, thus protecting resources (Vandkunsten har tegnet et moderne træhus på Libjerg Bakke).

Figure: Diagram of structural principle (by Vandkunsten Architects)

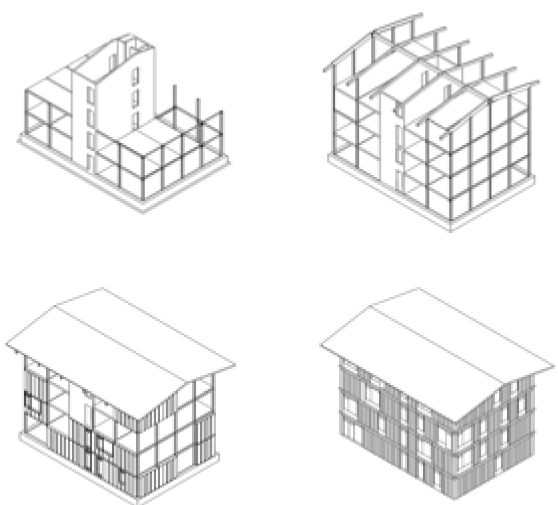


Figure: Building system (by Vandkunsten Architects)

Photo: Connection between column and beam (by Helene Høyer Mikkelsen)

Photo: Concrete staircase and construction of wooden elements (by Helene Høyer Mikkelsen)

Photo: Prefabricated wooden roof (by Helene Høyer Mikkelsen)

Materials and finishes

The façade walls are made of prefabricated wood-based panels and the cladding of untreated spruce. Many variations in the prefabricated panels grant flexibility in the façade design (Vandkunsten Architects (n.d.).

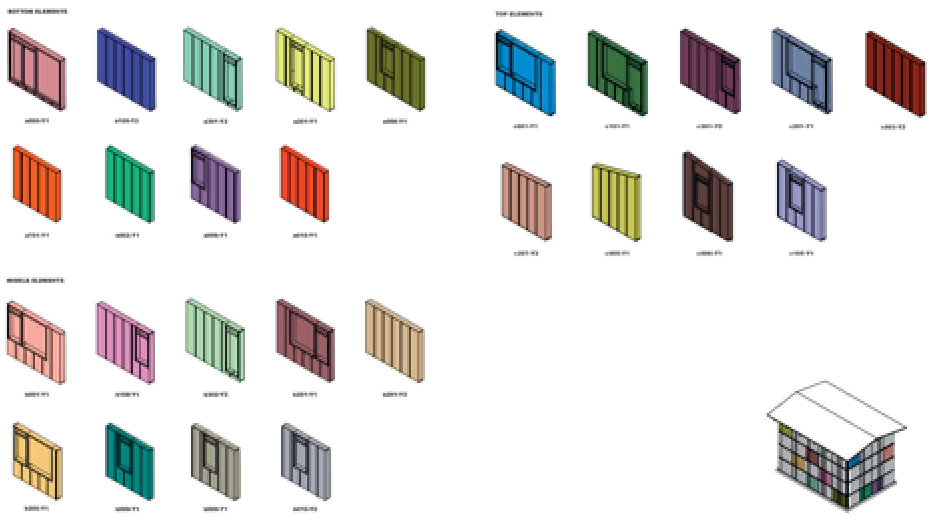


Illustration: Flexibility in the façade (by Vandkunsten Architects)

Photo: Mounting façade panel (by Helene Høyer Mikkelsen)

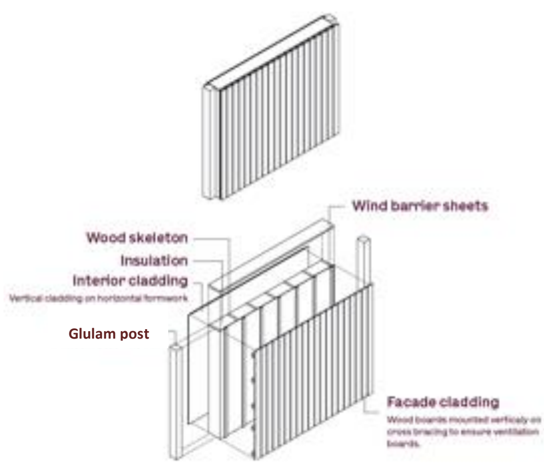
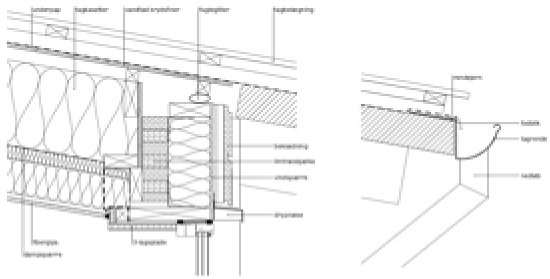


Illustration: System of façade element (by Vandkunsten Architects)

Photo: Roof overhang and spruce façade (by Søren Nielsen/ Vandkunsten)



Drawing: Detail of roof overhang (by Vandkunsten Architects)

The apartments are finished with wooden parquet for the floors, plasterboard or wooden boards for the interior walls, and fibre plasterboard for the ceilings.

Photo: Interior of apartment (photo by Helene Høyer Mikkelsen)

Resource consumption in the use stage

From the perspective of LCA/LCC, the Lisbjerg Hill project offers potential economic benefits compared to conventional construction methods. The lifecycle cost is calculated at 33% less than a reference building. The slender external wall increases the net floor area, which is 3–4% larger than an ordinary concrete building (Vandkunsten Architects, n.d.).

According to LCIA calculations[1] based on a 50-year lifespan:

- Embodied carbon (construction + replacements + end-of-life)
  GWP: 2.3 kg Co2 eq/m2/year
- Embodied energy (construction + replacement + end-of-life)
  PEnr: 34 kWh/m2/year

The project is certified for DGNB Gold (Vandkunsten Architects, n.d.).

Additional information

The Lisbjerg Hill project received the Matilde Baffa Ugo Rivolta European Architecture Award 2019.

It also received the Aarhus Municipality´s 2018 juried architecture prize.

Source

Vandkunsten Architects (n.d.). *Lisbjerg Bakke / The future of wood construction is hybrid*. Report about Lisbjerg Bakke / Baffa.

Vandkunsten (n.d.). *Et moderne dansk træhus*. Retrieved 19th of February 2022 from: Vandkunsten har tegnet et moderne træhus på Libjerg Bakke

Photo

Helene Høyer Mikkelsen, architectural photographer and architect MAA

Søren Nielsen / Vandkunsten Architects

[1] Method used: CML based on generic data from ökobau.dat and product-specific EPDs (standard used in DGNB certifications in Denmark). Source: "Lisbjerg Bakke / The future of wood construction is hybrid", by Vandkunsten Architects.

9.2. Moxy Hotel

Location: Copenhagen, Denmark

Functional type: Hotel

Architects: BWM Architekten und Partner (Austria), in collaboration with Anders Helweg Arkitekter (Denmark)

Client: Moxy Hotel (owned by the hotel chain Marriott and Vastint Hospitality)

Year of construction: 2018–2019

Number of floors: 5

Photo: Moxy Hotel (by Mihoko Goto Brethvad / VIA University College)

Description of the building

Copenhagen, the capital of Denmark with a population of 1.8 million (Befolkningstal - Danmarks Statistik (dst.dk) as of 1st quarter 2022), is in the midst of a construction boom as its population and economy grow. In 2012, the energy plan CPH 2025 Climate plan was formulated with the aim of making Copenhagen the world´s first carbon-neutral capital city by 2025. In order to create a carbon-neutral city, it is necessary to solve the various holistic elements that make up the city (The CPH 2025 Climate Plan | Urban Development (kk.dk)).

Thus, Denmark is paying more and more attention to wood that emits less CO2 in the manufacturing process. Using wood in mid-rise buildings is no longer an exception in Denmark.

The Moxy Hotel, which is located in Copenhagen´s south harbour, is a large five-storey wooden building with 208 guest rooms. The building is so far the largest wooden building made with prefabricated wooden modules in Denmark (Danmarks største træbyggeri - uden synligt træ - Træ.dk (trae.dk)).

Photo: Main entrance
(by Mihoko Goto Brethvad /
VIA University College)

Photo: Reception and café/bar
on the ground floor
(by Mihoko Goto Brethvad /
VIA University College)

Design and structural principles

The guest rooms in the Moxy Hotel were produced in a prefabricated module system of boxes in which the CLT elements were made in Austria and then assembled along with the installations and plaster, et cetera, at a factory in northern Italy. Afterward, the wooden modules arrived at the construction site in Copenhagen, where they were simply lifted into position and assembled together (Danmarks største træbyggeri - uden synligt træ - Træ.dk (trae.dk)).

Using the module system allowed building six guest rooms a day with a team of 8–9 workers. Then, a few more days were spent on preparing the construction site, finishing the interior, and assembling the façade (København får hotel i træ: 208 værelser skal være klar på tre måneder | Ingeniøren).

The advantages of the prefabricated module method is that it shortens the construction process and ensures high quality products. However, one remaining problem is that an excessively long transport distance is inconsistent with strategies to reduce CO2 emissions.

Concrete was used to build the ground floor, where the lobby, reception, and the café/bar are located, while the upper four floors are built of prefabricated wooden modules. The staircases and elevator shafts are also made of concrete (København får hotel i træ: 208 værelser skal være klar på tre måneder | Ingeniøren).

Photo: Lounge and café/bar on the ground floor (photo by Mihoko Goto Brethvad / VIA University College)

Materials and finishes

To comply with the regulatory 120 minutes of fire resistance, the wooden elements are cladded with plaster. Comparative analysis shows that this is just as safe as if it had been built in concrete or steel (København får hotel i træ: 208 værelser skal være klar på tre måneder | Ingeniøren).

The guest rooms have plasterboard cladding on the ceilings and walls, with carpeted floors. The wooden elements are invisible.

Photo: Guest room
(by Mihoko Goto Brethvad / VIA University College)

The façade is clad mainly with corten steel (weathered steel).

Photo: Façade (photo by Mihoko Goto Brethvad / VIA University College)

Resource consumption in the use stage

According to calculations by TimberDesign LT, the Moxy Hotel uses approx. 2,000 m3 of CLT and stores approx. 1.3 million kilos of CO_2 in the building ([Danmarks største træbyggeri - uden synligt træ - Træ.dk (trae.dk)](trae.dk)).

Source

Træ.dk, Danmarks Træportal (2018). *Danmarks største træbyggeri – uden synlit træ*. Retrieved 19th of February 2022 from: Danmarks største træbyggeri - uden synligt træ - Træ.dk (trae.dk)

ING (2018). *København får hotel i træ: 208 værelser skal være klar på tre måneder*. Retrieved 19th of February 2022 from: København får hotel i træ: 208 værelser skal være klar på tre måneder | Ingeniøren

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Urban Development, Københavns Kommune (n.d.). *The CPH 2025 Climate Plan*. Retrieved 19th of February 2022 from: The CPH 2025 Climate Plan | Urban Development (kk.dk)

9.3. Knudrisrækkerne

Location: Aarhus, Denmark

Functional type: Residential (social housing units)

Architects: SWECO

Client: Boligkontoret Aarhus

Duration of construction: Begun in 2019, still under construction as of February 2022

Number of floors: 5

Cost: 110 m DKK (approx. 14.8 m €)

Photo: Façade facing Knudrisgade Street (by Mihoko Goto Brethvad / VIA University College)

Description of the building

This new wooden building with 89 social housing units is situated on Knudrisgade Street in Aarhus. This location was previously the site of the Population Register Office, which was closed in 2017 and afterward designated to become a youth cultural centre. Thus, the area has become very familiar to all citizens (Knudrisrækkerne i Aarhus C (sweco.dk)).

The project aims to provide a communal space for the local area – not only for the residents of the housing units, but also for the surrounding local community. An unusually sustainable concept was adopted, where the local history is taken into account by reusing parts of the existing building. Therefore, the main concepts are community, unusual public housing, and upcycling (Knudrisrækkerne i Aarhus C (sweco.dk)).

Photo: Façade facing Knudrisgade Street (photo by Mihoko Goto Brethvad / VIA University College)

Photo: Façade toward courtyard (photo by Mihoko Goto Brethvad / VIA University College)

Design and structural principles

The buildings are made of wood, concrete, and steel in a hybrid construction That applies a column-beam-slab system. Several load-bearing pieces are made of wood and cladded with fireproof plasterboard.

The staircases and elevator shaft are made of concrete.

Photo: Glulam columns, concrete staircase and elevator shaft
(by Jerry Bak de Ridder / VIA University College)

Photo: Ground floor (by Jerry Bak de Ridder / VIA University College)

Photo: Joint between glulam column and steel beam (by Jerry Bak de Ridder / VIA University College)

Photo: Ground floor – glass panels are placed, and beams and first floor slabs are cladded with fireproof plasterboard. (by Mihoko Goto Brethvad / VIA University College)

Photo: Wooden deck slab is casted concrete, and wooden wall is cladded with fireproof plasterboard. Ceiling will be placed later. (by Mihoko Goto Brethvad / VIA University College)

Materials and finishes

Because Knudrisrækkerne must be built sustainably, both construction and long-term operation must reduce CO_2 emissions, which is why the project has prioritized efforts to use upcycled materials.

Aluminium ceiling plates were upcycled for the new façade, and the existing building's windows have been upcycled as a part of new distinctive double-height window. These upcycled materials provide the new building with visible sustainability and express the history of the old building (Knudrisrækkerne | Q-Construction (qconstruction.dk)).

Photo: Upcycled window in the new façade
(by Mihoko Goto Brethvad /
VIA University College

The apartments are finished with wooden parquet floors and plasterboard for the interior walls and ceilings. All the wooden materials are invisible.

Photo: Apartment interior - wooden elements are invisible
(photo by Mihoko Goto Brethvad / VIA University College)

Resource consumption in the use stage

The above measures help raise the DGNB score and ensure that the client obtains a gold certificate. The criteria for life cycle, environment, demolition, and recycling will especially score high (Knudrisrækkerne i Aarhus C (sweco.dk)).

Source

Sweco (n.d.). Knudrisrækkerne - Nyt træhusbyggeri til Aarhus fra udtjente loftsplader til levende facader. Retrieved 19th of February 2022 from: Knudrisrækkerne i Aarhus C (sweco.dk)

Q-Construction (n.d.). Knudrisrækkerne. Retrieved 19th of February 2022 from: Knudrisrækkerne | Q-Construction (qconstruction.dk)

9.4. Mjøstårnet (Mjøsa Tower)

Location: Brumunddal, Norway

Functional type: Mjøstårnet consists of offices, technical rooms, 32 apartments, 72 hotel rooms, one hotel suite on level 15, a cafeteria, a restaurant, a conference room on level 17, and a rooftop terrace.[2]

Architects: Voll Arkitekter. Architect In Charge: Øystein Elgsaas. Design Team: Kathrine Slørdahl Skjærpe, Claudia Arnaut.

Client: AB Invest

Year of construction: 2019

Duration of construction: From April 2017 to March 2019

Height: 85.4 meters

Number of floors: 18

Cost: Contract was valued at about NOK 450 million (approx. 52 million euros) excluding VAT.

[2] Abrahamsen, R. (2017). Mjøstårnet - Construction of an 81 m tall timber building. Moelv, Norway: Internationales Holzbau-Forum IHF 2017.

Photo: Mjøstårnet (by Paulius Milčius)

Description of the building

Mjøstårnet is located in Brumunddal, a small city of 10,000 residents that is about a one-and-a-half-hour drive north of Oslo. Mjøstårnet is a Norwegian name that means

“The tower of Lake Mjøsa”. Mjøstårnet (Mjøsa Tower) is a mixed-use building with 18 storeys at an official height of 85.4 meters, thus granting it recognition by the Council on Tall Buildings and Urban Habitat as the world’s tallest timber building. With a footprint of only 17 m in width and 37.5 m in length, each floor covers about 640 m^2. The total floor space of the tower is about 10,500 m^2, with an additional 4,900 m^2 dedicated to a public bath.

The ground floor is open to the public, with a lobby, reception area, and restaurant. The building is complemented by a public swimming pool with two 25-meter-long pools in the low-rise building adjacent to the tower. One storey above the entrance level is where the building services and conference floors are. Next are five office storeys and a four-storey hotel with 72 rooms. Thirty-three residential units with balconies overlooking the lake are on floors 12–16. The top two floors are divided into three further residential units, an exhibition room, and a public viewing terrace on both the 18^{th} and 19^{th} floors.[3]

[3] https://www.archdaily.com/934374/mjostarnet-the-tower-of-lake-mjosa-voll-arkitekter

Photo: Mjøstårnet (by Paulius Milčius)

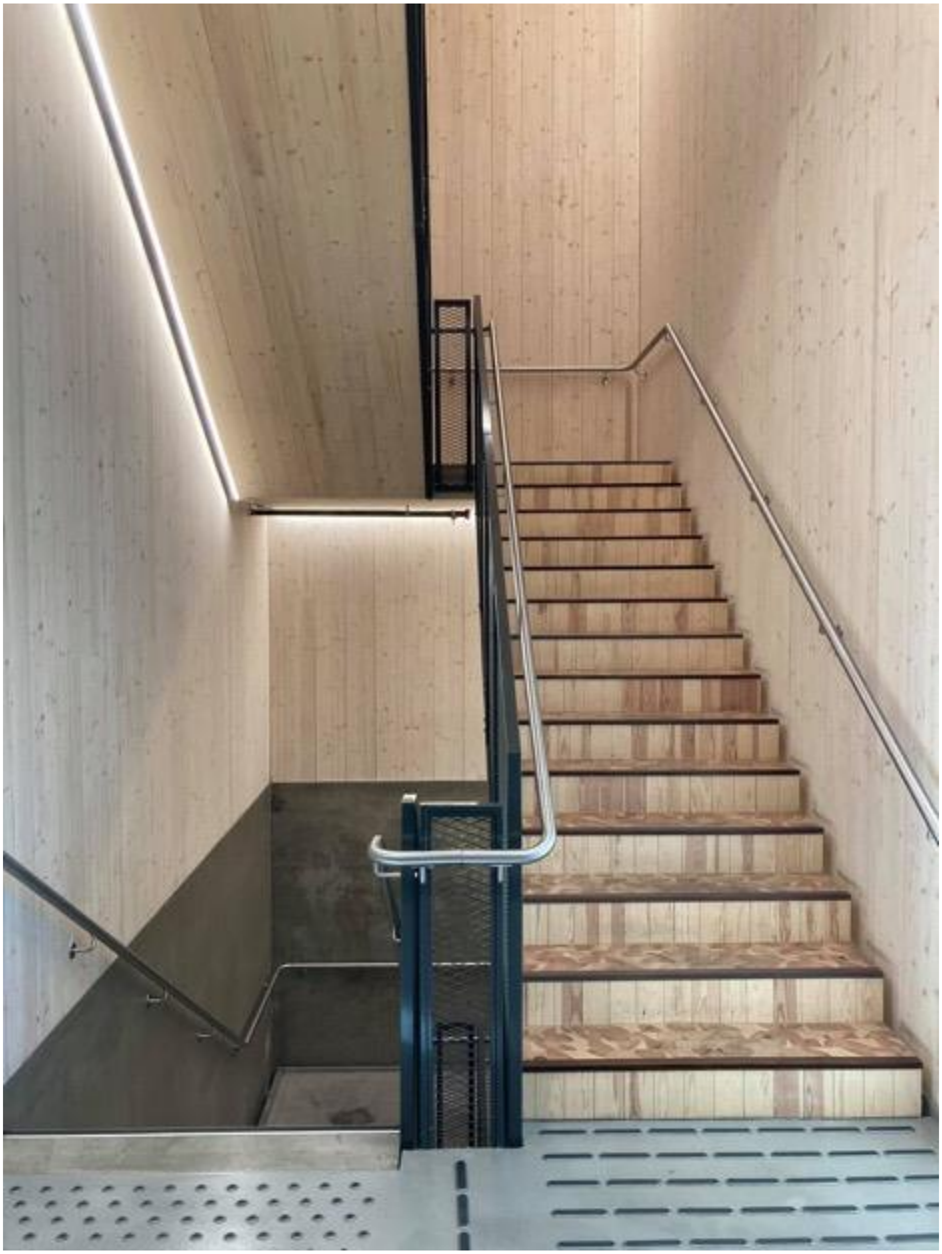


Photo: Mjøstårnet (by Paulius Milčius)

Design and structural principles

The design approach for Mjösa Tower comes from the Norwegian tradition of using wood in architecture. It was hoped that this approach to building the tower would inspire others to build the same way.[4]

The load-bearing structure is similar to conventional buildings, but the dimensions of the elements are much larger than usual: The wooden columns were 60 × 60 centimetres on average, and the largest ones used in the corners were almost 60 × 150 centimetres. The narrow yet wide shape of Mjösa Tower is ideal for hotel rooms.[5]

The Moelven Limtre company produced and installed the glulam columns, beams, and diagonals for the primary load-bearing system, which consists of large-scale glulam trusses along the façades as well as internal columns and beams. The trusses handle the global forces in the horizontal and vertical directions and give the building its necessary stiffness. CLT walls are used for secondary load-bearing for three elevators and two staircases. CLT was also used for the elevator shafts and balconies, and Trä8 deck slabs were used for the floors up to level 11. Large prefabricated façade elements are attached to the outside of the timber structures and make up the envelope of the building. These sandwich-type elements come with incombustible insulation and external panels that were already fixed.

Mjøstårnet was assembled four storeys at a time, in five construction stages, and without external scaffolding. Instead, the project used a large crane and internal scaffolding combined with lifts. First, the glulam structure was assembled on the ground next to the building, then hoisted up and in. Next, the floor slabs were hoisted into place. Ringsaker Takelementer AS installed the external façade, followed by Moelven, who proceeded with the assembly upwards.[6]

Materials and finishes

Both the structure and façade of Mjøstårnet are made of wood.

Mjøstårnet's footprint is about 17 x 37 m^2. A concrete slab on the ground floor is supported by piles driven into the bedrock below. The main load-bearing structure consists of large-scale glulam trusses along the façades as well as internal columns and beams. The trusses handle the global forces in the horizontal and vertical directions, thereby giving the building its necessary stiffness. CLT walls are used as secondary load-bearing for the three elevators and two staircases. The CLT does not contribute to the building's horizontal stability.

[4] https://www.metsawood.com/global/news-media/references/Pages/Mjosa-Tower-worlds-tallest-wood-building.aspx

[5] https://www.metsawood.com/global/news-media/references/Pages/Mjosa-Tower-worlds-tallest-wood-building.aspx

[6] https://www.moelven.com/mjostarnet/

Powder coated S355 steel is used in connections combined with acid-proof steel dowels. The wooden cladding has fire retardant properties.

While floors 2 to 11 are prefabricated wooden decks based on Moelven's Trä8 building system, floors 12 to 18 are 300 mm concrete floors that are a composite of a prefabricated bottom part that acts as formwork for a cast-in-place upper part. Replacing wood with concrete in the upper floors means the building will be heavier towards the top. This building is slender in its weak direction, so the extra mass is necessary to comply with comfort criteria for the apartments. The concrete decks also make it somewhat easier to deliver a high-standard acoustic performance in the upper-level apartments.

All glulam elements are connected by use of slotted-in steel plates and dowels. These are high-capacity connections that are commonly used in bridges and large buildings. The structural timber is on the inside of the façade and glass elements, which protects the timber from rain and sun, increases durability, and reduces ongoing maintenance needs. It also lets the glulam breathe freely on the inside.

All glulam surfaces are painted with one layer of varnish. Visible surfaces are painted with a top layer. The end grain of columns at the ground floor are sealed with epoxy, while the exposed end grain of column tops and exposed sides of LVL are also protected. To ensure correct handling of the wood on site, a moisture control plan was developed for measuring and monitoring the moisture content of specified parts of the structure. [7]

On the roof is an apartment and pergola to give the building a distinct architectural look. The pergola is a large wooden structure that is fixed to the concrete deck on level 18.[8]

[7] https://www.timbertradernews.com/2018/02/05/norwegian-wood/
[8] https://www.moelven.com/globalassets/moelven-limtre/mjostarnet/mjostarnet---construction-of-an-81-m-tall-timber-building.pdf

Resource consumption in the use stage (water, energy, etc.)

Mjøstårnet is made from about 3,500 m^3 of timber, constituting about 14,000 trees. Untreated Norway spruce is the main species used for the structural timber parts.

Mjøstårnet is designed to produce the same amount of energy as it spends by means of solar thermal energy, solar panelling, and ground and water heat pumps.[9]

Additional information (awards, etc.)

The Council on Tall Buildings and Urban Habitat (CTBUH) amended the official guidelines for evaluating tall buildings and added timber as a recognized structural material. The revised criteria state that the main structural elements and the floor spanning system must be constructed from timber, though there can be localized non-timber connections. The change coincided with verifying the completion of Mjøstårnet, which now has the unique title of World's Tallest Timber Building[10].

[9] Abrahamsen, R. (2017). Mjøstårnet - Construction of an 81 m tall timber building. Moelv, Norway:Internationales Holzbau-Forum IHF 2017.

[10] CTBUH (2022, July). Retrieved from https://www.ctbuh.org/buildings-of-distinction/mjostarnet.

9.5. Skellefteå Cultural Centre / Sara Kulturhus

Location: Skellefteå, Sweden

Functional type: Cultural centre, hotel with restaurant, bar, spa, and conference centre.

Architects: Architecture studio White Arkitekte. Lead architects: Oskar Norelius, Robert Schmitz.

Client: Skellefteå Municipality (competition organised in collaboration with the Swedish Association of Architects).

Year of construction: Autumn 2021.

Duration of construction: 2016–2021

Height: 76 m.

Number of floors: 20

Cost: 105000000 EUR (approx.)

Photo: Skellefteå Cultural Centre (Wikimedia Commons)

Description of the building

The Sara Kulturhus is located in Skellefteå on the Gulf of Bothnia, just below the Arctic Circle. It provides a home for the city's gallery, the Anna Nordlander art museum, the

Västerbotten regional theatre, a municipal library, and The Wood Hotel, which contains a restaurant, spa, and conference centre.[11]

Site area: 30,000 m^2; gross floor area: 28,000 m^2 (17,000 m^2 for the cultural centre and 11,000 m^2 for the hotel).

The building was designed to be open in all directions in order to activate the surrounding streets. The grand foyers are overhung with glue-laminated timber (GLT) and steel hybrid trusses, which allow an open-plan space that is adaptive to a range of functions. Beyond showcasing the flexibility of timber, the project was also designed to function as a cultural community hub. At the street level, timber volumes have varying degrees of scale and transparency that grant a human scale to the project, with smaller-sized volumes adjacent to the narrow streets around the city centre, where the grandeur of the high-rise hotel faces the town square.

The centrally located building features a double-skin glass façade that offers both literal and figurative transparency. This transparency serves as an invitation to the shared community programs within while also reflecting the Nordic sky. Multiple points of entry further enhance the welcoming atmosphere. The two ground floors are fully accessible and are centred around an unprogrammed public living room and stage for social engagements and performances. Surrounding this are a number of satellite foyers used as gallery and exhibition spaces that can be modified according to future needs and uses.[12]

The library, galleries, public living room, and grand foyers work together to create an open-plan space surrounded by workshops that “celebrate the craft behind the creative process”.

Design and structural principles

White Arkitekter designed this archetypal building using locally sourced timber as a sustainable structural material. The wood was processed in a sawmill roughly 50 km from the site. The columns, beams, slabs, and walls were prefabricated in a local off-site factory and simply assembled on site. The Sara Cultural Centre’s timber structure appropriates more than twice the carbon emissions caused by operational energy and embodied carbon from the production of materials, transportation, and on-site construction.

In collaboration with the structural engineers Dipl. -Ing. Florian Kosche, two different construction systems were developed for the cultural centre and hotel. The high-rise

[11] https://www.globalconstructionreview.com/white-arkitekters-75m-tall-timber-built-cultural-centre-and-hotel-opens-in-swedish-lapland/

[12] https://archello.com/news/newly-opened-sara-cultural-centre-demonstrates-the-viability-of-timber-as-a-sustainable-and-innovative-highrise-and-complex-building-material

hotel, which is presently the world's fourth highest timber building, is built from prefabricated CLT modules stacked between two CLT elevator cores. The low-rise cultural centre is built with columns and beams of GLT with CLT walls. The structural design eliminated the need for concrete to beef up the load-bearing qualities of the 30,000 m^2 building.[13]

In addition to the timber is a double-skin glass façade that reveals the timber core structure, while GLT–steel hybrid beams are used to avoid columns in the atrium. The glazing process of this building required producing a total of 800 m^2 of glass panes, including triple glazing with a construction of 6 / 16Ar / 4/16 / 8.76T (VSG 44.2T). These units are characterized by the use of hardened and HST tested Sunguard SNX 60 HT solar control glass. On the inside, safe VSG glass with a low-emission coating was used.[14]

Materials and finishes

Structural materials: massive wood, GLT and steel hybrid trusses, concrete, prefabricated CLT modules.

Façade materials: wood-clad panels and louvres, structural glazing.

Resources consumption in the use stage (water, energy, etc.)

Sara Cultural Centre showcases the latest energy-based solutions. ABB, a local energy firm and power technology company, implemented smart solutions to build this sustainable property. To achieve 100% renewable energy, the property's power system is optimised and integrated with the city's central energy solutions using new smart algorithms.[15]

Additionally, solar panels on the roof produce renewable energy that, along with the timber structure, compensate for the CO_2-emissions produced by the building. The building was designed to have a lifespan of at least 100 years and will be carbon negative within 50 years.[16]

Additional information (awards, etc.)

[13] https://whitearkitekter.com/news/sara-cultural-centre-opens-one-of-the-worlds-tallest-timber-buildings/

[14] https://lignas.eu/news/sara-kulturhus-wood-and-glass-in-an-impressive-symbiosis/

[15] https://smartcitysweden.com/best-practice/394/sara-cultural-centre-one-of-the-worlds-tallest-timber-buildings/

[16] https://www.theplan.it/eng/architecture/sara-cultural-centre-in-skelleftе%C3%A5-sweden-a-magnificent-state-of-the-art-green-building

Sara Cultural Centre received the MIPIM (Le Marché International des Professionnels de L'immobilier) Future Project Award in 2018 and was nominated for WAF 2018 and the MIPIM Awards 2018, in the category of Best Futura Project. MIPIM is an internationally renowned real-estate competition.

The building was certified according to Miljöbyggnad Silver. This means that the building must be energy efficient, which places high demands on the installations.

9.6. Valle Wood

Location: Oslo, Norway

Functional type: Office building

Architects: Lund & Slaatto Arkitekter AS

Client: NCC

Year of construction: 2019

Duration of construction: From 2017 to 2019

Height: 22.74 m

Number of floors: 7 floors

Cost: The total contract value of Valle Wood and Valle View was SEK 2 Bn (approx. 194 mil. euros)

Photo: Valle Wood (by Paulius Milčius)

Description of the building

Situated in Oslo, Valle Wood – with its 6,700m^2 of office space – is the largest massive commercially used wood construction project in Norway. The project took a holistic and highly ambitious approach to environmental protection in the construction phase by minimising energy use, waste, transport, and the use of chemicals. The building has a green roof and has been certified BREEAM excellent, which takes a full view of the building's entire lifecycle perspective.[17]

Photo: Valle Wood (by Paulius Milčius)

[17] https://norden.diva-portal.org/smash/get/diva2:1297443/FULLTEXT03.pdf

Photo: Valle Wood (by Paulius Milčius)

Design and structural principles

Valle Wood was designed with a distinct identity that stands out from the surrounding concrete and steel buildings, thanks to its dynamic wood façade. Inside the building, wood is the dominant material; even the elevator shaft and stairs between floors are made from wood.[18] Posts and beams throughout the project have been left visible for better indoor climate and acoustics. The façades were inspired by wood fibres and annual rings, whose variations in density are visible in open and closed sections, depending on the sun conditions and points of view. The dynamic façade's wood cladding will, over time, fade and change with the weather and seasons, thereby taking on a silver patina.[19]

Materials and finishes

[18] https://norden.diva-portal.org/smash/get/diva2:1297443/FULLTEXT03.pdf
[19] https://www.bdcnetwork.com/valle-wood-norways-largest-commercial-building-made-solid-timber

The building is constructed of glulam columns and beams, CLT shafts, and timber–concrete composite floors. The glulam beams and columns are Norwegian produced, while all the massive wood panels and slabs are from an Austrian CLT producer.

Valle Wood was built with a combination of spruce and pine.

Resources consumption in the use stage (water, energy, etc.)

Valle Wood has been awarded the BREEAM Excellent certificate for consuming 40% less energy than equivalent office buildings and storing 1300 tonnes of CO_2 equivalent emissions in the building structure.[20]

Additional information (awards, etc.)

Valle Wood was a lighthouse project intended to demonstrate how maximising wood in the construction of office buildings can benefit both the environment and the people working inside, and it has thus successfully set a new standard for office buildings in Norway.[21]

[20] https://norden.diva-portal.org/smash/get/diva2:1297443/FULLTEXT03.pdf
[21] https://norden.diva-portal.org/smash/get/diva2:1297443/FULLTEXT03.pdf

9.6. Cirerers building

Location: Carrer del Pla dels Cirerers, 2-4, Barcelona (Spain)

Functional type: Collective housing

Architects: Celobert SCCL

Client: Sostre Cívic SCCL

Year of construction: 2021

Duration of construction: 19 months

Height: 24m.

Number of floors: 8 (Ground floor +7)

Cost: ---

Main façade of the Cirerers building (by Joan Guillamat)

Description of the building

Cirerers is an 8-storey community building (PB + 7) that houses 32 cohabitation units and occupies a total of about 2,700 m² built on a public plot of 430 m². The architecture of this building responds to a collective commitment and is the result of a participatory process between future users and the technical team of the project.

The project is conceived as an urban piece that articulates an old fabric of small single-family houses between partitions and another of more contemporary and massive. It also ensures that the existing PB + 2 skyline is maintained along the entire façade of Pla dels Cirerers Street and resolves the five floors above it through a stepping stone that adapts to the topography of the land.

The spaces that make up a cohabitation building are the collective and community spaces. In the case of Cirerers, four types of spaces are proposed, which are defined by their degree of openness and connection with the community:

- Open spaces in the neighbourhood, located on the ground floor, where there is more relationship and connection with the public space. On the corner that connects with the square is the Social Economat, a hybrid space between a consumer cooperative and a shop selling organic and local products. There is also a multipurpose space on the ground floor, which can be used both by the members of Cirerers and by people and entities external to the project.
- Spaces for a community use defined by Cirerers users themselves; they consist of 240 m² of community space on the ground floor and 240 m² of outdoor terraces. The latter are located on the roofs of the 3rd, 6th and 7th floors and can be used as a community dining room, for outdoor recreational activities and for a vegetable garden.
- Spaces for intermediate collective use, which is neither 100% private nor 100% community. It is a covered outdoor space of about 240 m² distributed over six floors which, in addition to giving access to housing and housing the shared laundry on each floor, will be a space for the expansion of the homes themselves and the relationship between the neighbours.
- Spaces for private use (32 in total), for exclusive use for each cohabitation unit and with three different types, most of which have an outdoor area: 22 apartments between 40-45 m², 5 apartments on the corner of between 60-65 m² and 5 apartments of between 60-65 m².

Facade facing the Square de les dones de Nou Barris (by Joan Guillamat)

Interior view of the Cirerers building (by Guifré de Peray)

From left to right and from top to bottom: first and second floor, third floor, fourth and fifth floor and finally sixth floor (by Celobert SCCL)

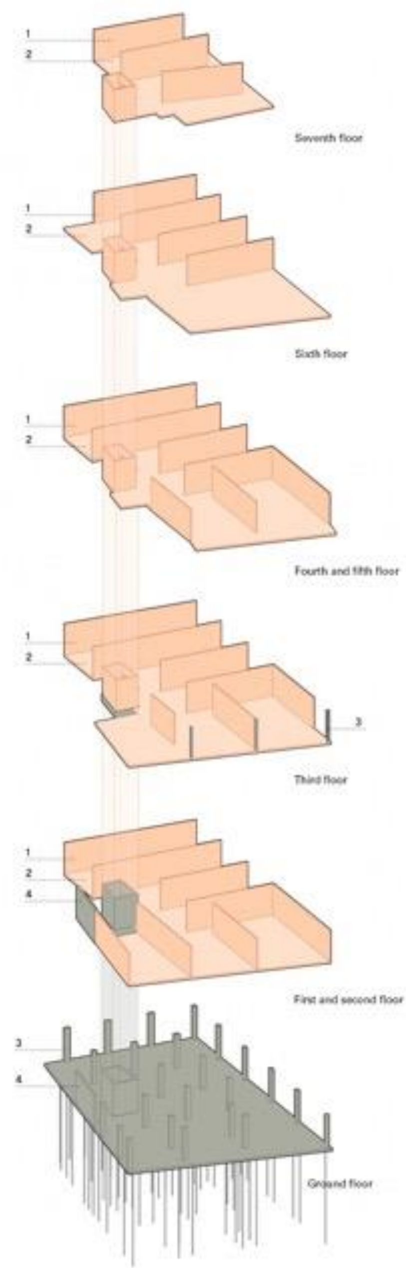
Design and structural principles

Cirerers is a building that consumes very little energy, its construction process has generated a minimal ecological footprint and incorporates efficient and renewable facilities. These three strategies make it a building that moves away from traditional constructions because it has been designed with the environmental cost associated with the manufacture, transport, commissioning and future recycling of the building to be minimal, and for a once in operation, it has reached a level of efficiency of a passive house or almost zero consumption building (nZEB) that will go beyond what is required by current energy saving regulations.

The design of the building has taken into account that the living space that will be air-conditioned has a minimum surface area in contact with the outside and that it has good thermal insulation.

The geometry of the building, as well as the dimensions and position of the openings of the facades have been designed in order to protect the building from the sun's entrances in summer and to take advantage of them in winter, favouring the natural light input and minimizing heat loss.

The cantilever elements such as the south and east façade balconies, as well as the position of the exterior shutters, are fundamental elements for the control of solar radiation that have been designed based on the simulation of shadows of the whole envelope.



1 Cross laminated timber walls
2 Cross laminated timber slabs
3 Combined metal structure
4 Reinforced concrete structure over piles

Inner courtyard and access to the houses (by Guifré de Peray)

Facade of the building during the construction process (by Guifré de Peray)

Materials and finishes

The main building materials used are:

- Cross laminated timber (CLT), of Austrian origin (in the structure and façade enclosures of the whole building above the ground floor).
- Lime mortar, used as exterior cladding for all facades.
- Gypsium fiber panels, used as acoustic coating between homes and for interior partitions. It is a material composed of gypsum and cellulose fiber, obtained from paper recycling, and without any other binder or chemical, which is placed dry.
- Rock wool, used as thermal and acoustic insulation throughout the building. It is a material of natural origin and recyclable.
- Dry construction above the ground floor, without wet binders (mortars, concretes, gypsum), with the exception of the exterior coating of lime mortar and the interior tiles of the bathrooms.

Resources consumption in the use stage

The Cirerers building has been designed so that the houses reach a very high level of water tightness, taking special care of the watertight line (the whole envelope has a solution that prevents air infiltration. unwanted). It is expected to reach a tightness value of n50 <= 1.7 / h. Kitchens are also expected to use two different smoke extraction systems:

- The recirculation one that will circulate by default (more efficient and watertight because it will not expel air to the outside), with an extractor hood with carbon or plasma filters.
- The extraction one (the one required by regulations), by means of the conventional hood that will expel fumes to the outside, with the consequent loss of tightness.

In addition to natural ventilation, all homes have a controlled mechanical ventilation (VMC) system that constantly renews the air in all rooms of the home, minimizing heat loss and avoiding having to open windows. This is possible thanks to a heat recuperator that takes advantage of the thermal energy of the air before being expelled for its renewal. The recuperator fans move the air in two different directions: one to remove the damp, foul-smelling air to the outside and the other to re-enter it once it has been filtered and tempered.

To get the most out of this ventilation system, a battery is incorporated into the recuperator of each home to increase or decrease the temperature of this air, taking advantage of the centralized air heating system to produce cold and heat. This system consists of high-performance heat pumps, which are stored in the form of heated or cooled water in centralized accumulators. This whole system is located on the seventh floor of the building. There are 3 batteries that each have the following function:

- Store domestic hot water that is distributed by pipes to all points of consumption in homes.
- Anti-legionella treatment of domestic hot water from the smallest accumulator.
- Store hot or cold water to cool (in summer) or heat (in winter) the air in the ventilation system of the homes using the batteries mentioned above.

On the roof of the seventh floor there are solar capture areas to produce electricity for self-consumption with photovoltaic panels of about 8 kWp.

Additional information

Advanced Architecture Awards 2022, Aldes Award for Sustainability, decarbonisation or greater self-generation of energy in a building.

It is currently the tallest wooden building in Spain.

9.8. La Borda building

Location: Constitució 85-89, Barcelona (Spain)

Functional type: Collective housing

Architects: Lacol SCCL

Client: Habitatges La Borda, SCCL (private)

Year of construction: 2018 (begun in 2017)

Duration of construction: 20 months

Height: 24m aprox.

Number of floors: 7 (Ground floor+6)

Cost: 840 €/m2

View of the building from Carrer Constitució (by Laia Haurie)

Description of the building

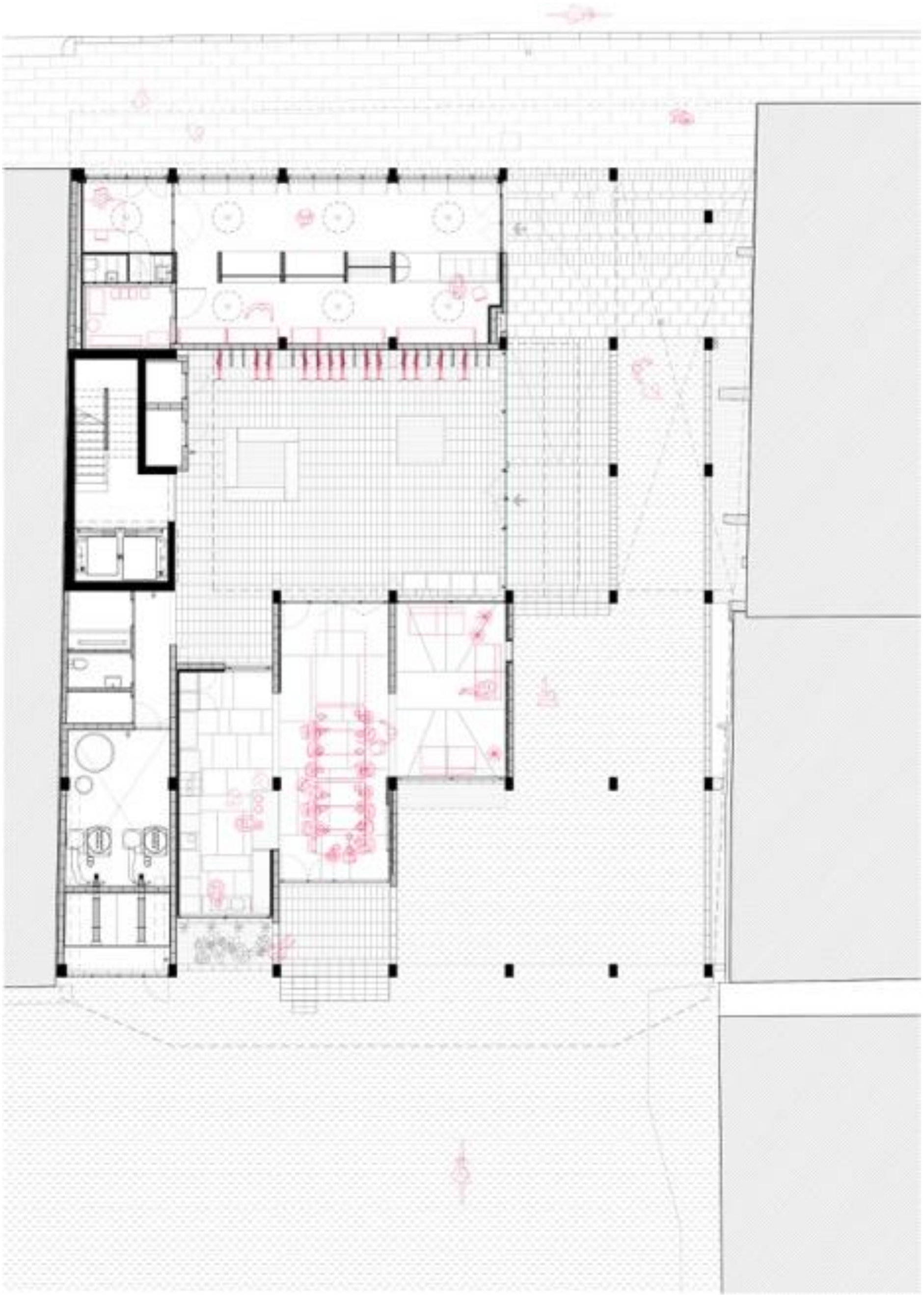
La Borda cooperative housing was born from the creation of the cooperative of the same name, with the aim of managing the promotion in a self-organized way by its users to access a decent, non-speculative home that puts its use value at the center, through of a collective structure.

The building is located on a plot of land (VPO) ceded by the city council for 75 years on Constitució street, located in a position bordering the Can Batlló industrial complex with a façade facing the historic fabric of the Bordeta neighborhood, in the city of Barcelona.

At the time of its construction, La Borda was the tallest building built with a wooden structure in Spain.

Rear facade of La Borda building (by Lacol Arquitectura Cooperativa)

Inner courtyard view (by Lluc Miralles)



Ground floor plan (by Lacol Arquitectura Cooperativa)

First, second, third and fourth floor plan (by Lacol Arquitectura Cooperativa)

Fifth and sixth floor plan (by Lacol Arquitectura Cooperativa)

Design and structural principles

The building program is structured in 28 dwellings with variable surfaces (40, 60 and 75m²) and spaces for community use that allow community and neighborhood life to be promoted. These spaces are: kitchen-dining room, laundry, multi-purpose space, space for guests, health and care space, storage by floors, and exterior and semi-exterior spaces such as the patio and the roof terraces. The community spaces are articulated around a central courtyard reminiscent of the "corralas", a type of popular housing in central and southern Spain.

The building has been built with the aim of reducing the initial demand of all the environmental factors of the building (energy, water, materials and waste), especially at the energy level, for which passive strategies have been prioritized to achieve maximum use of existing resources.

The central courtyard is a semi-outdoor and open space, which allows cross-ventilation of all homes in the summer and moderates the common space naturally in winter.

The roof of this space is made up of a large polycarbonate lantern, measuring 9.5 x 22.50 m, which, using temperature and rain sensors, opens and closes the floodgates to reach the set temperature in the common areas.

Section of La Borda building (by Lacol Arquitectura Cooperativa)

Perspective section (by Lacol Arquitectura Cooperativa)

Materials and finishes

The structure of the building is made of wood. It is a system that is prepared in a workshop on project plans and can be assembled in just 17 days with the help of a crane. The walls and ceilings up to the sixth floor are made of 10 and 12 cm cross-laminated panels (CLT) and, in some cases, such as the stairwell, 30 cm thick. The reasons for using these construction solutions lie in the lightness of the material compared to concrete, as well as in the negative contribution of wood in terms of CO_2 emissions.

Only the contact with the ground is solved as reinforced concrete: both the foundation and the structure of the ground floor are made with this technology on site. The foundation is a reinforced concrete slab, above which there is a sanitary slab that functions as a cooling air chamber, allowing air currents to be established between the sanitary slab and the roof that contribute to cooling the courtyard environment.

Resources consumption in the use stage

The building does not have parking spaces as there is no basement. The preferred means of users are cycling, public transport or walking. This significantly reduces the environmental impact, which, valued at 75 years, allows for savings of between 500 and 800 T of CO2 in the environment.

From the beginning, the building has been designed to minimize the demand for energy from fossil resources. To this end, the materials used, the construction solutions, the orientation of the spaces, etc. have been studied. By combining radiation, ventilation and insulation, an acceptable level of comfort is achieved, especially inside homes. The label obtained in the energy efficiency assessment is the maximum, an A.

Domestic hot water and heating are generated from a community pellet boiler located on the ground floor.

Additional information

City of Barcelona Award 2018.

BBConstrumat 2019 Built in Architecture Award.

Awarded in the 3rd edition of the Mostra d'Arquitectura Catalana de Barcelona.

Special Innovation Award at the European Responsible Housing Awards 2019.

Winner of the Catalunya Construcció Awards 2019, category of Construction Management (also selected in the category of Innovation in Construction).

Selected for the XV Spanish Biennial of Architecture and Urbanism 2021.

Honorable Mention for the Fassa Bartolo 2021 International Award for Sustainable Architecture.

Zumtobel Group Award 2021.

Special mention in the European Architecture Prize Matilde Baffa Ugo Rivolta 2021.

Emerging winner in the European Union Prize for Contemporary Architecture Mies van der Rohe Awards 2022.