

# 1

## Timber as a Structural Material

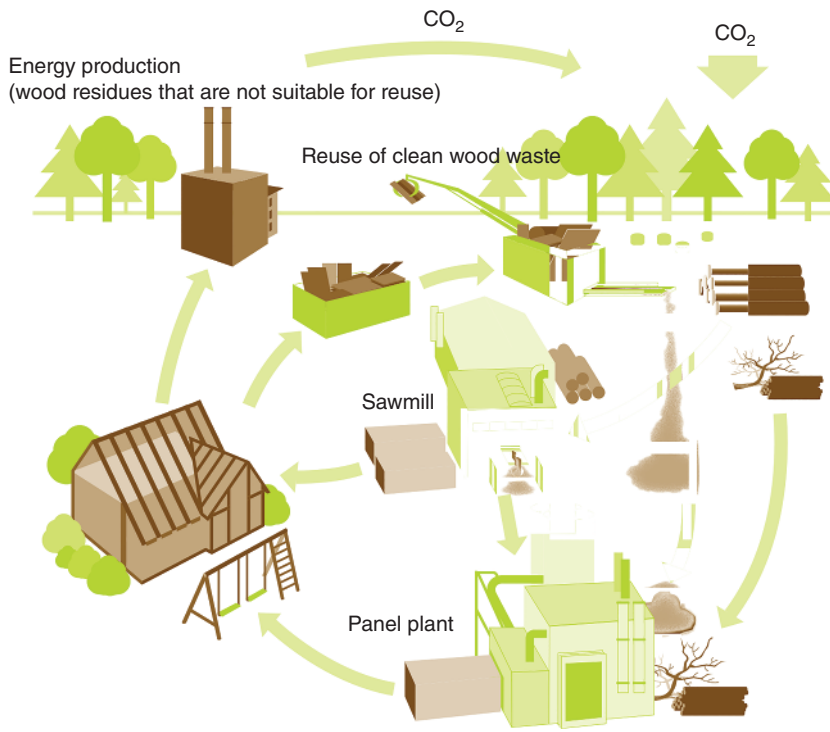
In this chapter, the most important physical properties of wood are described with regard to its use as a construction material. These include fibre structure, irregularities and moisture absorption and release. Timber and wood-based materials used in construction are introduced and their mechanical properties are presented.

With regard to the manifold topics of wood physics and wood chemistry, selected literature for further reading is recommended and listed.

### 1.1 Building with Timber: Advantages and Challenges

Alongside masonry using natural stones, timber construction is one of the oldest building methods known to humankind. Until the industrial production of steel profiles, timber was the only building material available for beam-type building components subjected to normal forces and bending moments. In the course of history, carpenters developed a multitude of applications for this comparatively easy-to-handle material. Timber has been used for roof constructions, timbered-framed buildings, bridges, ships and much more. Wood is locally available in most regions of the northern hemisphere and can be transported from the forest via the sawmill to the construction site in a short span of time. Timber is the only natural growing material that is widely used for building constructions and other load-bearing structures. Wood has excellent potential for optimised cascade use, as depicted schematically in Figure 1.1.

In Europe, approximately 35% of the land area is forested. Finland tops the list with over 70%, while Ireland with 10%, is among the countries with sparse forests. Monaco is the only country without any forests. Forests store significant amounts of CO<sub>2</sub> through photosynthesis. Burning or rotting of wood releases as much CO<sub>2</sub> as was absorbed from the atmosphere during its growth. When wood is used as a construction material in buildings or other structures, the CO<sub>2</sub> remains sequestered for the entire lifespan of the building. The management of forests follows the principle of sustainability: only as much wood is harvested per year as will regrow during that time. Wood, as a natural material, can be destroyed by fungi or insects under certain conditions. Thus, the service life of wooden structures depends significantly on



**Figure 1.1** Cascade use of wood in the construction sector. Source: VHI Verband der deutschen Holzwerkstoffindustrie (Association of the German Wood-based Materials Industry).

the construction details and the selected preservation method. The fact that wooden buildings can last several hundred years with the right construction and care is evidenced by the numerous mediaeval roof constructions and half-timbered houses that have been preserved throughout Europe, some dating back more than 800 years.

The most characteristic feature of timber construction is in the connections. In addition to the traditional joints, the twentieth century witnessed an increasing development of new joining techniques in timber construction. The development of adhesive bonding technology, and the associated possibility of producing timber cross sections regardless of the dimensions of the trees, has continuously expanded the potential applications of timber construction. Today, sports halls and exhibition halls, multi-storey residential and commercial buildings, industrial buildings as well as towers and bridges are designed and constructed in timber.

## 1.2 Mechanical Properties of Solid Timber

Wood is a natural material, and every wooden component was once part of a tree. Since it is hardly possible to influence the ‘production’ of wood as a material, the mechanical properties are subject to the conditions of natural growth.

The properties of the subsequent timber component are fundamentally influenced by the direction of the fibres, the density, and the irregularities in the fibre structure.

Anatomy, physics and chemistry of wood are comprehensively explained by Fengel and Wegener (2011), Shmulsky and Jones (2019) and by Rowell (2005). The standard work by Kollmann and Côté (1968) is available in antiquarian form or as print on demand. In the following, the most important mechanical properties are described with regard to their application in load-bearing structures and building constructions.

### 1.2.1 Influence of the Fibre Direction

Wood is an anisotropic material, a characteristic that is clearly evident in its cell structure (see Figure 1.2a). In coniferous wood, also known as softwood, the tubular thick-walled tracheids (latewood) form the load-bearing element parts, imparting strength to the wood. Consequently, the strength of the wood is greatest in the direction of the grain. However, perpendicular to the grain, the strength is relatively low. The structure of wood can be explained as a tube model – like a bundle of straws (see Figure 1.2b). This tube model can serve as an effective tool for explaining the different types of failure in wood material (Figure 1.3).

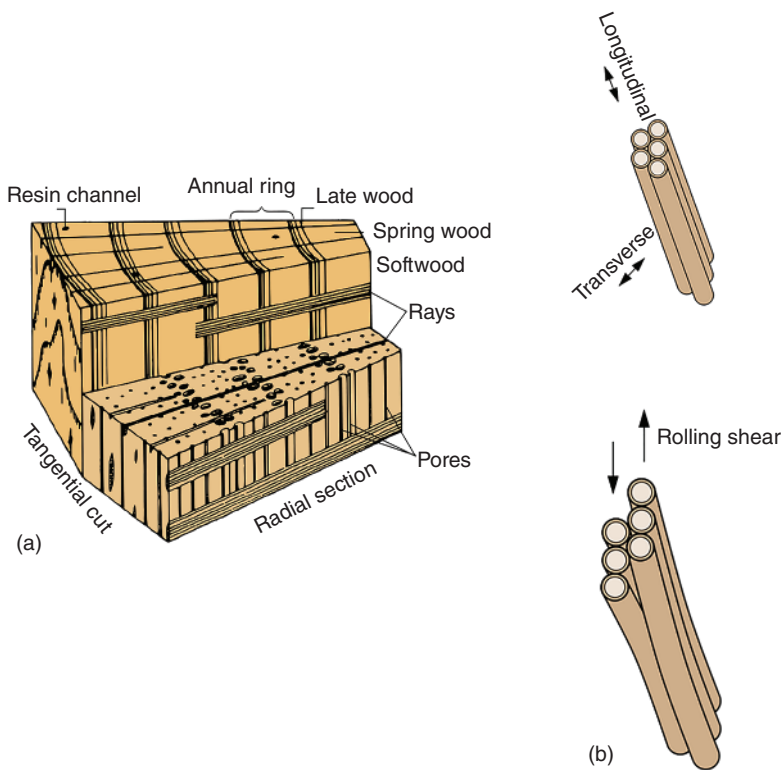
- Tension: In the longitudinal direction, the individual fibres fail only when they reach their tensile strength. Conversely, in the transverse direction, the fibres can be easily separated.
- Compression: Compression stress in the longitudinal direction leads to buckling of the individual fibres. However, in the transverse direction, the fibres can be crushed under comparatively low stresses.
- Bending: When a beam is bent, both tensile and compression strength are mobilised in the longitudinal direction.
- Shear: Shear stress aligned with the fibre direction is more favourable than rolling shear stress, which occurs perpendicular to the fibre direction.

### 1.2.2 Strength Values of Solid Timber

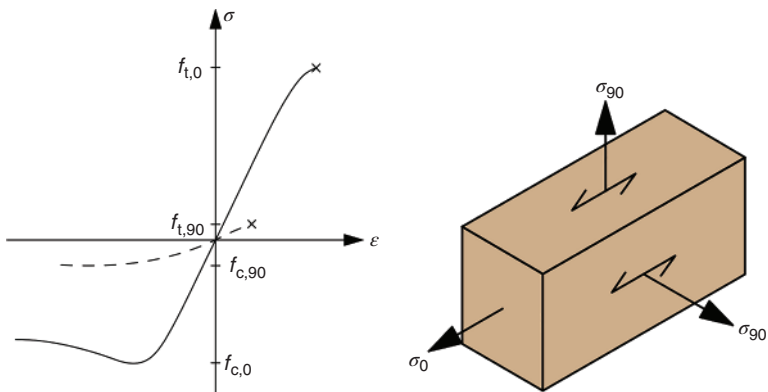
The decisive factor for the strength of the timber is how densely the fibres are ‘packed’. In this context, the density of the wood is an important reference value. This is determined using oven-dried samples (compare Section 1.2.4).

$$\rho = \frac{m_0(\text{kg})}{V(\text{m}^3)} \quad (1.1)$$

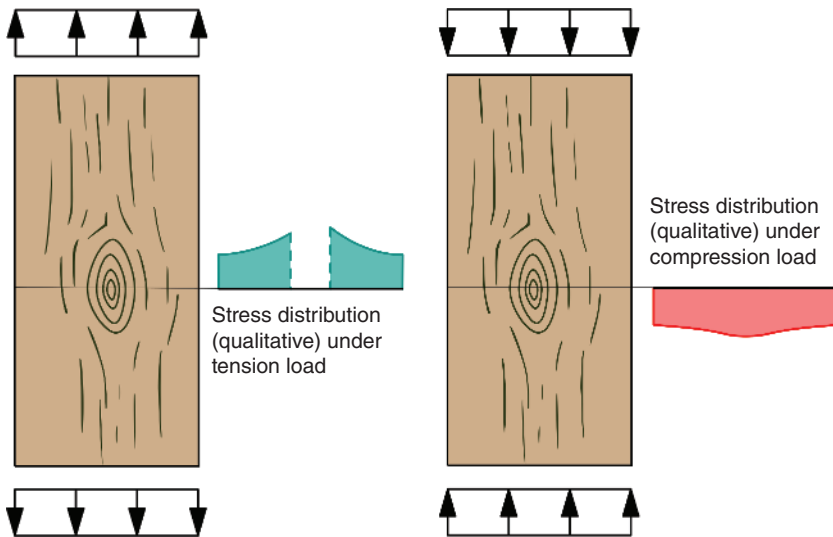
Other properties that influence the strength of the timber components include cracks, knots and twisted growth, as well as infestation by plants (e.g. fungi, mistletoe) or insects. All timber components are afflicted with more or less major wood defects. Some are an exclusion criterion with regard to the use of the timber for load-bearing components, while others can be tolerated to a certain extent. The



**Figure 1.2** (a) Wood structure of softwood and hardwood in comparison. Source: Fengel and Wegener (2011); (b) Tube model with different stresses.



**Figure 1.3** Schematic of stress–strain curve of defect-free wood under compression and tensile stress parallel and perpendicular to the grain.



**Figure 1.4** Influence of a knot under tension and compression loading.

influence of irregularities on the strength of the timber can be well explained using knottiness as an example.

Under a tensile load, the area of the knot becomes a void. This implies that the tensile strength of a real wood cross section is lower than the tensile strength of a defect-free wood sample. In contrast, the influence of a knot on the compression strength is rather small, as clearly illustrated in Figure 1.4. This is because the knot, having a higher density compared to the surrounding wood, is resistant to compression.

To specify the strength of different types of wood, sawn timber is classified into grades. These grades can be determined visually or by machines. Table 1.1 provides an example of the criteria for visual grading, according to German code regulations. The strength classes C16, C24 and C30 are assigned to the characteristic value of the bending strength. The meaning of the term characteristic and the statistical basis to calculate characteristic values will be explained in Section 2.1. Other strength values, which depend on the direction of stress, are summarised in Table 1.2. Figure 1.5 provides an example of how knottiness is defined in relation to the visible side surfaces of a rectangular cross section.

Knottiness  $A$  is determined as the ratio of diameter of the knot to cross-sectional width or height.

$$A = \max \left\{ \frac{d_1}{b}, \frac{d_2}{h}, \frac{d_3}{b}, \frac{d_4}{h} \right\} \quad (1.2)$$

### 1.2.3 Deformation Properties of Solid Timber

Similar to strength, the deformation properties of wood also depend on the direction of loading in relation to the grain. Up to a load level that corresponds

**Table 1.1** Grading criteria for solid timber according to DIN 4074-1.

Grading criteria	Grade		
	S 7	S 10	S 13
1. Knots			
– Single knot	≤1/2	≤1/3	≤1/5
– Group of knots	≤2/3	≤1/2	≤1/3
– Edge knots <sup>a)</sup>	—	≤2/3	≤1/3
2. Inclination of grain	≤16%	≤12%	≤7%
3. Pith	Allowed	Allowed	Not allowed
4. Growth ring width			
– General	≤6 mm	≤6 mm	≤4 mm
– For Douglas fir	≤8 mm	≤8 mm	≤6 mm
5. Cracks			
– Shrinkage cracks <sup>b)</sup>	Allowed	Allowed	Not allowed
– Lightening cracks, ring shake	Not allowed	Not allowed	Not allowed
6. Wane	≤1/3	≤1/3	≤1/4
7. Warping <sup>b)</sup>			
– Longitudinal	≤12 mm	≤8 mm	≤8 mm
– Twist	2 mm/25 mm	1 mm/25 mm	1 mm/25 mm
– Transverse	Width ≤ 1/20	Width ≤ 1/30	Width ≤ 1/50
8. Discolourations, rot			
– Blue stain	Allowed	Allowed	Allowed
– Nailable brown/red strips	≤3/5	≤2/5	≤1/5
– Brown rot, white rot	Not allowed	Not allowed	Not allowed
9. Compression wood	≤3/5	≤2/5	≤1/5
10. Damage from greenwood insects	Worm holes until 2 mm diameter: allowed		

a) Criteria do not have to be applied to boards for glulam.

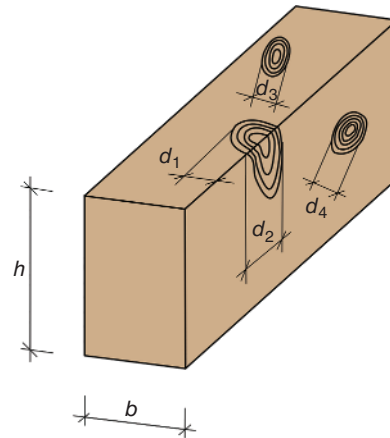
b) Criteria are not considered for wood that has not been dry sorted.

to approximately 70–80% of the strength, wood exhibits almost linearly elastic deformations in all stress directions. Mean values for the modulus of elasticity  $E_0$ , which are applied for tensile, compression and bending stress, as well as for the shear modulus  $G$  and the modulus of elasticity  $E_{90}$  are provided in Table 1.2. The characteristic values for moduli of elasticity and shear moduli are obtained by reducing the mean values by one-third.

Typical characteristics of wood are its swelling and shrinkage deformations due to changes in humidity. While this effect is relatively small in the longitudinal direction, shrinkage in the radial and tangential directions can lead to considerable deformations along the cross section.

**Table 1.2** Mechanical parameters for solid timber according to EN 338.

Wood class	C16	C18	C24	C30
	(N/mm <sup>2</sup> )			
Bending $f_{m,k}$	16	18	24	30
Tension parallel $f_{t,0,k}$	8.5	10	14.5	19
Tension perpendicular $f_{t,90,k}$	0.4	0.4	0.4	0.4
Compression parallel $f_{c,0,k}$	17	18	21	24
Compression perpendicular $f_{c,90,k}$	2.2	2.2	2.5	2.7
Shear and torsion $f_{v,k}$	3.2	3.4	4.0	4.0
Modulus of elasticity parallel $E_{0,mean}$	8 000	9 000	11 000	12 000
Modulus of elasticity perpendicular $E_{90,mean}$	270	300	370	400
Shear modulus $G_{mean}$	500	560	690	750
	(kg/m <sup>3</sup> )			
Density $\rho_k$	310	320	350	380
Density (mean) $\rho_m$	370	380	420	460

**Figure 1.5** Definition of knottiness according to DIN 4074-1.

The wood moisture content is defined as the moisture content in relation to the oven-dried wood sample:

$$u (\%) = \frac{m_u - m_0}{m_0} \cdot 100 \quad (1.3)$$

with

- $m_u$  Mass of the moist wood sample
- $m_0$  Mass of the oven-dried wood sample ( $u = 0\%$ )

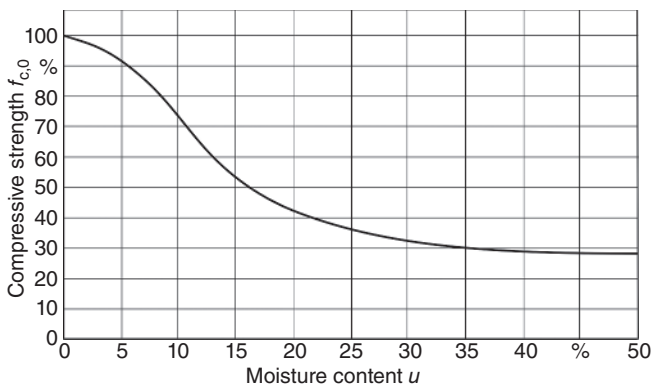
It becomes particularly critical when wooden components are installed with excessive moisture content and subsequently dry out. If the wood moisture content of a building component is more than 3% above, the so-called equilibrium moisture content, cracks in the building component are inevitable. In heated and well-ventilated buildings, the equilibrium moisture content usually reaches values between 6 and 8%.

### 1.2.4 Influence of Load Duration and Humidity

The mechanical properties of the timber depend on the load application time and the wood moisture content. An increase in wood moisture leads to lower strength (see Figure 1.6) and also lower moduli of elasticity. This effect can be partly attributed to the swelling of the cell wall, which implies that less cell wall material is available per unit area. More importantly, however, water penetrates the cell wall and weakens the hydrogen bonds that hold the cell walls together. Moisture changes above the fibre saturation point do not impact the mechanical properties, as only free water is stored in the cell cavities at this stage.

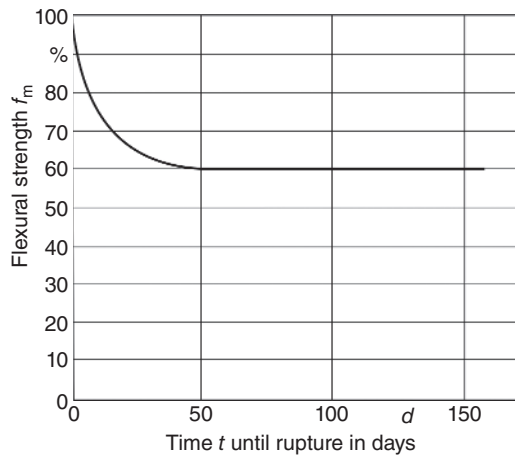
In long-term tests, the reduction of the strength under permanent load could be quantified (see Figure 1.7). The design takes into account the influence of wood moisture and loading duration on the strength through the modification factor  $k_{\text{mod}}$  (see Section 2.1.2). Service classes SC1, SC2 and SC3 are defined to categorise the expected equilibrium moisture content (see Table 1.3). The load duration is described by five classes, ranging from permanent to instantaneous, for various actions (see Table 1.4).

Under a constant load, deformations of timber increase over time. The key factors influencing creep are the loading duration and the wood moisture. Further influencing factors are the temperature and the stress level. A sufficiently precise consideration of creep for engineering practice is made by deformation factors  $k_{\text{def}}$  for the different service classes. The calculation procedure will be explained in Section 2.1.2.



**Figure 1.6** Compression strength of spruce as a function of wood moisture content according to Kollmann and Côté (1968).

**Figure 1.7** Flexural bending long-term strength of defect-free softwood in relation to short-term strength according to Möhler (1980).



**Table 1.3** Service classes with reference to EN 1995-1-1.

Service class	Equilibrium moisture content $\omega_u$ (%)	Relative humidity of the surrounding air at 20 °C	Examples of structures
SC1	10 ± 5	65% <sup>a)</sup>	Inside insulated and heated buildings
SC2	15 ± 5	85% <sup>a)</sup>	Under shelter, not exposed to rain, unheated
SC3	18 ± 6	95% <sup>a)</sup>	Exposed to weather, water will run off

a) Upper limit should not be exceeded for more than a period of a few consecutive weeks per year.

### Fact Sheet 1.1

#### The fibre structure of the wood leads to anisotropic material characteristics of the timber

$$f_{t,90} \cong 0.03 \cdot f_{t,0}$$

$$f_{c,90} \cong 0.10 \cdot f_{c,0}$$

- ⇒ Strength and MOE depend on the angle between grain and acting stresses
- ⇒ Tension perpendicular to the grain (and rolling shear) should be avoided whenever possible!

#### Quality control needs grading criteria

- ⇒ Grade classes and strength classes

#### Improvement of wood properties is possible with wood-based products and wood-based materials

- ⇒ Lower moisture content, lower tendency for cracking
- ⇒ Fewer defects (knots)
- ⇒ Improved scattering of irregularities