Chapter 2

Wood as a Construction Material

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CHAPTER 2. WOOD AS A CONSTRUCTION MATERIAL

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Acknowledgement

The author would like to thank Dr Morwenna Spear from Bangor University for sharing her knowledge about microscopic characteristics of timber.

2.1. INTRODUCTION: TIMBER IN THE CLIMATE EMERGENCY

According to the Intergovernmental Panel on Climate Change (Masson-Delmotte, 2018), a 1.5 °C increase in annual global temperature since pre-industrial times as a consequence of man-made climate change will place a lot of pressure on numerous natural, human and managed systems as defined. Nevertheless, trying to limit temperatures increases to just 1.5 °C will require a very significant and rapid change to our global economy and our consumption patterns. The IPCC presents four possible pathways for this transition. Some of these pathways rely strongly on Bioenergy with Carbon Capture and Storage (BECCS), which fundamentally consists of using plants to capture carbon, then transforming the biomass into energy but ensuring that the CO_2 released is captured and stored permanently on land or in the ocean.

When this scenario is coupled with UN projections that there will be 2.3 billion more urban dwellers by 2050 (United Nations, 2018), it is likely that this rapid urbanisation will require a great expansion in housing, buildings and infrastructure. It is feared that the development of this new infrastructure could claim between one and two thirds of the remaining carbon budget (Churkina, 2020). In light of this, a recent report from C40 cities (C40 cities, Arup and University of Leeds, 2019) recommends a 35 % reduction in steel usage, a 56 % reduction in cement usage and that 90 % of all new residential buildings and 70 % of all new commercial buildings are made from timber by 2030. Churkina et al. (2020) also propose that if buildings were to be made from bio-based materials (e.g. timber, bamboo, hemp, etc.), not only would the carbon released during construction be significantly reduced, but the buildings themselves could act as carbon stores (Churkina, 2020). Humanity has been building with timber and other bio-based materials for millennia because it was for many applications the best material available. In the 21st century, this still remains the case. Figure 2.1 shows commercial timber plantation.

Fig. 2.1. Commercial timber plantation in Scotland, UK. © David Trujillo.

2.2. MACROSCOPIC CHARACTERISTICS OF WOOD

What is wood? The question seems trivial, but it is not so simple when considering the variety of plants that can generate wood-like products. For example, we do not call 'wood' the wood-like products that we can obtain from palm trees (belonging to the *Arecaceae* family of monocotyledons – Fig. 2.2) or from bamboo (belonging to the *Poaceae* or *Gramineae* family of monocotyledons – Fig. 2.3). It is commonly accepted that wood is obtained from plants that exhibit secondary growth (i.e. they become wider over time), these are *Gymnosperms* and *Angiosperms*, which are more commonly known as softwoods and hardwoods respectively. The names hardwood and softwood can be deceptive, as not all hardwoods are stronger than all softwoods, though in general hardwoods are denser. Hardwoods come from broadleaved trees

Fig. 2.2. Coconut palms (*Cocos nucifera*). © David Trujillo.

Fig. 2.3. Giant bamboo (*Guadua angustifolia Kunth*). © David Trujillo.

Fig. 2.4. Two intertwined types of broadleaf trees: oak (*Quercus robur*) and horse-chestnut (*Aesculus hippocastanum*). ©David Trujillo.

that generally have a broad crown (see Fig. 2.4). In temperate regions most broadleaved trees are deciduous (i.e. they lose their leaves in winter), though in the tropics they are evergreens. There are some 20,000 commercial species of hardwoods. Softwood comes from trees with needle-like leaves, which generally have narrow, conical crowns. There are around 650 species. In European codes and standards (e.g. EN 338), hardwoods are denoted with prefix 'D' for 'deciduous', whereas softwoods are denoted with prefix 'C' for 'coniferous'.

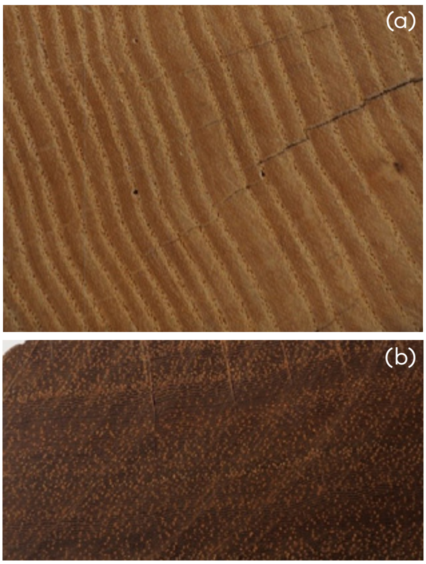

Fig. 2.5. Tangential section through two hardwood timbers: (a) Ash and (b) Ekki. © David Trujillo.

Softwoods constitute the bulk of the worldwide construction industry. In

Europe and North America, timber structures tend to be made from softwood timber. Instead, hardwood tends to be more costly and therefore reserved for applications that require greater hardness, such as floors, or greater durability, such as window frames, cladding or external decking. Tables 2.1, 2.2 and 2.3 and Figure 2.5 provide some examples of common softwood and hardwood timbers.

Table 2.1
Examples of Softwood Species (TRADA, 2015)

Common name	Scientific name	Density at 15 % moisture content (kg/m^3)
Cedar, Western red	*Thuja picata*	390
Douglas fir	*Pseudotsuga menziesii*	530
Larch, European	*Larix decidua*	550
Pine, Canadian red	*Pinus resinosa*	450
Pine, Caribbean pitch	*Pinus caribaea*	720
Redwood, European	*Pinus sylvestris*	510
Spruce, Sitka	*Picea sitchensis*	450
Whitewood, European	*Picea abies, Abies alba*	470
Yew	*Taxus baccata*	670

Table 2.2
Examples of Temperate Hardwood Species (TRADA, 2015)

Common name	Scientific name	Density at 15 % moisture content (kg/m^3)
Ash, European (see Fig. 4(a))	*Fraxinus excelsior*	710
Beech, European	*Fagus sylvatica*	720
Birch, European	*Betula pendula*	670
Cherry, European	*Prunus avium*	630
Chestnut, sweet	*castanea sativa*	560
Elm, European	*Ulmus spp*	560
Oak, European	*Quercus robur*	720
Walnut, European	*Juglans regia*	670

Table 2.3
Examples of Tropical Hardwood Species (TRADA, 2015)

Common name	Scientific name	Density at 15 % moisture content (kg/m^3)
Balau	*Shorea spp*	980
Balsa	*Ochroma lagopus*	160
Ebony	*Diospyros spp*	1160
Ekki/azobé (see Fig. 4(b))	*Lophira alata*	1070
Iroko	*Milicia excels, M. Regia, Chlorophora excels, Chlorophora regia*	660
Lignum vitae	*Guaiacum spp*	1230
Sapele	*Entandrophragma cylindricum*	640
Teak	*Tectona grandis*	660
Utile	*Entandrophragma utile*	660

Parts of the trunk

Wood is sourced from the stem, or trunks, of trees that exhibit secondary growth. The characteristics of a tree trunk are discussed hereafter – also refer to Fig. 2.6. The wood within the trunk provides three fundamental functions: 1) it transports water solutions (sap) from the roots to the leaves in the branches, 2) it stores carbohydrates, and 3) it provides mechanical strength. Sugars that are synthesised in the leaves flow as dissolved sugars along the inner bark and migrate from the bark into the trunk. The outer bark protects the wood and the inner bark. There is a thin layer of cells between the bark and the wood called *cambium*. Throughout the life of the tree, cambium cells divide to form wood towards the inside and bark towards the outside – this is what is referred to as secondary growth. The activity of these cells varies throughout the year, especially in temperate regions, as they will only be active during spring and summer, which leads to the distinctive growth rings visible in timber. In tropical regions growth may be continuous, unless interrupted by drier seasons.

As trees grow older the inner cells within the wood cease to conduct sap and store sugars, instead, in some cases this wood starts to accumulate tannins and oils. This inner wood is known as heartwood and in some species may have a distinctive colour – refer to Fig. 2.7. In contrast the outer wood is known as sapwood. The absence of sugars and presence of oils and tannins makes heartwood more durable than sapwood.

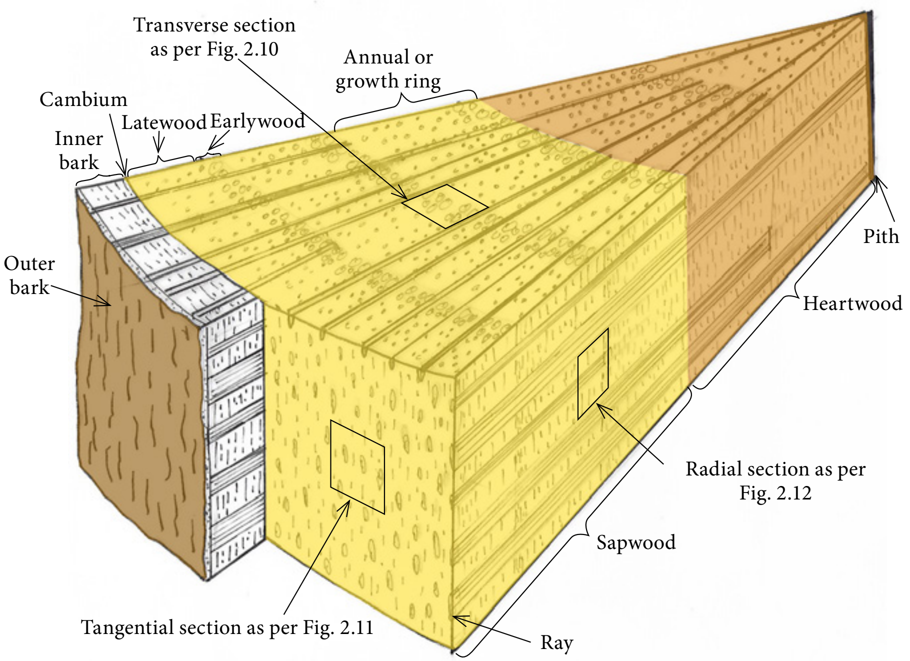

Fig. 2.6. Diagrammatic illustration of a wedge-shaped segment cut from a hardwood tree, showing principal structural features – adapted from a figure produced by the Building Research Establishment.

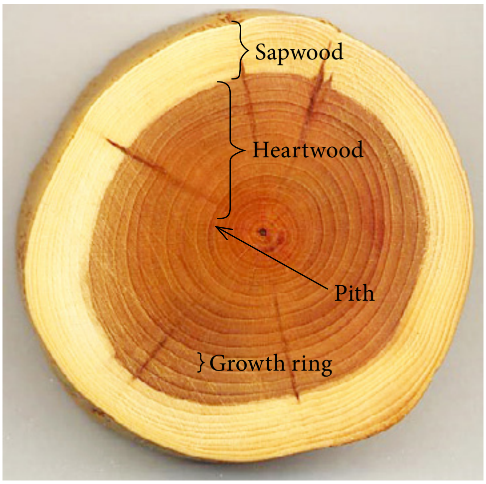

Fig. 2.7. Section through Yew wood (*Taxus baccata*). The dark radial lines are small knots. Source: Wikimedia.

2.3. MICROSCOPIC CHARACTERISTICS OF WOOD

The differences between softwoods and hardwoods are also visible at a microscopic level. Softwoods tend to be simpler and are predominantly composed of tracheids and parenchyma. In the living tree, tracheids provide a dual function to transport sap and provide mechanical support, whilst parenchyma cells transport and store sugar. Figure 2.8 shows a transverse section of Scots pine, showing earlywood or springwood (i.e. wood that grows in spring) and latewood or summerwood (i.e. wood that grows in summer). The earlywood tracheids have larger cross section than the latewood tracheids, so appear bright in this image. Some softwoods also include resin canals. A resin canal is enclosed in the red circle. The darker lines crossing the image vertically are rays, which contain the parenchyma cells. Rays transport sugars between the inner bark and the wood.

Hardwoods are a great deal more complex. They have evolved to have cells that undertake specialised functions. Sap is transported through vessels, and mechanical resistance is provided by fibre cells. Typically, rays are also more prominent in hardwoods than in softwoods. Figure 2.9 presents a transverse section of beech, showing earlywood (with large open vessel cells) and latewood (with smaller diameter vessel cells). The vessels in earlywood are larger than in latewood. The rays in beech are also much more prominent than in the Scots pine, with some being many cells wide (e.g. large ray on left hand side), while others are narrower (central region of image).

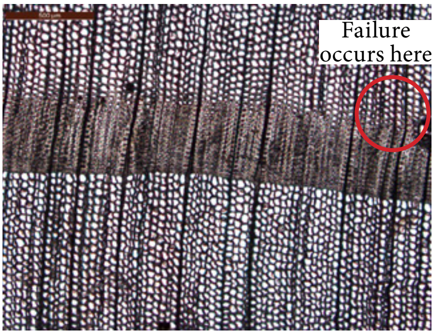

Fig. 2.8. Transverse section through a Scots pine. Morwenna Spear © Chris Miles.

Fig. 2.9. Transverse section through beech. Morwenna Spear © Chris Miles.

Figures 2.10, 2.11 and 2.12 show respectively transverse, tangential longitudinal and radial longitudinal sections for birch. Figure 2.11 shows a large vessel on the left-hand side (the white space). The vessel has a 'perforation plate' near the bottom of the image. These act as connections between one wide vessel cell and the next. Several rays are shown in cross section, with 2-3 parenchyma cells in width and 10–30 parenchyma cells in height. Figure 2.12 shows a tall ray running horizontally across the image, with many rows of brick-like parenchyma cells. A vessel cell is visible in the middle of the image. In this instance the perforation plates appear like ladders.

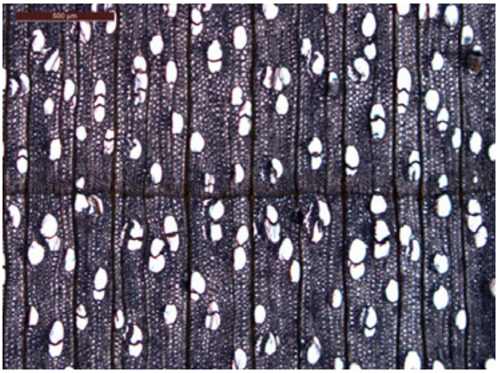

Fig. 2.10. Transverse section through birch. Morwenna Spear © Chris Miles.

Fig. 2.11. Tangential longitudinal section through birch. Morwenna Spear © Chris Miles.

Fig. 2.12. Radial longitudinal section through birch. Morwenna Spear © Chris Miles.

2.4. PHYSICAL PROPERTIES OF WOOD

2.4.1. Moisture Content

As is the case for all life forms, water is an essential component of a tree when it is alive. When a tree is felled, a significant part of the wood's mass will be water. Within the wood's cell, water is held in two significant ways: free water, which is held in the cell cavity, and bound water that is held in the cell walls. The amount of water contained in a wood specimen is called the 'moisture content', which in accordance to EN 13183-1 is calculated as follows:

$$\omega = \frac{m_1 - m_0}{m_0} \times 100,$$

where ω is the moisture content expressed as a percentage (sometimes also expressed as MC); m_1 is the mass of a wood specimen before drying; m_0 is the oven-dry mass of the specimen; drying is undertaken in an oven at (103E2) °C.

Timber is a hygroscopic material, which means that it releases and absorbs moisture from the atmosphere until achieving an equilibrium with the water vapour pressure of the surrounding air. After felling, water will be released to the atmosphere. At first it will be free water. This drying process continues until a moisture content of around 30 % is attained, which is known as the Fibre Saturation Point (FSP) – it should be noted that FSP values are species dependant. At this point, all free water has been released, and any further drying will occur as a consequence of releasing bound water to the atmosphere.

When wood has a moisture content below the FSP, significant changes start occurring to the wood. Most noticeably, dimensional changes start to take place, these may manifest themselves as radial and tangential shrinkage, which may lead to warping and splitting. Mechanical properties also change significantly, as will be discussed later. The wood will continue drying, but unless it is placed in an oven as described above, it will not reach a 0 % moisture content. Instead, it will reach an equilibrium with the environment dependent on water vapour pressure of the atmosphere, hence it is dependant on the temperature and relative humidity of the surrounding environment. This moisture content is known as the Equilibrium Moisture Content (EMC).

As it dries, wood gains strength and stiffness, yet it also becomes more brittle.

Figure 2.13 shows fairly typical test results of two similarly sized clear wood specimens that were subjected to a bending test. The solid line displays the behaviour of a dry specimen ($\omega = 12$ %), whilst the dashed line displays the behaviour of a wet specimen ($\omega \approx 40$ %). The red lines represent the linear elastic range for each specimen. Note that the dry specimen is both stiffer (i.e. the gradient of the red line is steeper) and stronger (i.e. the maximum load attained is higher). Note also that once the dry specimen reaches its maximum load failure occurs soon after.

Moisture content also affects the durability of timber. At moisture content above 20 %, fungi can develop in the timber. Timber that has suffered fungal attack is also more susceptible to insect attack. Therefore, the primary requirement to ensure timber can be considered a durable material is to keep its moisture content below 20 %.

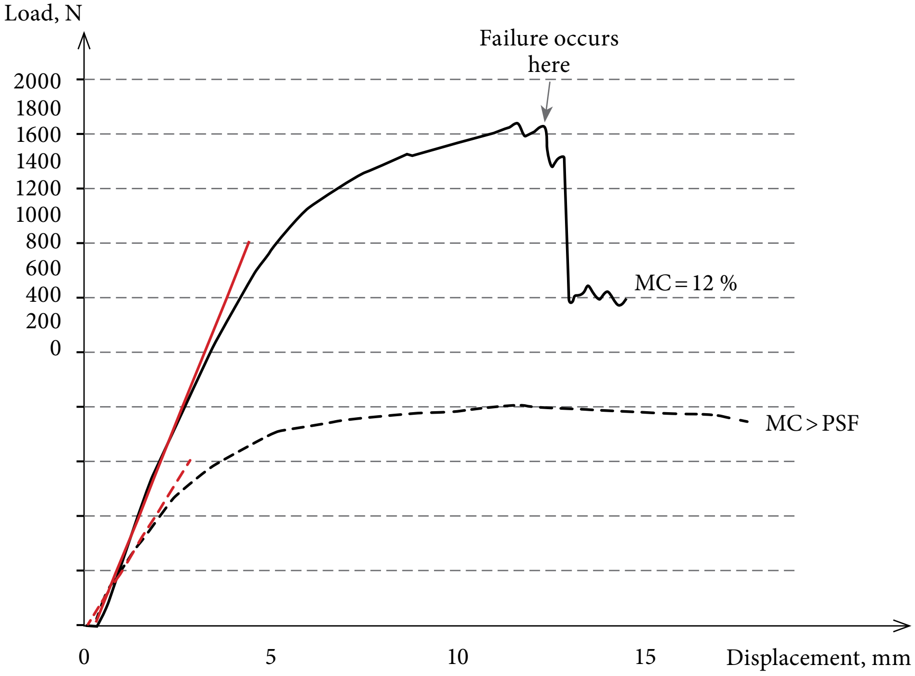

Fig. 2.13. Comparison of bending test results for dry and wet timber.

2.4.2. Density

Density is fundamentally the ratio between mass and volume. Density in timber correlates well to numerous other properties such as strength, stiffness and fire-resistance, it therefore is a very useful property to measure. Density is species dependent. It is also fairly easy to measure provided the moisture content is known. Otherwise, it is impossible to know what percentage of the mass is water and what is wood. Similarly, when moisture content is below the FSP, timber undergoes dimensional changes, which changes the volume of a specimen. Therefore, density measurements are affected by moisture content. There are several ways that can be used to determine and report density, Table 2.4 lists some of them. Tables 2.1, 2.2 and 2.3 list the densities for a range of species. Tables 2.5 and 2.6 provide 5th percentile and mean densities for a range of timber strength classes in accordance to EN 338:2016.

Table 2.4
Different Ways to Determine and Report Density

Name	Symbol	Equation	Commentary
Basic density	ρ_b or D_b	$\rho_b = \frac{m_0}{V_w}$	In some scientific contexts basic density is a preferred measurement because oven-dry mass (m_0) and water saturated volume (V_w) are both stable values.
Oven dry density	ρ_0	$\rho_b = \frac{m_0}{V_0}$	This is also a favoured measurement in scientific contexts because it is also fairly stable. In this context both volume and mass are measured at 0 % moisture content.
Density at 12 % moisture content	ρ_{12}	$\rho_{12} = \frac{m_{12}}{V_{12}}$	This is a preferred measurement in engineering because it is representative of typical in-service conditions.
5 percentile density	ρ_k	Calculated from a sample's ρ_{12} values	Used in Eurocode 5 connection strength and fire resistance calculations. Refer also to Tables 5 and 6.
Mean density	ρ_{mean}	Calculated from a sample's ρ_{12} values	Used in Eurocode 5 connection stiffness calculations. Maybe used for calculation of self-weight. Refer also to Tables 5 and 6.

Table 2.5

Density in kg/m³ According to Strength Classes for Softwood Based on Edgewise Bending Tests (Adapted from EN 338:2016)

Strength class	5 percentile density (ρ_k)	Mean density (ρ_{mean})
C14	290	350
C16	310	370
C18	320	380
C20	330	400
C22	340	410
C24	350	420
C27	360	430
C30	380	460
C35	390	470
C40	400	480
C45	410	490
C50	430	520

Table 2.6

Density in kg/m³ According to Strength Classes for Hardwood Based on Edgewise Bending Tests (Adapted from EN 338:2016)

Strength class	5 percentile density (ρ_k)	Mean density (ρ_{mean})
D18	475	570
D24	485	580
D27	510	610
D30	530	640
D35	540	650
D40	550	660
D45	580	700
D50	620	740
D55	660	790
D60	700	840
D65	750	900
D70	800	960
D75	850	1020
D80	900	1080

2.5. MECHANICAL AND ELASTIC PROPERTIES

Four-point bending test to a piece sawn softwood is shown in Fig. 2.14.

2.5.1. Anisotropy

As observed in Figs. 2.8 to 2.12, wood is constituted primarily of longitudinal cells. Their distribution obeys the functional needs of the tree whilst alive, for example resisting wind-loads and transporting water to the branches and leaves. The outcome of this is that timber is an anisotropic material, i.e. its properties are direction dependant. Consider Fig. 2.16, which represents the stress-strain behaviour of two clear-wood specimens subject to compression stresses. The continuous line represents the behaviour of a specimen loaded perpendicular to the direction of growth of the tree, also termed 'compression perpendicular to the grain'. Figure 2.15 shows the way in which a specimen tested in compression perpendicular to the grain 'fails'. Fundamentally the

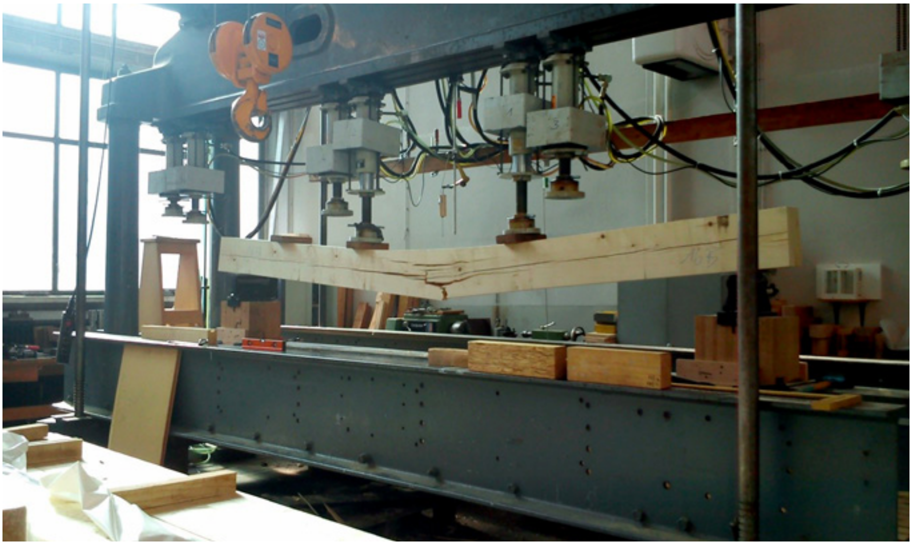

Fig. 2.14. Four-point bending test to a piece sawn softwood at the University of Stuttgart. © David Trujillo.

specimen is 'densified'. The cavity within the cells is crushed. The dashed line in Fig. 2.16 represents the behaviour of a specimen loaded parallel to the grain. Note that it resists a stress about ten times larger than compression perpendicular to the grain, and it is also much stiffer. Figure 2.17(a) represents a typical failure mode for a clear-wood specimen loaded in compression parallel to the grain. In this instance, failure occurs through the buckling of the cells. It requires significantly more stress to induce this failure mode, which explains the differences visible in Fig. 2.16.

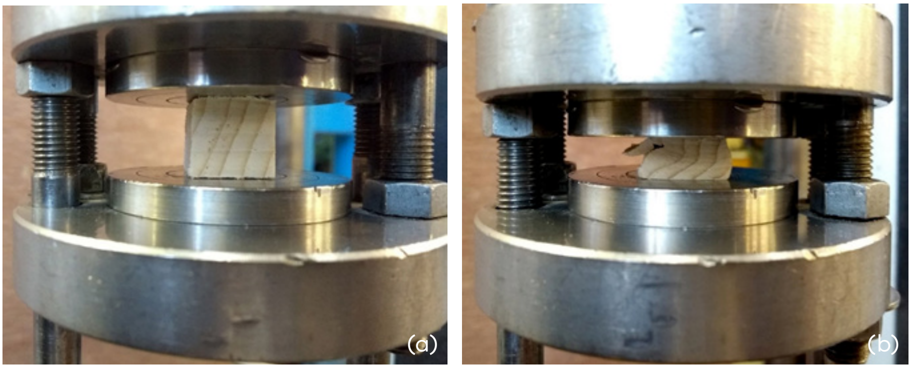

Fig. 2.15. A wood specimen subjected to compression perpendicular to the grain: (a) before testing, and (b) afterwards.

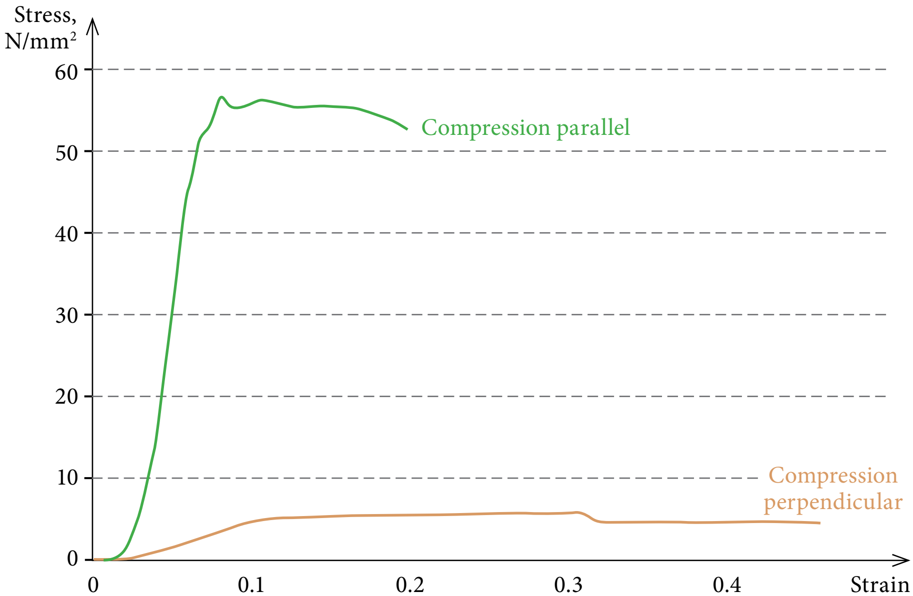

Fig. 2.16. Graph representing stress-strain behaviour for wood in compression parallel and perpendicular to grain.

There are also very significant differences in tensile strength parallel or perpendicular to the grain. This is noticeable in circumstances where tensile stresses are induced, such as in bending tests. Figure 16(b) and (c) represent the failure modes of two timber specimens. Figure 2.17(b) represents a fairly typical failure mode for a clear-wood specimen subject to bending. Whereas Fig. 2.17(c) represents a phenomena called 'grain inclination'. The wood grain is not horizontal, instead it is inclined at a shallow angle. In the presence of a tensile stress (induced through bending), the wood has broken in a direction perpendicular to the grain as a consequence of this inclination.

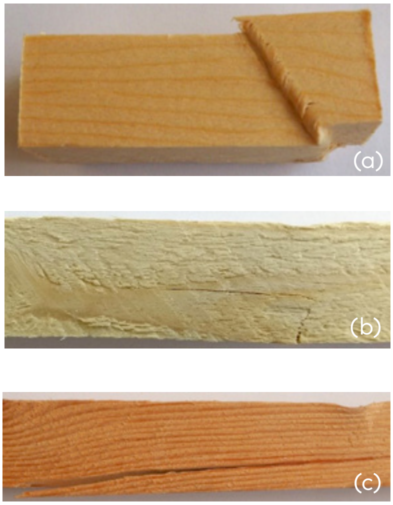

Fig. 2.17. Different failure modes: (a) compression parallel to grain, (b) bending failure, (c) bending failure in the presence of inclined grain.

Anisotropy needs to be accounted for in structural design. Structures should be conceived to avoid circumstances that induce stresses perpendicular to the axis of the member (Fig. 2.18). Anisotropy of timber could be regarded as one of the material's limitations, however, products such as cross-laminated timber (or CLT)

Fig. 2.18. Cross-laminated timber consists of orthogonally glued laminations. It is a versatile product that can be used as a slab or a wall, as seen here.

and plywood resolve this limitation by creating panels with laminations of timber glued orthogonally.

Table 2.7 lists several strength and stiffness properties for softwood strength classes. Note the difference of magnitude between properties measured parallel to the grain and perpendicular to grain.

Table 2.7

Strength and Stiffness Properties According to Strength Classes for Softwood Based on Edgewise Bending Tests (Adapted from EN 338:2016)

Strength class	Strength properties in N/mm²						Stiffness properties in kN/mm²	
	Bending ($f_{m,k}$)	Tension parallel ($f_{t,0,k}$)	Tension perpendicular ($f_{t,90,k}$)	Compression parallel ($f_{c,0,k}$)	Compression perpendicular ($f_{c,90,k}$)	Shear ($f_{v,k}$)	Mean modulus of elasticity parallel bending ($E_{m,0,mean}$)	Mean modulus of elasticity perpendicular ($E_{m,90,mean}$)
C14	14	7.2	0.4	16	2.0	3.0	7.0	0.23
C16	16	8.5	0.4	17	2.2	3.2	8.0	0.27
C18	18	10	0.4	18	2.2	3.4	9.0	0.30
C20	20	11.5	0.4	19	2.3	3.6	8.5	0.32
C22	22	13	0.4	20	2.4	3.8	10.0	0.33
C24	24	14.5	0.4	21	2.5	4.0	11.0	0.37
C27	27	16.5	0.4	22	2.5	4.0	11.5	0.38
C30	30	19	0.4	24	2.7	4.0	12.0	0.40
C35	35	22.5	0.4	25	2.7	4.0	13.0	0.43
C40	40	26	0.4	27	2.8	4.0	14.0	0.47
C45	45	30	0.4	29	2.9	4.0	15.0	0.50
C50	50	33.5	0.4	30	3.0	4.0	16.0	0.53

2.5.2. Brittleness and Ductility

Timber also exhibits another phenomena that should be observed. As is noticeable in Fig. 2.16, compressive failure of non-slender members tends to exhibit a ductile behaviour (i.e. the material can hold the maximum load whilst undergoing continued strain) regardless of direction of loading. Other failure modes in timber tend to be more brittle (i.e. the material rapidly loses load-bearing capacity after reaching the maximum load. As discussed, this is noticeable in bending when specimens are dry (Fig. 2.13). Tension failures, both parallel and perpendicular to the grain are brittle as well. Similarly, shear failures are very brittle – Fig. 2.19. Therefore, structural designers should avoid circumstances in which shear failures may be induced, as they will occur with little warning.

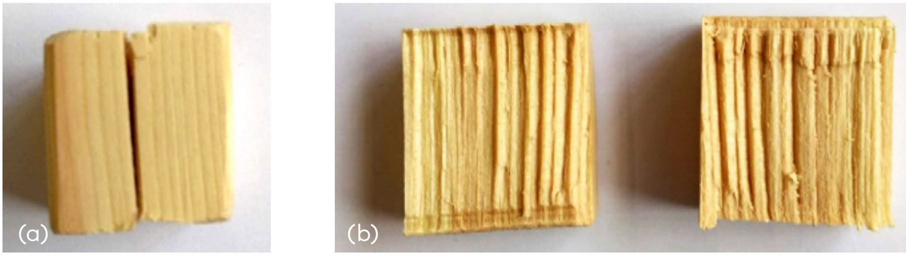

Fig. 2.19. Image of clear-wood specimen subject to shear: (a) side elevation, (b) view of failure plane.

2.6. DURABILITY OF TIMBER

In common with most bio-based materials, timber is destined to biodegrade. This means that there is a wide range of biological agents that have evolved to feed off timber. Obviously, throughout the existence of the building these biological agents need to be controlled and deterred. However, the fact that timber can be disposed of easily after fulfilling a useful role and reintegrated into the bio-sphere should be seen as an advantageous quality of timber. Most other construction materials, if not burnt, reused or recycled, will become waste causing a variety of environmental problems.

There are several factors that increase or reduce the durability of timber some of which are discussed hereafter. Firstly, the species. Some species, especially some tropical hardwoods are very durable, even when exposed to very harsh environments, for example in contact with the ground such as foundation piles or telephone poles. It should be noted that in most species heartwood is significantly more durable than the sapwood, in fact for most species sapwood should be avoided. As a rule, species that have high natural durability grow much slower. This makes their exploitation more expensive and less sustainable. An alternative is to impregnate the timber with a chemical preservative, which is the second factor to consider. There is a wide variety of chemical treatments, with variable complexity of application, toxicity and cost. The selected treatment should be closely matched to the location in which the timber will be used. These locations are referred to in EN 335-1 as Use Classes – refer to Table 2.8.

A careful inspection of Table 2.8 shows that the variety of possible biological agents that can attack timber increases as its location shifts from drier locations to wetter ones, especially if it comes in contact with the ground. Experience shows that the simplest and most effective way to increase the durability of timber is to avoid it becoming wet and to place it away from the ground through appropriate detailing (refer to the 'Durability by design' subsection below). This allows the designer / specifier to select either a less durable species – hence more economical – or a less intensive preservative treatment (or none at all), which will also be more economical.

Table 2.8
Use Classes for Timber and Biological Agents Present
(Adapted from EN 335-1)

Use class	General service situation	Description of exposure to wetting in service	Biological agents
1	Interior, covered	Dry	Wood boring beetles
2	Interior or covered	Occasionally wet	As above + Disfiguring fungi + Decay fungi
3	3.1 exterior, above ground, protected	Occasionally wet	
	3.2 exterior, above ground, unprotected	Frequently wet	
4	4.1 exterior, in ground contact and / or fresh water	Predominantly or permanently wet	As above + Soft rot
	4.2 exterior in ground (severe) and / or fresh water	Permanently wet	
5	in salt water	Permanently wet	Decay fungi Soft rot Marine borers

Note: termites may be present in all use classes.

2.6.1. Durability by Design

If timber is used in an appropriately designed building, where it is kept away from wetting and the ground, it can last indefinitely. In fact, there are examples of timber buildings that are over 500 years old in many parts of the world (refer to Figs. 2.20 to 2.22). As discussed, timber that is maintained below a 20 % moisture content is inhospitable to the development of any fungus, and the only remaining biological agents that can attack it are wood boring beetles and termites, though beetles thrive in timber with a higher moisture content. Termites are known to attack dry wood, but they live underground and require tunnels to reach the wood. A careful design will force them to expose their tunnels and the infestation can be prevented by a routine inspection accompanied by the destruction of the tunnels.

Chemical preservatives can enhance the durability of timber by making it harder for insects to attack or fungi to grow, but chemical treatment cannot fully substitute appropriate design. It is the designers' responsibility to ensure that locations that could result in the trapping of moisture are avoided from the conception of the structure. Every source of moisture should be considered and addressed, these sources include: rainfall, capillarity from the ground, condensation and water sources (e.g. bathrooms). Water should be shed rapidly, and water vapour allowed to move away through appropriate ventilation. It is the builder's responsibility to observe these details and specifications and question any poor detailing.

Fig. 2.20. Toji Buddhist Temple, Kyoto, Japan, dating from the 15th century. © David Trujillo.

Fig. 2.21. Rengeoin Sanjusangendo, Kyoto, Japan, dating from the 13th century. © David Trujillo.

Fig. 2.22. Middleton Hall – parts of the hall date from the 13th century. © David Trujillo

2.7. VARIABILITY

In common with all natural materials, there is a diverse range of factors that affect the quality of the final 'product'. No two trees are identical. There is a range of genetic and environmental reasons why they will differ. In fact, there is substantial variation in quality within a tree. The way the forest is managed and then the wood is sawn creates additional permutations. Natural 'defects', such as knots, create irregularities in the wood grain, that introduce further variability to the material's performance. For all the aforementioned reasons, there is a great deal of variability within timber. For instance, Fig. 2.23 shows the load-deformation graph for five identically sized clear-wood (i.e. free from knots) softwood specimens. The strength and behaviour are significantly different and apparently quite unpredictable.

The large variability of timber creates a great deal of uncertainty about its structural performance. One way in which this uncertainty can be addressed is to assume in design that the element will be weaker than most of the

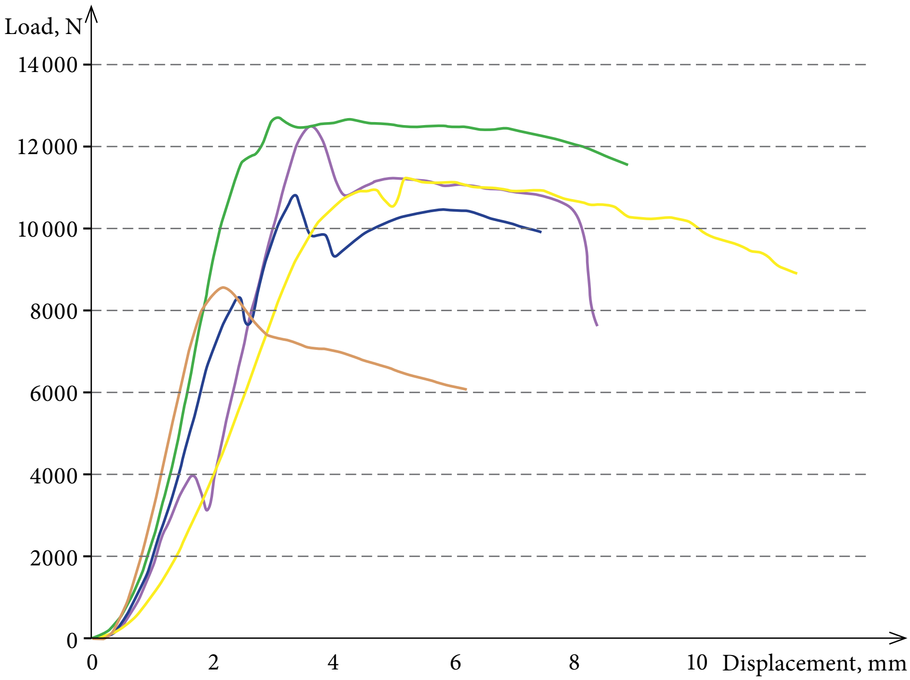

Fig. 2.23. Load-deformation graph for five clear wood specimens subject to compression parallel to grain.

population of results. In the Eurocodes (and their harmonised EN standards), we use the concept of characteristic values. For strength and density, a characteristic value is the fifth percentile with a 75 % confidence. This means that if we tested 100 specimens, we would expect that 95 of them would be stronger than what we have assumed in design. This ensures structures remain safe.

However, some defects, such as knots, can significantly debilitate timber, and it makes more economical sense to limit their presence than to assume an excessively low strength in design. Therefore, producers try to exclude and/ or control the presence of these strength-reducing defects. There are different ways they can control defects. One of these is to subject the timber to a process called 'strength grading'. This process can be undertaken by a trained person through a process called 'visual grading', by which they will reject specimens that contain too many defects. Alternatively, a machine can be used to infer the strength of timber by measuring non-destructively measurable properties in a process called 'machine grading. Figure 2.24 shows two types of grading machines. An alternative way to obtain a less variable property is to combine laminations, veneers or strands of timber into what are known as 'engineered timber products' – refer to Figs. 2.25 and 2.26.

Fig. 2.24. Two types of grading machines: (a) Metriguard lumber grader, (b) Brookhuis handheld Timber Grader.

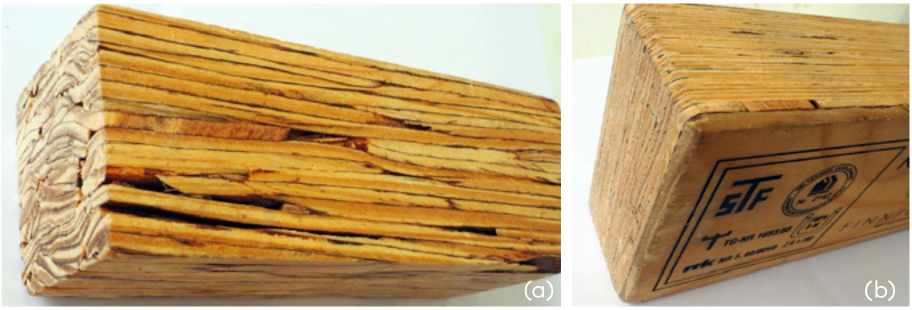

Fig. 2.25. Two types of engineered timber products: (a) Parallel Strand Lumber – PSL, and (b) Laminated Veneer Lumber – LVL.

Fig. 2.26. Glued laminated timber, or glulam, is another engineered timber that can adopt varied shapes (a) and achieve very impressive sizes (b): (a) Scottish Parliament, (b) GlaxoSmithKline Carbon Neutral Laboratory for Sustainable Chemistry, University of Nottingham.

2.8. BEHAVIOUR IN FIRE

Timber is a combustible material which affects its perception as a structural material. Obviously, combustibility is a hazard that needs to be controlled by both the building designer and constructor. The perceived risk presented is deeply engrained in popular culture. However, its combustibility offers the possibility that at the end of its useful life it can be burnt for energy generation, hence offering one final service.

As timber burns it develops an external layer called 'char'. The rate at which the char develops, known as 'charring rate', is slow and predictable. Char has very good insulating properties which maintain the unburned timber cool and unaltered. The consequence of this is that timber only loses resistance as a result of loss of cross-sectional area. Charring rates are contained in design codes (Table 2.9) and are used to calculate the fire resistance of a member through quite a simple process.

Table 2.9

Design Charring Rates for Timber and Some Wood-based Products (Adapted from EN 1995-1-2:2004)

Type of timber or wood-based product	Charring rate	
	β_0 for one-dimensional charring mm/min	β_n notional mm/min
Softwood and beech		
Glulam with a characteristic density of ≥290 kg/m^3	0.65	0.7
Solid timber with a characteristic density of ≥290 kg/m^3	0.65	0.8
Hardwood		
Solid or glulam hardwood with a characteristic density of ≥290 kg/m^3	0.65	0.7
Solid or glulam hardwood with a characteristic density of ≥450 kg/m^3	0.50	0.55
LVL		
With a characteristic density of ≥480 kg/m^3	0.65	0.7
Panels*		
Wood panelling	0.9	–
Plywood	1.0	–
Wood-based panels other than plywood	0.9	–
*with a characteristic density of ≥450 kg/m^3 and thickness ≥20 mm		

The rate of burning is proportional to the exposed surface area, therefore, a large timber element will take longer to burn than numerous smaller pieces, even if they constitute overall the same volume. Charring rates are also species specific, as they are affected by density. Denser timber burns slower.

2.8.1. Reaction to Fire

Reaction to fire refers to the behaviour of a material when exposed to fire; it reflects how easily it 'catches fire', and then what contribution it will make to the fire and its spread. Materials are tested and then classified accordingly. EN 13501-1:2018 sets the classes outlined in Table 2.10, where timber would be classified as *D*. Wood-based panel products (e.g. plywood and OSB) tend to be classified as *D* or *E*. Through the use of fire-retardant products, timber's performance can be improved up to class *B*. Nevertheless, timber is difficult to set alight. In the absence of a naked flame, temperatures typically have to exceed 400 °C for ignition to occur.

Table 2.10
Reaction to Fire Classes for Construction Materials According to EN 13501-1:2018

<table>
<tr><th>Class</th><th>Smoke classification</th><th>Burning droplets / particles classification</th></tr>
<tr><td>A1</td><td>Not applicable</td><td>Not applicable</td></tr>
<tr><td>A2</td><td rowspan="4">Test for smoke production classes: s1, s2 and s3</td><td rowspan="5">Test for burning droplets / particles: d0, d1, d2</td></tr>
<tr><td>B</td></tr>
<tr><td>C</td></tr>
<tr><td>D</td></tr>
<tr><td>E</td><td rowspan="2">Not applicable</td></tr>
<tr><td>F</td><td>Not applicable</td></tr>
</table>

2.8.2. Fire Resistance

Fire resistance refers to the ability of a building item, or element, to fulfil specific requirements during a fire test for a given amount of time. The specific requirements are: 1) the building item or element must not collapse, 2) it must not allow fire to penetrate, and 3) it must offer adequate resistance to transfer of heat. The three criteria are sometimes referred to as 'stability, integrity and insulation', respectively. Fire resistance is not a property of a material but of a building system, as such, different materials may be combined to obtain a targeted resistance. Building codes and regulations across the world typically state the required fire-resistance in minutes and the test used to determine the resistance.

2.8.3. Improving Performance

The fire performance of timber can be improved by the adoption of any, or a combination of the following passive strategies.

1. Oversizing of members. As discussed, the charring process provides good fire-protection to the internal unburnt section, and loss of strength occurs only as a consequence of cross-sectional area. Therefore, the designer can oversize a section to ensure a given member will not fail during a fire of a specified duration. The process fundamentally consists in multiplying the values from Table 2.9 by the required time of fire exposure. The member is then increased in every exposed dimension by whatever dimension was obtained.
2. Encapsulating in a board product. Some board products – such as plasterboard – have very good fire performance, thus performance is improved by enclosing the timber members within a board product.
3. Modification to reaction to fire. As discussed, fire-retardant coating products may be used to slow down ignition and spread of flame.

It is important to observe that some strategies are implemented during the latter stages of a construction project, for example, plasterboard may not be fixed until the structure is finished. Therefore, timber buildings may be particularly vulnerable to fire during construction.

2.8.4. Further Points

As stated previously, timber is combustible; therefore, once it ignites, the timber structure starts contributing to the fire-load, in this respect it is unlike most other conventional *structural* materials[1]. Nevertheless, non-combustibility does not guarantee good fire performance. For example, steel and aluminium rapidly lose strength and stiffness during a fire, and due to their high thermal conductivity, the effects propagate rapidly. Figure 2.28 shows a detail in which a steel connector has been concealed by timber. This is because timber offers the steel some fire protection. If the steel connector were exposed directly to the fire it could rapidly lose its strength or burn the wood in its proximity.

Fig. 2.28. Due to its better fire performance, timber conceals the steel beam-to-column connection – GlaxoSmithKline Carbon Neutral Laboratory for Sustainable Chemistry, University of Nottingham. © David Trujillo.

[1] It should also be noted that there are numerous other construction materials that are combustible, these are either bio-based (e.g. bamboo) or polymer-based, such as PVC, Polyurethane, Polystyrene and Fibre Reinforced Polymers. These materials are either non-structural or non-conventional construction materials.

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