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Introduction to timber as an engineering material

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This chapter includes a description of the anatomy of wood, a discussion on timber properties and the factors that influence these properties, information on the testing and grading of timber, and the methods used to derive design properties. It concludes with a short discussion on timber as a sustainable material.

doi: 10.1680/mocm.00000.0001

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Introduction

Wood is a natural organic material that has been used for many centuries for the construction of buildings, bridges and a variety of other structures. It remains an important construction material today as research and improved technology have led to a better knowledge of the material behaviour. This has helped designers to use timber more efficiently and safely and in more challenging and exciting applications.

Timber has many important attributes. It has a warm texture and attractive appearance and is often used for internal finishing as well for the main structure (**Figure 1**). It is easy to work with and can be produced in a wide range of shapes and sizes. It has a high strength-to-weight ratio and has good thermal insulation properties. Timber can be used compositely with concrete and steel. It is the only construction material that does not contribute to greenhouse emissions and is a fully renewable and largely recyclable material.

Because it is a naturally grown material, timber is a complex building material. Its properties are highly variable and are sensitive to environmental and loading conditions. It is a highly anisotropic material with high strength and stiffness parallel to the grain but low properties perpendicular to the grain. These factors must be taken into account in the design of timber structures.

In this chapter, the behaviour and properties of timber are discussed. Starting with an examination of the microstructure of wood, the properties of wood and the factors that influence them are elaborated. The performance of structural timber is influenced not only by the basic wood properties, but also by the presence of 'defects' such as knots. The influence of these defects on the structural properties is examined. Testing and grading is used to classify timber into different grades or strength classes to satisfy different end user requirements and ensure product reliability. Methods of testing and grading are described together with procedures for determining characteristic values for design purposes. Finally, the environmental impact of timber construction is considered.

Basic properties of wood

Tree species are normally grouped into two categories, namely softwoods and hardwoods. The softwood species are coniferous and include spruces, pines, and firs. These trees generally retain their needle-like leaves throughout the year. The hardwood species are deciduous and include oaks, birches, and maples. They have broadleaves, which they lose in winter. The wood from both species is used for structural timber, but softwoods are much more common in Europe due to their greater availability and lower costs.

The cross-section of a tree trunk has a number of important features, as shown in **Figure 2**. Working from the outside in, these are the bark, the cambium, the sapwood, the heartwood and finally the core or pith. The cambium is where new wood cells are formed. The younger outer part of the trunk, or sapwood, is used to store nutrients and to transport them along the axis of the tree. The width of the sapwood band can vary from about 25 mm to about 150 mm. The main function of the older heartwood is to provide structural support for the tree. There is no difference in the mechanical performance of sapwood and heartwood. Sapwood is, however, more susceptible to insect attack due to the presence of nutrients. The inner 5 to 20 growth rings are known as juvenile wood and this usually displays greater longitudinal shrinkage than more mature wood.

The trunk cross-section in both the sapwood and heartwood is characterized by distinctive annual growth rings. These occur because the wood formed during the early part of the season when the growth is more active (earlywood) is less dense and therefore lighter in colour than that produced later in the season (latewood). Under conditions of rapid growth, the growth rings are wider resulting in wood of lower density and strength. For this reason, ring width is sometimes used as an indicator of the strength of timber.

The majority of wood cells is tubular in section and elongated. They are called fibres or tracheids and are about 2 to 5 mm long and 10 to 50 μm wide. Cell wall thicknesses for

Figure 1 Coillte headquarters, Ireland (reproduced with permission of Coillte)

softwoods are in the range 2 to 5 μm. They are aligned parallel to the axis or trunk of the tree. This is referred to as the grain direction. The individual cells are glued together by a lignin-rich layer called the middle lamella.

The cell wall itself has a multi-layered structure which gives the wood its strength and stiffness. Each layer comprises cellulose microfibrils embedded in a matrix of lignin and hemicellulose with the microfibrils oriented differently in the different layers. The thickest layer has microfibrils oriented parallel to the cell axis and as a result is very effective in carrying tension loads. The other layers have microfibril angles of between 50–70° and these layers help prevent buckling of the cell wall under compressive loading. In softwoods, the central core of the cell, or lumen, is used to transport nutrients. In hardwoods, the nutrient transport is by means of special large diameter tubular cells called vessels embedded in the fibres. Hardwood fibres generally have smaller lumen diameters and thicker cell walls than softwoods.

The arrangement of wood cells or fibres parallel to the trunk is very efficient in carrying the actions sustained by the living tree. These are primarily axial compression forces due to self weight and bending moments due to wind loading. Wood is very strong in tension and compression parallel to the grain direction. However, the properties perpendicular to the grain direction tend to be poor. The actual strength values vary significantly not only between species but also between individual trees within a species and indeed within an individual tree. The differences between trees can result from different environmental conditions and forestry practices. Within an individual tree, the difference is due not only to local density variations but also due the presence of knots, spiral grain and reaction wood.

Non isotropic characteristics

The properties of wood are strongly influenced by direction because of the arrangement of its fibres and the orientation of the microfibrils in the cell walls. In particular, wood is orthotropic as three orthogonal directions of symmetry can be identified. The longitudinal (L) direction, or the direction parallel to grain, is aligned with the axis of the tree trunk. The radial (R) direction lies along the radius of the tree cross-section while the tangential (T) direction is tangential to the growth rings (**Figure 3**). The radial and tangential directions are referred to as directions perpendicular to grain. The wood strength, modulus of elasticity and other characteristics such as shrinking and swelling differ in the three directions. The load carrying capacity in the direction parallel to grain is significantly greater than in the perpendicular direction. The dimensional stability or resistance to distortion under fluctuating moisture content is also greater. Structural timber is normally sawn into boards with the long axis of the board aligned parallel to grain.

Moisture and wood

Wood is a hygroscopic material in that it exchanges moisture with its surroundings and its properties vary significantly with moisture content. The moisture content in wood is defined as the ratio of the mass of water that can be removed from the wood to the mass of the dry

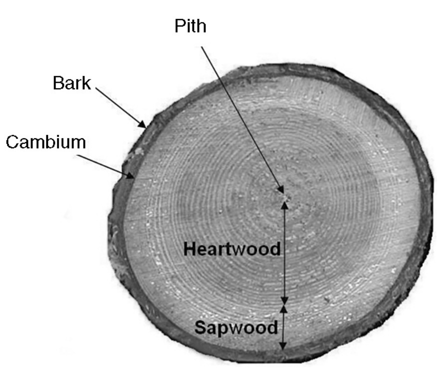

Figure 2 Cross-section of tree trunk

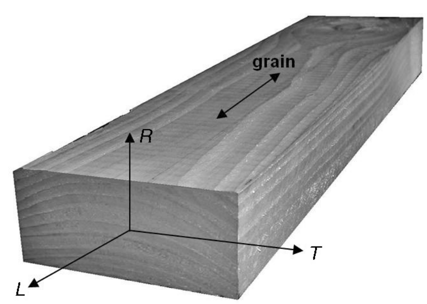

Figure 3 Orthotropic directions for wood properties

wood. In a growing tree the moisture content is highly variable and can be as high as 200%. This moisture is present as free water in the cell cavities or lumens and as bound water in the cell walls. When wood is harvested and processed, the wood dries from the green state to a moisture content that is in equilibrium with the relative humidity and temperature of the surroundings. This is known as the equilibrium moisture content (EMC).

As the wood dries, the free water in the cell cavities is lost first. After this the bound water in the cell walls is lost. The moisture content at which all of the free water has been removed and the cell walls are still saturated is known as the fibre saturation point (FSP). For most species, the FSP is in the range 25 to 35%. An average value of 30% is normally assumed. The physical and mechanical properties of the wood change significantly as the moisture content is reduced below the FSP, with strength and stiffness values increasing with decreasing moisture content. Above the FSP most properties remain constant.

Changes in moisture content below the FSP also result in swelling and shrinkage of the wood. If these moisture induced deformations are prevented in a structure, stresses will develop. For this reason, it is important that, before installation, structural timber is dried to a moisture content close to that which it will experience in service – normally its EMC. When timber is used in an environment where there are wide fluctuations in relative humidity and temperature, significant moisture induced stresses can develop, particularly in directions perpendicular to grain.

At a standard indoor climate with a temperature of 20°C and a relative humidity of 65%, the equilibrium moisture content of softwoods is about 12%. This is the accepted reference moisture content at which testing of wood is performed and at which international codes and standards generally specify design values.

The moisture content of wood can be measured by oven drying or by use of moisture metres. These metres operate on the principle that the moisture content influences the electrical resistance and are calibrated for individual species.

Physical properties of wood

Density

The density of wood is determined mainly by the amount of wood substance per unit volume and the moisture content. The higher the proportion of wood substance is the greater the density and also the higher the mechanical properties. Mean values for the density of softwoods and hardwoods range from about 400 to 650 kg/m^3 and 500 to 1200 kg/m^3, respectively. Wood of high density tends to shrink and swell more with changes in moisture content than wood of low density.

Shrinking and swelling

Below the fibre saturation point, wood shrinks and swells as its moisture content falls and rises. The rate of shrinkage/swelling varies with direction. Values in the parallel to grain direction are 5 to 10% of those in the perpendicular to grain direction while values in the tangential direction can be 1 to 2 times those in the radial direction. Because of these differences in shrinkage rate, cross-sections can distort during drying. Splits can occur in large cross-sections when the drying rate is too high. In the region of knots, the grain direction is distorted which can result in warping of the specimen during drying. The tangential shrinkage of softwoods such as spruce can be as much as 8% when dried from 30% to 0% moisture contents. Compression wood and juvenile wood often display high levels of longitudinal shrinkage resulting in bow, spring and twist (**Figure 4**). In the presence of spiral grain, twist occurs during moisture changes. Differential movements in the radial and tangential directions result in cupping (**Figure 4**). Limits on the level of acceptable distortion are given in grading rules for structural timber.

Thermal properties

Timber has low thermal conductivities and coefficients of thermal expansion (CTE). The degree of anisotropy in thermal properties is less than in structural properties. The thermal conductivity parallel to grain is about 2 to 3 times that perpendicular to grain. The average value for softwoods is 1.2 W/mK. The CTE parallel to grain is about 10 to 20% of the perpendicular to grain value and is typically of the order of 3.5×10^{-6}/°C.

Durability

Wood is susceptible to attack by a variety of organisms. Fungi, which use the wood as a source of food, cause decay that can result in a reduction in mechanical properties. These fungi require moist conditions for growth and can be prevented by ensuring that the moisture content of the wood is kept below 20%. A number of insects and borers attack wood and destroy it, including termites or white ants. In many cases, keeping wood dry will prevent damage from their attack so it is important in designing with wood to minimize the absorption of water by wood. If the moisture content cannot be controlled, then the timber should be treated with preservative or a species of timber with a high level of natural durability should be used. Application of preservatives is carried out using pressure to ensure adequate penetration. Commonly used preservatives are organic solvent or micro-emulsion preservatives, such as ACQ, copper triazole and borates. Chromated copper arsenate (CCA), which was one of the most common wood preservatives, is now banned for use in residential construction in many countries because of

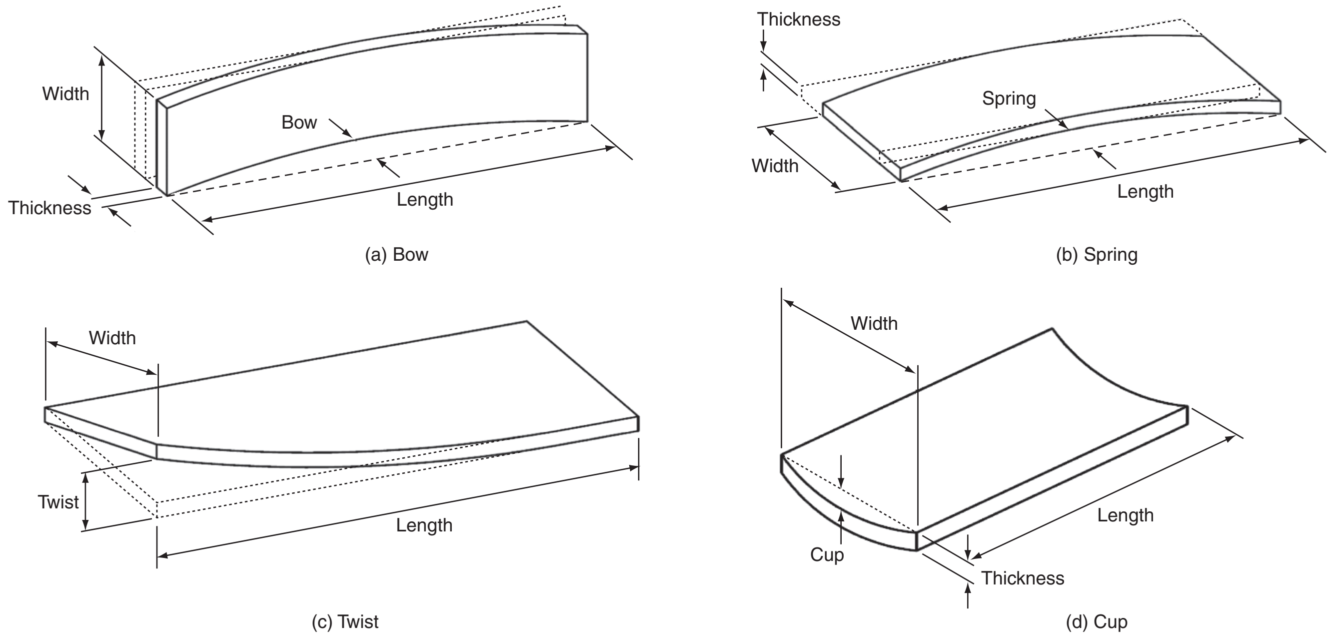

Figure 4 Geometrical imperfections and distortion in timber

health concerns. The selection of the appropriate preservative is based on the hazard level to which the timber will be exposed during service. It is very difficult to quantify the level of strength reduction due to decay or insect attack and for this reason they are prohibited in wood for structural applications.

Mechanical properties of wood

Parallel-to-grain properties

The parallel-to-grain direction is the strongest and stiffest from a structural perspective. The tensile strength of softwoods parallel to grain at 12% moisture content generally ranges between 70 to 140 MPa. The compression strength is lower and is usually in the range 30 to 60 MPa. For hardwoods, these values are generally higher. These values are for clear, straight-grained wood samples. For structural timber, the effects of knots and other strength reducing characteristics (commonly referred to as defects) can reduce these values by a factor of as much as 10. The failure mode is load dependent with tension failure being brittle while compression failure is ductile. The modulus of elasticity in tension and compression are generally taken as the same. At 12% moisture content, typical values for both softwoods and hardwood are in the range 7 to 14 GPa.

Perpendicular-to-grain properties

Perpendicular-to-grain properties are significantly lower than the equivalent parallel to grain properties. The tensile strength in the radial and tangential directions can be as low as 5 to 8% and 3 to 5%, respectively, of the values in the grain direction. Because of these low strength values, it is advisable to design timber structures in such a way that tension stresses perpendicular to grain do not occur or are minimized. Situations where tension perpendicular to grain stresses arise include at joints, in tapered or curved members and in notched beams. Compressive strengths perpendicular to grain are approximately 10 to 20% of the parallel to grain values. In compressive failure, the cells flatten and the cells walls touch resulting in a densification of the wood and increasing compressive resistance. However, this is also accompanied by large deformations which can occur even at relatively low load levels.

Engineered wood products

Research into finding ways of making more efficient use of timber as a structural material has led to development of a wide range of engineered wood products. These include panel products, such as oriented strand board (OSB) and plywood, structural elements, such as glued-laminated timber (glulam), laminated veneer lumber (sometimes referred to as Kerto) and I-joists. These products are made from wood strands, flakes, veneers or boards that are bonded together under heat and pressure generally with their grain angle parallel to the principal axis of the element formed. A major advantage of the manufacturing process is that defects are distributed throughout the element resulting in greater product reliability, strength, stiffness and dimensional stability compared to an equivalent solid timber element. Elements with greater depths and spans compared with solid wood can be easily produced. These products utilize wood that would otherwise be unsuitable for use in the construction industry such as fast growing small diameter trees and low grade wood material. This relieves some of the demand on mature high grade wood material.

The modulus of elasticity values perpendicular to grain are approximately equal in the radial and tangential directions and are about 4 to 9% of the parallel to grain values for softwoods.

Flexure and shear

The most commonly referenced strength property of wood is its modulus of rupture. This is defined as the bending stress in a flexural member at the failure load and is computed assuming an elastic stress distribution. For clear or defect-free wood, this is lower than the tensile strength parallel to grain. The converse is true for structural timber, which normally contains large numbers strength reducing characteristics or ‘defects’. Research has shown that size effects are important in flexural members as the larger the member the greater the probability of having a large defect which will reduce strength.

The shear strength is characterized by three types of failure, namely, shear parallel to grain, shear perpendicular to grain and rolling shear. In shear parallel to grain, the failure mode is quasi-brittle with shear strengths of about 5 to 12 MPa.

Joints

As with all structures, the structural capacity of timber structures is often limited by the joint capacity. A number of different joint configurations is used, including those made with mechanical fasteners/connectors, adhesives and traditional carpentry techniques.

Dowel-type fasteners are the most common form of mechanical fastener and include nails, screws, lag screws, dowels, drift pins, drift bolts and bolts. Nails are used for light loads and are commonly used for diaphragms, shear walls and trusses. Screws are better than nails in resisting vibratory or pull-out loads. Bolts, dowels and special timber connectors such as split-rings and shear plates are used to transfer heavy loads. Punched metal plate connectors are used in roof truss construction.

Structural adhesives in timber are commonly used to produce larger sections and longer members. Finger jointing and scarf jointing are used to increase the length of a member but finger jointing is also used to form corner joints. Glued laminated timber beams, I-joist and box-section beams are generally assembled using glued joints. Structural adhesives are also used in hybrid joints which also incorporate steel or fibre reinforced plastic rods or plates.

The use of traditional carpentry joints in large structural elements is becoming feasible with the wider availability of CNC machines for use in off-site manufacture.

Factors that influence mechanical behaviour

Strength reducing characteristics or naturally occurring defects

The processing of logs into structural timber results in a disruption of the structure of the naturally grown wood. This timber is referred to as in-grade timber and it has inferior properties to clear wood. This is due to the presence of strength-reducing characteristics or defects such as knots, slope of grain, gum veins, reaction wood, etc. Because of this, reliable mechanical properties of timber cannot be directly derived from the clear wood properties but must be determined by testing of in-grade specimens according to standardized procedures. In addition to a reduction in strength, the behaviour of structural timber is considerably more variable than clear wood as the pattern and frequency of defects varies from one piece to the next. Due to the random distribution of defects, the strength of a piece of timber depends on the size of the piece and the way in which it is loaded.

Knots occur where branches joined the main stem of the tree and formed very efficient joints. They affect the strength due to the fact that the fibre orientations in the knot are generally perpendicular to the fibre direction of the member and the grain of the wood surrounding the knot is also severely distorted. The strength reducing effect depends both on the size of knot and its location. The larger the knot, the greater will be the grain deviation and resulting loss of strength. Similarly, a higher frequency of knot occurrence will generally result in a lower strength than timber with fewer knots. Location of these characteristics is important; edge knots in a member subject to bending are more detrimental than the same sized knot located at the neutral axis. Knots can be present in large numbers in timber members (particularly softwoods) and their effect in degrading of strength properties is significant. In tension or bending tests of timber members, failure almost always occurs at the location of a knot (in the tension zone for bending members).

Sloping grain or cross grain occurs when the fibre direction is not parallel to the axis of the structural member. This may occur for a number of reasons. It may be due to the way the piece is cut from the log or alternatively, the fibre direction may not have been parallel to the axis of the log. Spiral grain is an anomaly whereby the wood fibres grow in a spiral direction around the tree axis instead of parallel to it. Sloping grain reduces the strength of the timber because the stress parallel to the axis has components parallel and perpendicular to the grain direction. Since the strength perpendicular to grain is very low, this limits the strength of the board. The strength reduction increases with increasing slope of grain. Another consequence of sloping grain is the tendency of pieces to warp with changes in moisture content.

Reaction wood is abnormal wood which may develop, for example, in a young tree leaning from the vertical due to wind, or it may occur in branches. In softwoods, the abnormal wood is called compressive wood as it occurs in areas of high compressive stress. Reaction wood in hardwoods develops in regions of high tension and is called tension wood. Reaction wood has higher density than normal wood and may be stronger. However, it displays high levels of dimensional instability with changes in moisture content and is therefore not used in structural members.

Fissures, in the form of shakes, checks and splits, may arise due to stresses developed during drying of the timber, due to mechanical loading or may occur during the growth of the tree. Their main effect is a reduction in the shear strength of the member. They can also act as a pathway for moisture to penetrate into the interior of the members, which may result in decay.

Moisture

The mechanical properties of clear wood can be assumed to vary linearly with moisture content below the FSP and the influence of moisture content on the properties of timber varies with respect to the property being considered. The tensile strength is slightly reduced with increasing moisture content, with the higher grades most affected. The bending strength is also reduced with increasing moisture content and the failure mode in bending is moisture dependant. At low moisture contents, bending failures occur in the tensile zone, whereas at high moisture contents failures tend to occur in the compression zone. Design codes around the world include stress modification factors to account for the influence of moisture.

Duration of load

The duration of load has a significant impact on both strength and stiffness. For a given magnitude of load, the strength of a timber member is reduced as the duration of the load increases. This loss of strength may be as high as 40%, which basically means the long-term strength for permanent loads such as self-weight or dead loads is only about 60% of that for the timber when it is first loaded in a structure. On the other hand, the duration of load effect on strength is less and the load carrying capacity is higher for members subjected to rapidly applied and very short term loading, such as peak wind events.

Significant creep deformations are also experienced under sustained load. Under constant climatic conditions, the creep deformation is approximately the same as the instantaneous elastic deformation for seasoned timber and can be 2 to 3 times the instantaneous deformation for unseasoned timber. Changes in moisture content have a major influence on the duration of load behaviour. As the moisture content is increased, the time to failure for a particular stress level is reduced and creep effects are much greater. Moisture cycling together with mechanical loading results in what is known as the mechano-sorptive effect. If wood is loaded in the unseasoned (green) state and subjected to varying climatic conditions, creep deformations of up to five times the initial deformation may result during the drying process.

Cyclic loads

Strength values for members subject to repeated loading should be reduced by about 50% for static clear samples where small knots are present and by 70% where knots and sloping grain is present.

Temperature and fire

In the normal range of ambient temperatures, the strength of wood does not vary, whilst at higher temperatures strength values are generally reduced. If the exposure time to higher temperatures is short, strength recovery is possible. However, for longer exposures permanent damage generally will result depending upon both the temperature and duration of exposure.

Wood is a combustible material and will ignite when exposed to fire. Light structural members are normally protected from fire by using a fire-resistant cladding, such as plasterboard. Large structural members have good inherent fire resistance because a char is formed on the exposed surface that acts as an insulator and the wood inside the char experiences only a small increase in temperature. The rate of charring is almost constant and is about 0.5 mm/minute for softwoods and 0.67 mm/minute for hardwoods. The strength and stiffness of the un-burnt wood remain unchanged and the capacity of the section after a period of fire can be determined from the residual cross-section. Fire protection can be provided by using intumescent coatings or by impregnating wood with flame or fire retardant salts, which raise the energy level required to cause wood to burn.

Measurement of mechanical properties

Standard test methods are available to determine the mechanical properties of timber. These tests are normally performed on timber that has been conditioned to about 12% moisture content. The size of the specimens and the rate of loading are prescribed. In Europe, testing is usually performed to the standard BS EN 408: 2003.

Bending properties are normally determined by symmetrically loading a specimen at the third points of a simply supported span of 18 times the specimen depth. This method is referred to as a 'four-point' bending test and the intent is to create a zone of constant moment with no shear in the most highly stressed mid third of the beam under test. The modulus of elasticity is determined from the slope of the load-midspan deflection curve and the bending strength is determined from the maximum load and the section modulus. This same test setup may also be used to determine the shear modulus.

Tension and compression parallel to grain properties are found by applying an axial force to a test piece having a full-size cross-section and sufficiently long to provide a test length clear of the grips. For perpendicular to grain tests, the test piece dimensions are prescribed. In all cases, the deformation is measured over a central gauge length. The modulus of elasticity is determined from the slope of the load-deformation curve. The tension or compression strength is found by dividing the failure load by the cross-sectional area.

Characteristic values

Due to the presence of random defects, the testing of samples from a population will result in mechanical properties that can be represented by a statistical distribution. Limit state design codes are based on characteristic values of these properties. Characteristic values are determined as the weighted means of the sample lower 5-percentiles for strength properties and density, whereas the weighted mean of the sample averages (50-percentile) is used for determining modulus of elasticity. Representative samples from a population, defined in terms of species, source, stress grade and manufacturing process, are tested in accordance with standard procedures. For each sample, the 5-percentile strength value, f_{05}, is found by ranking all the test values for a sample in ascending order and finding the value below which 5% of the values fall. A larger test sample will usually give a much more reliable estimation of the 5-percentile value and a variety of statistical methods are employed to fit the data distribution, with a log normal analysis being one of the more popular that is used.

The 5-percentile density values are often determined from assuming a normal distribution with a coefficient of variation of 10% as follows:

$$\rho_{05} = \rho_{\text{mean}} - 1.65(0.1\rho_{\text{mean}}) = 0.84\rho_{\text{mean}}$$

where ρ_{mean} is the mean density.

Characteristic values are adjusted for sample size and variability and for any deviation to the standard test conditions, such as sample dimensions and moisture content (BS EN 384: 2004).

Strength classes

The European strength class system assigns structural timber to grades or strength classes with defined properties. It comprises 12 classes for poplar and softwood species, namely C14, C16, C18, C20, C22, C24, C27, C30, C35, C40, C45 and C50, and six classes for hardwood species, namely D30, D35, D40, D50, D60 and D70.

The letters C and D refer, respectively, to coniferous and deciduous while the numerical values represent the characteristic bending strength in MPa for the class. Timber populations are assigned to a strength class if the characteristic values of bending strength and density of the population are equal to or greater than the values for the strength class and if the characteristic mean modulus of elasticity in bending equals or exceeds 95% of the value for the strength class. The European Standard BS EN 338: 2003 defines the characteristic strength, stiffness and density values for each strength class, a selection of which is given in **Table 1**.

Property		C16	C18	C24	C30	C35	C40	D35	D50	D60
Bending strength: MPa	$f_{m,k}$	16	18	24	30	35	40	35	50	60
Mean MOE parallel: GPa	$E_{0,\text{mean}}$	8	9	11	12	13	14	10	14	17
Density: kg/m^3	ρ_k	310	320	350	380	400	420	560	650	700

Table 1 Characteristic properties for selected strength classes

Research has shown that all important characteristic strength and stiffness properties can be calculated from either bending strength, modulus of elasticity or density. For any strength class, the characteristic values of other mechanical properties can be found using the following relationships:

Tensile strength parallel to grain
$$f_{t,0,k} = 0.6f_{m,k}$$

Compression strength parallel to grain
$$f_{c,0,k} = 5(f_{m,k})^{0.45}$$

Shear strength
$$f_{v,k} = \min\{3.8\,\text{MPa}: 0.2(f_{m,k})^{0.8}\}$$

Tensile strength perpendicular to grain
$$f_{t,90,k} = \min\{0.65\,\text{MPa}: 0.0015\rho_k\}$$

Compressive strength perpendicular to grain
$$f_{c,90,k}c = 0.007\rho_k \text{ for softwoods}$$
$$= 0.015\rho_k \text{ for hardwoods}$$

Modulus of elasticity parallel to grain
$$E_{0.05} = 0.67E_{0,\text{mean}} \text{ for softwoods}$$
$$= 0.84E_{0,\text{mean}} \text{ for hardwoods}$$

Mean modulus of elasticity perpendicular to grain
$$E_{90,\text{mean}} = E_{0,\text{mean}}/30 \text{ for softwoods}$$
$$= E_{0,\text{mean}}/15 \text{ for hardwoods}$$

Mean shear modulus
$$G_{\text{mean}} = E_{0,\text{mean}}/16$$

Grading of timber

The grading of timber for structural purposes is essential to ensuring that the material is reliable and has defined properties that can be used in design. As the timber cannot be tested to failure during a grading process, non-destructive evaluation procedures are used. This grading procedure is essentially a sorting process that assigns each individual piece of timber to a strength grade/class by defining grade limits for characteristics (known as grading parameters) that are correlated to the strength of the timber. In Europe the grade limits are related to a reference moisture content of 20%. Two main methods of grading are currently in use, namely visual grading and machine grading. BS EN 14081: 2005 is the European standard for strength grading of rectangular structural members.

Visual stress grading is the oldest form of strength grading. It involves carrying out a visual inspection of the strength reducing defects in a board. Different grading rules have developed in different countries with different numbers of grades, grade limits and ways of measuring the grading characteristics. However, all national visual grading standards must comply with the general requirements specified in BS EN 14081-1: 2005. In the UK, visual grading of softwoods and hardwoods are carried out to BS 4978: 2007 and BS 5756: 2007, respectively.

The grading process involves a visual examination of the four faces of each piece. The following characteristics are assessed: knots, slope of grain, rate of growth, wane, fissures, resin and bark pockets and distortion. The codes give limits for these characteristics for assignment to a particular grade. There are two softwood grades, namely, 'general structural' (GS) and 'special structural' (SS), one tropical hardwood grade, 'structural tropical hardwood' (HS) and four temperature hardwood grades, 'heavy structural temperate hardwood' (THA and THB) and 'general structural temperate hardwood' (TH1 and TH2). Any piece containing abnormal defects such as compression wood, insect damage, fungal decay, damage, combination of knots and/or other characteristics that could result in a significant decrease in strength resulting in a lack of serviceability, is excluded from the grades. Timber that has been visually graded to visual grading standards can be assigned to a strength class. The grade assignment depends not only on the visual grade but also on the species of timber and its source.

Machine stress grading operates on the principle that the strength of the timber is strongly correlated with one or more properties of the timber that can be measured by the machine – most commonly, minor axis deflection. By setting limits to these properties, timber is graded directly to a strength class. Most grading machines currently in use are designed to bend each piece of timber over a short span about its minor axis as it passes though the machine at high speed. The machine determines the bending modulus of elasticity of the timber at regular intervals along the length of the piece in one of two ways: the deflection induced by a fixed load or the load required to induce a fixed deflection are measured. Newer methods of determining the modulus of elasticity of the piece of timber use methods such as vibration, ultrasound and microwave techniques. These methods ensure that the timber is not damaged during the grading process. Machines that measure several grading parameters can give better accuracy. A combination of modulus of elasticity and knot parameters are better correlated with strength than modulus of elasticity alone. Optical scanners can be mounted on the grading machine to detect the presence of knots. These higher efficiency machines are more expensive than bending only machines and therefore are not as widely used at the present time.

Machine grading is carried out using one of two systems known as 'machine controlled' and 'output controlled'. The output controlled system is used for grading large volumes of a limited number of sizes, species and grades. This system involves destructive tests on specimens of the daily output. The machine controlled system was developed in Europe because of the wide variety of sizes, species, and grades that are produced. This system does not require destructive testing of the timber but instead involves strict assessment and control of the grading machines and the derivation of machine settings for different species, sources and grades. Further details of grading processes are discussed in Chapter 2.

Sustainability

Wood is a natural resource capable of being grown in most parts of the world. Implementation of proper management of a forest resource means that, at least in theory, it is possible to grow an endless supply of timber. The environmental benefits of wood are immense. Trees absorb CO_2 from the atmosphere, store the carbon and release O_2 to the atmosphere, and so wood forms a carbon sink – which is unique for an engineering material. Timber harvested from trees and used in construction continues to store carbon. The carbon is only released back into the atmosphere when the wood decays or is burned. This situation is carbon neutral as it releases the carbon originally absorbed from the atmosphere during photosynthesis. At the end of life of a timber structure, a certain percentage of the material can be recycled for direct reuse in construction or in the manufacture of panel products. Wood waste arising from harvesting and processing as well as from construction and demolition of buildings can be used as a replacement for fossil fuels. The development of engineered wood products has led to maximisation of the use of the material and a reduction in resource use and wastage.

The processing and transportation of timber requires little energy compared to the manufacture of steel and concrete. This embodied energy is given in **Table 2** for the three materials. As the embodied energy is expressed in

Material	Wood	Concrete	Steel
Embodied energy: MJ/kg	1.2	12.0	32.0
Emission: kgCO_2/kg	0.0000	0.0194	0.5168

Table 2 Embodied energy and CO_2 emissions in construction materials (Gonzalez, 2006)

MJ/kg and is therefore a function of the material density, care should be taken in interpreting this data. As the densities of steel, concrete and timber are approximately 7800 kg/m^3, 2400 kg/m^3, and 500 kg/m^3, respectively, the actual differences in embodied energy are very significant. In addition, wood is a good insulator and as a result the energy required for heating and cooling of timber buildings is reduced and this can result in significant savings in operating costs over the life of a building. A number of comparative studies of residential construction have shown that timber elements have less global warming emissions than steel or concrete, as shown in **Table 2**.

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