Wood: Strength and Stiffness

Wood is one of the oldest and best-known structural materials, and one of the few renewable natural resources. Wood is a desirable material for construction because it requires less energy to produce a usable end product than do other materials. Wood is also extremely versatile. Because wood has a wide range of physical and mechanical properties, species can be selected on the basis of how well they fit the requirements for a particular product. The ability of wood to resist loads depends on a number of factors, including the type, direction, and duration of loading; ambient conditions of moisture content and temperature; and the presence or absence of defects such as knots and splits. This article is concerned with the properties of clear wood and the factors that influence these properties.

1. *Orthotropic Nature of Wood Properties*

The cellular structure of wood and the physical organization of the cellulose chain within the cell wall make the physical and mechanical properties of wood dependent upon the direction of loading (see Wood Ultrastructure). Wood may be described as an orthotropic material; that is, it has unique and independent mechanical properties in the directions of three mutually perpendicular axes (Fig. 1). The longitudinal axis L is parallel to the cylindrical trunk of the tree and therefore also to the long axis of the wood fibers (parallel to the grain). The tangential axis T is perpendicular to the grain but tangent to the annual growth rings, and the radial axis R is normal to the growth rings. Collectively, the tangential and radial directions are referred to as being perpendicular to the grain. The properties of wood parallel to the grain are higher than those perpendicular to the grain, since the grain direction is also the direction of the primary bonds of the major chemical constituents of the wood cell wall.

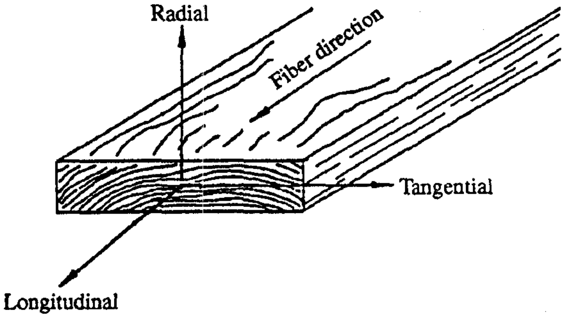

Figure 1
Three principal axes of wood with respect to grain direction and growth rings.

1.1 Elastic Properties

The elastic properties of wood are those produced at low stress levels and are completely recoverable after the loads are removed. Twelve constants, nine of which are independent, are needed to describe the elastic behavior of wood: three moduli of elasticity (E), three moduli of rigidy (G), and six Poisson ratios (μ). The three moduli of elasticity are denoted by E,, E_T, and E_R for the three orthotropic axes. These moduli are used to characterize the unit deformation (or strain) in the orthotropic directions, and are usually determined from compression tests. However, data for E_T and E_R are not extensive. Average values for a few species are presented in Table 1 as ratios with E_L. The modulus of elasticity determined by bending (E_B) rather than by axial load may be the only value available for a given species. Average values of E_B determined by bending tests are given in Table 2 for selected species. As tabulated, these E_B values include an effect of shear deflection. The E_B values determined from bending tests are usually increased by 10% when estimating E_L for axial tests.

Values for the moduli of rigidity, also called shear moduli, are also given in Table 1 as ratios with E_L. The three shear moduli are denoted G_{LR}, G_{LT}, and G_{RT}, where the subscripts refer to the plane over which the shear strain is measured. When a member is loaded axially, the deformation perpendicular to the direction of loading is proportional to the deformation in the direction of loading. The constants that characterize this proportionality are called Poission ratios, and are denoted μ_{LR}, μ_{LT}, and μ_{RT}. Here, the first subscript refers to the direction of applied load and the second subscript to the direction of lateral deformation. The elastic constants, as well as the ratios of elastic constants, vary by species and the moisture content and temperature at which they are measured.

1.2 Strength Properties

When wood is loaded to higher stress levels beyond the elastic range, plastic deformation or failure occurs. Five strength properties that are commonly measured for design purposes include bending, compression parallel and perpendicular to the grain, tension parallel to the grain, and shear parallel to the grain. In addition, measurements are sometimes required for tensile strength perpendicular to the grain and side hardness. Strength data for clear, defect-free specimens for a few species are given in Table 2. Procedures for making these measurements using clear, straight-grained material are given in ASTM standard D143.

For clear defect-free wood, the bending test

Table 1
Major elastic constants for five wood species at 12% moisture content.[a]

Property	Loblolly pine	Sitka spruce	Red oak	Yellow poplar	Balsa
E_T/E_L	0.078	0.043	0.082	0.043	0.015
E_R/E_L	0.113	0.078	0.154	0.092	0.046
G_{LR}/E_L	0.082	0.064	0.089	0.075	0.054
G_{LT}/E_L	0.081	0.061	0.081	0.069	0.037
G_{RT}/E_L	0.013	0.003	—	0.011	0.005
μ_{LR}	0.328	0.372	0.350	0.318	0.229
μ_{LT}	0.292	0.467	0.448	0.392	0.488
μ_{RT}	0.382	0.435	0.560	0.703	0.665
μ_{TR}	0.362	0.245	0.292	0.392	0.231

[a] Values for μ_{RL}, and μ_{TL} are small, seldom used, and often not available. Values of E_L may be estimated by multiplying the modulus of elasticity in static bending given in Table 2 by 1.10.

Table 2
Mechanical properties for five wood species at 12% moisture content.[a]

	Bending		Compression		Shear	Tension		
Species	Modulus of rupture (MPa)	Modulus of elasticity (GPa)	Parallel to grain (MPa)	Perpendicular to grain (MPa)	Parallel to grain (MPa)	Parallel to grain (MPa)	Perpendicular to grain (MPa)	Side hardness (kN)[a]
Loblolly pine	88.0	12.3	49.2	5.4	9.6	88.0	3.2	3.1
Sitka spruce	70.0	10.8	38.7	4.0	7.9	75.8	2.6	2.4
Red oak	99.0	12.5	46.6	7.0	12.3	101.4	5.5	5.7
Yellow poplar	70.0	10.9	38.2	3.4	8.2	154.4	3.7	2.4
Balsa	21.6	3.4	14.9	—	2.1	—	—	—

[a] Force at 5.6mm indention.

probably provides the most widely available strength property. The modulus of rupture (MOR) reflects the maximum load-carrying capacity in bending and is proportional to the maximum moment borne by the specimen. Modulus of rupture is an accepted criterion of strength, although it is not a true stress because the formula by which it is calculated is valid only within the elastic range. Compression strength parallel to the grain is much lower than tensile strength. During a bending test, initial yielding occurs on the compression side, followed by visible compression failures and enlargement of the compression zone. The neutral surface shifts toward the tensile side of the specimen as the tensile stress continues to increase. The maximum moment in the member is reached when failure in tension occurs. The MOR of clear wood is intermediate between tensile and compression strength parallel to the grain.

Ultimate compression stress parallel to the grain, UCS, when tested as a short column, is initially characterized by folding of the cellulose microfibrils. This folding can begin to occur at stress levels as low as one-half that of the ultimate failure stress. At higher stress levels, a similar folding takes place at the cell wall level, and eventually leads to gross failure of the specimen. In *compression perpendicular to the grain,* C-perp, failure occurs by collapse and flattening of the wood cells. During testing, clearly defined maximum load cannot usually be obtained, and only fiber stress at the proportional limit or stress at a defined deformation limit is reported. Although C-perp values do not show a particular maximum for either the radial or tangential orientation, values are often found to be a minimum at 45° to the annual growth increment for softwood species.

Ultimate tensile stress parallel to the grain, UTS, is difficult to obtain experimentally with clear defect-free wood. The value parallel to the grain is of the order of 45–120 MPa at 12% moisture content, whereas the *tensile stress perpendicular to the grain,* T-perp, may only be 2–6% of the parallel-to-grain value. Thus, it is difficult to get wood to fail in tension parallel to the grain without having excessive failure in tension perpendicular to the grain. For this reason, only a limited amount of data is available on the tensile strength of clear wood parallel to the grain. Values for T-perp are determined as an average of the values in the radial and tangential directions.

Shear strength parallel to the grain ranges from 3 to 15 MPa at 12% moisture content. Because wood is highly orthotropic, it is very difficult to get it to fail in shear perpendicular to the grain. Attempts to obtain shear failure perpendicular to the grain usually result in failure in another failure mode, such as compression perpendicular to the grain. A very limited amount of data suggests that shear strength perpendicular to the grain may be 2.5–3 times that of shear parallel to the grain.

2. *Factors Affecting Wood Properties*

2.1 Natural Characteristics Related to Wood Structure

Much of the variation in wood properties within and between trees can be attributed to density. The cell wall substance is actually heavier than water; with a specific gravity of about 1.5 kgm^{-3} regardless of species. The dry wood of most species nevertheless floats in water, and thus it is evident that part of the volume of a piece of wood is occupied by cell cavities and pores. Variations in the size of these openings and in the thickness of the cell walls cause some species to have more wood substance per unit volume than do other species. In the absence of knots and other defects, specific gravity is therefore an excellent indicator of the amount of wood substance present and is a good predictor of mechanical properties. Approximate relationships between various mechanical properties and specific gravity for clear straight-grained wood are given in Table 3.

A *knot* is that portion of a branch that has become incorporated in the bole of a tree. The influence of a knot on mechanical properties is primarily due to the interruption of continuity and change in direction of wood fibers around the knot. The influence of a knot on the performance of lumber depends upon the size, location, and shape of the knot as well as attendant grain deviation around the knot and the type of stress to which the wooden member is subjected. Knots have a much greater effect on strength in axial tension than in axial compression. The effect on bending is somewhat less than that in axial tension.

In some wood products the direction of critical stresses may not coincide with the orthotropic axes of the material. This may occur by choice in design, or it may be a result of the way the wood was removed from the log. This *cross-grain* can have a major effect on mechanical properties. Elastic properties in directions other than those along the orthotropic axes can be obtained from elastic theory. Strength properties in directions other than parallel (P) or perpendicular (Q) to the grain can be approximated using a Hankinson-type formula:

$$N = \frac{PQ}{P \sin^n \theta + Q \cos^n \theta}$$

where q is the angle to the grain. For bending and tensile strength, N ranges from 1.5 to 2, and for compressive strength from 1.5 to 2.0. For the modulus of elasticity an N value of 2 is often recommended.

2.2 Effects of Manufacturing and Use Environments

Many mechanical properties are affected by changes in *moisture content* below the fiber saturation point. Generally, most mechanical properties increase as wood is dried. The strength P at moisture content M in the range from 8 to 25% can be estimated by the following equation:

$$P = P_{12}\left(\frac{P_{12}}{P_g}\right)^{(12-M)/(M_p-12)}$$

For the purposes of the formula, moisture content of green wood (M_p) is often assumed to be 25% for most species. ASTM D2555 gives “dry/green” ratios of mechanical properties at 12% moisture content compared with green wood. Care must be taken if this formula is used at moisture contents very far below 12%. At low moisture content levels, the rate of change of properties becomes less than that predicted by the equation, and for some properties there may even be a maximum value with loss in property during further drying. Above the fiber saturation point, most mechanical properties are not affected by change in moisture content.

Table 3
Functions relating mechanical properties to specific gravity of clear straight-grained wood.[a]

	G (r –strength relationship)	
Property[b]	Softwoods	Hardwoods
Static bending		
Modulus of rupture (MPa)	$170.7G^{1.01}$	$171.3G^{0.13}$
Modulus of elasticity (GPa)	$20.5G^{0.84}$	$16.5G^{0.7}$
Compression parallel (MPa)	$93.7G^{0.97}$	$76.0G^{0.89}$
Compression perpendicular (MPa)	$16.5G^{1.57}$	$21.6G^{2.09}$
Shear parallel (MPa)	$16.6G^{0.85}$	$21.9G^{1.13}$
Tension perpendicular (MPa)	$6.0G^{1.11}$	$10.1G^{1.3}$
Side hardness (kN)	$85.9G^{1.5}$	$15.3G^{2.09}$

a Wood at 12% moisture content. b Compression parallel to grain is maximum crushing strength: compression perpendicular to grain is fiber stress at proportional limit. Specific gravity based on oven dry mass and volume at 12% moisture content (USDA 1999).

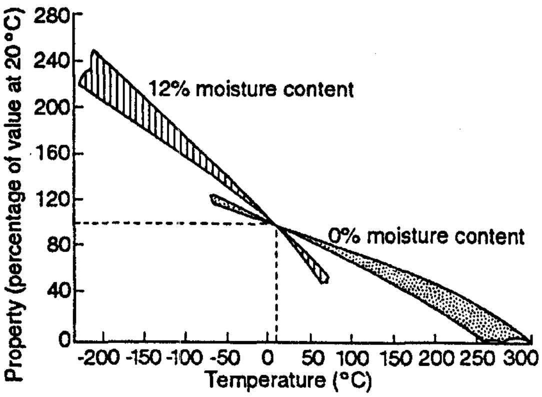

Figure 2
Immediate effect of temperature on bending strength, tensile strength perpendicular to grain, and compression strength parallel to grain. Variability is indicated by the width of bands.

Temperature can have both immediate (reversible) and permanent (irreversible) effects on wood properties (see *Wood Products: Thermal Degradation and Fire).* In general, one immediate effect is that mechanical properties tend to decrease as the temperature is increased (Fig. 2). There is an interaction with moisture content because dry wood is less sensitive to temperature change than is green wood. However, increases in temperature are usually accompanied by a reduction in moisture content. Permanent loss in mechanical properties can occur if wood is subjected to high temperatures over long periods. The magnitude of this effect depends upon temperature, duration of exposure, wood moisture content, and wood property. Permanent effects resulting from temperature are discussed in a report by the US Department of Agriculture Forest Service (1999).

In warm, moist conditions wood may be subject to *decay*. Decay fungi remove wood substance, thus lowering the gross specific gravity of the material. Strength losses can occur rapidly, even during the early stages of decay before noticeable loss in mass has occurred (see *Wood Products: Decay During Use).*

Mechanical properties, as given in Table 2, are usually referred to as static strength values. The tests of such properties are commonly conducted at a rate of loading such that failure occurs in 5–20 min. Higher values are obtained when wood is loaded faster, and lower values when it is loaded slower. Load capacity decreases from the static values by about 7–8% for each decade increase on a logarithmic time-scale. Thus, a wooden member subjected to a continuous bending load for 10 years may carry only 60% or less of the load required to produce failure in a static test. Creep is additional time-dependent deflection over that resulting from elastic deformation which occurs when wood is subjected to a constant load over a period of time. Changes in climatic conditions during a duration of load or creep test may produce a lower load capacity and more creep than that observed under constant conditions of temperature and moisture content. These effects can be quite substantial for small wood specimens. Fortunately, such changes are moderate for most wood structural members in typical serviceenvironments.

2.3 Allowable Engineering Properties of Lumber

When sawn, lumber yields wood of varying quality. Grading rules quantify the quality of lumber required for specific uses. Testing procedures for lumber and procedures for assigning allowable properties to the structural grades of lumber are given in ASTM standards such as D4761, D245, and D1990. In the USA, the National Design Specifications summarize allowable properties for structural grades of lumber and provide adjustment procedures for environmental and end-use conditions. The latest versions of national design specifications should be consulted when designing wood structures.

See also: Wood: Density; Wood: Creep and Creep Rupture; Wooden Structures

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