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Wood Properties

JERROLD E. WINANDY, ***USDA-Forest Service, Forest Products Laboratory,[1] Wisconsin***

Glossary

Allowable property Value of a property normally published for design use; allowable properties are identified with grade descriptions and standards, and they reflect the orthotropic structure of wood and anticipated end uses

Anisotropic Exhibiting different properties along different axes; in general, fibrous materials such as wood are anisotropic

Annual growth ring Layer of wood growth put on a tree during a single growing season. In the temperate zone, the annual growth rings of many species (e. g., oaks and pines) are readily distinguished because of differences in the cells formed during the early and late parts of the season; in some temperate zone species (e. g., black gum and sweetgum) and many tropical species, annual growth rings are not easily recognized

Diffuse-porous wood Certain hardwoods in which the pores tend to be uniformly sized and distributed throughout each annual ring or to decrease in size slightly and gradually toward the outer border of the ring

Earlywood Portion of the annual growth ring that is formed during the early part of the growing season; it is usually less dense and mechanically weaker than latewood

Hardwoods General botanical group of trees that has broad leaves in contrast to the conifers or softwoods; term has no reference to the actual hardness of the wood

Latewood Portion of the annual growth ring that is formed after the earlywood formation has ceased; it is usually denser and mechanically stronger than earlywood

Lumber Product of the saw and planing mill manufactured from a log through the process of sawing, resawing to width, passing lengthwise through a standard planing machine, and crosscutting to length

Orthotropic Having unique and independent properties in three mutually orthogonal (perpendicular) planes of symmetry; 3 special case of anisotropy

Ring-porous woods Group of hardwoods in which the pores are comparatively large at the beginning of each annual ring and decrease in size more or less abruptly toward the outer portion of the ring, thus forming a distinct inner zone of pores, the earlywood, and an outer zone with smaller pores, the latewood

Softwoods General botanical group of trees that in most cases has needlelike or scalelike leaves (the conifers); term has no reference to the actual hardness of the wood

Wood is an extremely versatile material with a wide range of physical and mechanical properties among the many species of wood. It is also a renewable resource with an exceptional strength-to-weight ratio. Wood is a desirable construction material because the energy requirements of wood for producing a usable end-product are much lower than those of competitive materials, such as steel, concrete, or plastic.

I. Wood Structure

A. Microstructure

The primary structural building block of wood is the tracheid or fiber cell. Cells vary from 16 to 42 μm in

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diameter and from 870 to 4000 μm long. Thus, a cubic centimeter of wood could contain more than 1.5 million wood cells. When packed together they form a strong composite. Each individual wood cell is even more structurally advanced because it is actually a multilayered, filament-reinforced, closed-end tube (Fig. 1) rather than just a homogeneous-walled, nonreinforced straw. Each individual cell has four distinct cell wall layers (Primary, S_1, S_2, and S_3). Each layer is composed of a combination of three chemical polymers: cellulose, hemicellulose, and lignin (Fig. 1). The cellulose and hemicellulose are linear polysaccharides (i.e., hydrophilic multiple-sugars), and the lignin is an amorphous phenolic (i. e., a three-dimensional hydrophobic adhesive). Cellulose forms long unbranched chains. and hemicellulose forms short branched chains. Lignin encrusts and stiffens these polymers.

Because carbohydrate and phenolic components of wood are assembled in a layered tubular or cellular manner with a large cell cavity, specific gravity of wood can vary immensely. Wood excels as a viable building material because the layered tubular structure provides **a** large volume of voids (void volume), it has an advantageous strength-to-weight ratio, and it has other inherent advantages, such as corrosion resistance, fatigue resistance, low cost, and ease-of-modification at the job site.

B. Macrostructure

The cross-section of a tree is divided into three broad categories consisting of the bark, wood, and cambium (Fig. 2). Bark is the outer layer and is composed of a dead outer phloem of dry corky material and a thin inner phloem of living cells. Its primary functions are protection and nutrient conduction. The thickness and appearance of bark vary substantially depending on the species and age of the tree.

Wood, or xylem, is composed of the inner sections of the trunk. The primary functions of wood are support and nutrient conduction and storage. Wood can be divided into two general classes: sapwood and heartwood. Sapwood is located next to the cambium. It functions primarily in food storage and the mechanical transport of sap. The radial thickness of sapwood is commonly 35 to 50 mm but may be 75 to 150 mm for some species. Heartwood consists of an inner core of wood cells that have changed, both chemically and physically, from the cells of the outer sapwood. The cell cavities of heartwood may also contain deposits of various materials that frequently give heartwood a much darker color. Extractive deposits formed during the conversion of living sapwood to dead heartwood often make the heartwood of some species more durable in conditions that may induce decay.

The cambium is a continuous ring of reproductive tissue located between the sapwood and the inner layer of the bark. Usually, it is 1 to 10 cells wide depending on the season. All wood and bark cells are aligned or stacked radially because each cell in a radial line originated from the same cambial cell.

1. Growth

Growth in trees is affected by the soil and environmental conditions with which the tree must exist and

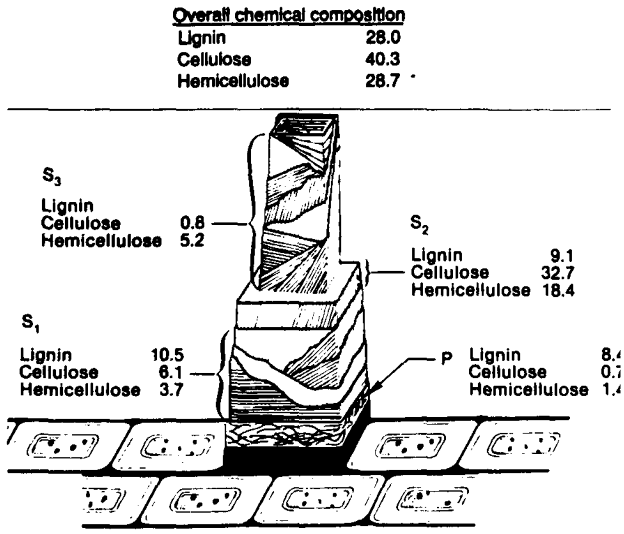

FIGURE 1 Microfibril orientation for each cell wall layer of Scotch pine with chemical composition as percentage of total weight. Cell wall layers are primary (P), S_1, S_2, and S_3.

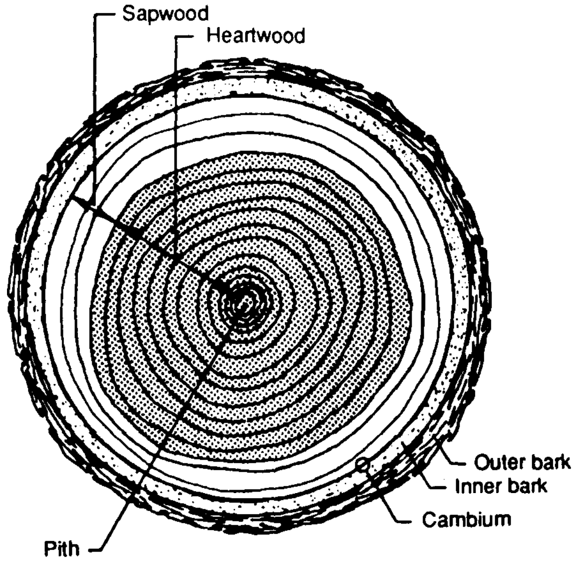

FIGURE 2 Elements of microstructure normally visible without magnification.

contend. Growth is accomplished by cell division. As new cells form, they are pushed either to the inside to become wood cells or to the outside to become bark cells. As the diameter of the tree increases, new cells are also occasionally retained in the cambium to account for increasing cambial circumference. Also, as the tree diameter increases, additional bark cells are pushed outward, and the outer surface becomes cracked and ridged. forming the bark patterns characteristic of each species.

The type and rate of growth vary between earlywood and latewood cells. Earlywood cells have relatively large cavities and thin walls, whereas latewood cells have smaller cavities and thicker walls. Because void volume is related to density and density is related to lumber strength. latewood is sometimes used to judge the quality or strength of some species. Earlywood is lighter in weight and color, softer, and weaker than latewood; it shrinks less across the grain and more lengthwise along the grain than does latewood.

2. Growth Rings

Growth rings vary in width depending on species and site conditions. Rings formed during short or dry seasons are thinner than those formed when growing conditions are more favorable. Also, rings formed in shady conditions are usually thinner than those formed by the same species in sunny conditions. It is commonly believed that the age of a tree may be determined by counting these rings. However, this method can lead to errors because abnormal environmental conditions can cause a tree to produce multiple-growth increments or even prevent growth entirely for a period.

3. Knots

As a tree grows, branches develop laterally from the trunk. These branches produce gross deviations in the normal grain of the trunk and result in knots when the log is sawn into lumber or timber. Knots are classified in two categories: intergrown knots and encased or loose knots. Intergrown knots are formed by living branches. Encased knots occur when branches die and the wound is surrounded by the growing trunk. Knots result in grain deviations. which is significant because straight-grained wood is approximately 10 to 20 times stronger parallel to grain than perpendicular to grain. Accordingly, knot size is a major predictor of sawn-timber strength.

4. Reaction Wood

Reaction wood is the response of a tree to abnormal environmental or physical stresses associated with leaning trees and crooked limbs. It is generally believed to bean attempt by the tree to return the trunk or limbs to a more natural position. In softwoods, reaction wood is called compression wood and results in the production of wood cells rich in phenolic lignin and poor in carbohydrates. It is found on the lower side of the limb or inclined trunk and effectively results in a higher cell wall packing density and high compression strength. ,Many of the anatomical, chemical, physical, and mechanical properties of reaction wood differ distinctly from those of normal wood. The specific gravity of compression wood is frequently 30 to 40% greater than that of normal wood, but the tensile strength is many times lower. This is why all grading rules restrict compression wood in any form from graded softwood lumber and timber.

||. Physical Properties

Physical properties are the quantitative characteristics of wood and its behavior to external influences other than applied forces. Included here are directional properties, moisture content, dimensional stability, thermal and pyrolytic (fire) properties, density, and electrical, chemical, and decay resistance. Familiarity with physical properties is important because they can significantly influence the performance and strength of wood used in structural applications.

The physical properties of wood most relevant to structural design and performance are discussed in this section. The effects that variations in these properties have on the strength of wood are more fully discussed in Section IV.

A. Directional Properties

Wood is an orthotropic and anisotropic material. Because of the orientation of the wood fibers and the manner in which a tree increases in diameter as it grows, properties vary along three mutually perpendicular axes: longitudinal, radial, and tangential (Fig. 3). The longitudinal axis is parallel to the fiber (grain) direction, the radial axis is perpendicular to the grain direction and normal to the growth rings, and the tangential axis is perpendicular to the grain direction and tangent to the growth rings. Although most wood properties differ in each of these three axis directions, differences between the radial and tangential axes are relatively minor when compared to differences between the radial or tangential axis and the

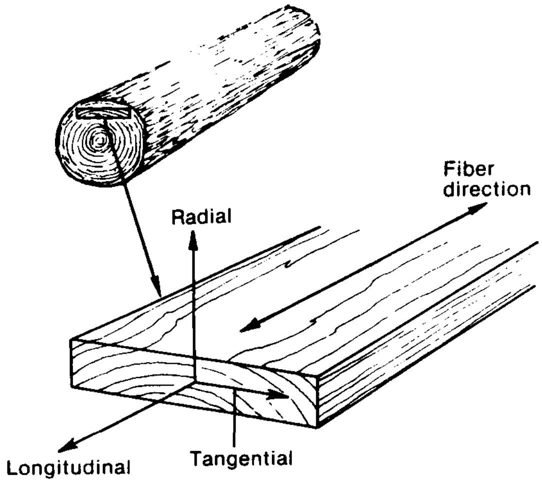

FIGURE 3 Three principal axes of wood with respect to grain direction and growth rings.

longitudinal axis. Property values tabulated for structural applications arc often given only for axis directions parallel to groin (longitudinal) and perpendicular to grain (radial or tangential).

B. Moisture Content

The moisture content of wood is defined as the weight of water in wood given as a percentage of ovendry weight. In equation form, moisture content (MC) is expressed as follows:

$$MC = \frac{\text{moist weight} - \text{dry weight}}{\text{dry weight}} \times 100\%. \tag{1}$$

Water is required for the growth and development of living trees and constitutes a major portion of green wood anatomy. In living trees, moisture content depends on the species and the type of-wood, and may range from approximately 25% to more than 250% (two and a half times the weight of the dry wood material). In most species, the moisture content of sapwood is higher than that of heartwood.

Water exists in wood either as bound water (in the cell wall) or free water (in the cell cavity). As bound water, it is bonded (via secondary or hydrogen bonds) within the wood cell walls. As free water, it is simply present in the cell cavities. When wood dries, most free water separates at a faster rate than bound water because of accessibility and the absence of secondary bonding. The moisture content at which the cell walls are still saturated but virtually no water exists in the cell cavities is called the fiber saturation point. The fiber saturation point usually varies between 21 and 28%.

Wood is a hydroscopic material that absorbs moisture in a humid environment and loses moisture in a dry environment. As a result, the moisture content of wood is a function of atmospheric conditions and depends on the relative humidity and temperature of the surrounding air. Under constant conditions of temperature and humidity, wood reaches an equilibrium moisture content (EMC) at which it is neither gaining nor losing moisture. The EMC represents a balance point where the wood is in equilibrium with its environment.

In structural applications, the moisture content of wood is almost always undergoing some changes as temperature and humidity conditions vary. These changes are usually gradual and short-term fluctuations that influence only the surface of the wood. The time required for wood to reach the EMC depends on the size and permeability of the member, the temperature, and the difference between the moisture content of the member and the EMC potential of that environment. Changes in moisture content cannot be entirely stopped but can be retarded by coatings or treatments applied to the wood surface.

C. Dimensional Stability

Above the fiber saturation point, wood will not shrink or swell from changes in moisture content because free water is found only in the cell cavity and is not associated within the cell walls. However, wood changes in dimension as moisture content varies below the fiber saturation point. Wood shrinks as it loses moisture below the fiber saturation point and swells as it gains moisture up to the fiber saturation point. These dimensional changes may result in splitting, checking, and warping. The phenomena of dimensional stability and EMC must be understood, recognized, and considered in good timber design.

Dimensional stability of wood is one of the few properties that significantly differs in each of the three axis directions. Dimensional changes in the longitudinal direction between the fiber saturation point and ovendry are between 0.1 and 0.2% and are of no practical significance; however, in reaction or juvenile wood, these percentages may be significantly higher. The combined effects of shrinkage in the tangential and radial axes can distort the shape of wood pieces because of the difference in shrinkage and the curvature of the annual rings (Fig. 4). Generally, tangential shrinkage (varying from 4.4 to 7.8% depending on species) is twice that of radial shrinkage (from 2.2 to 5.6%).

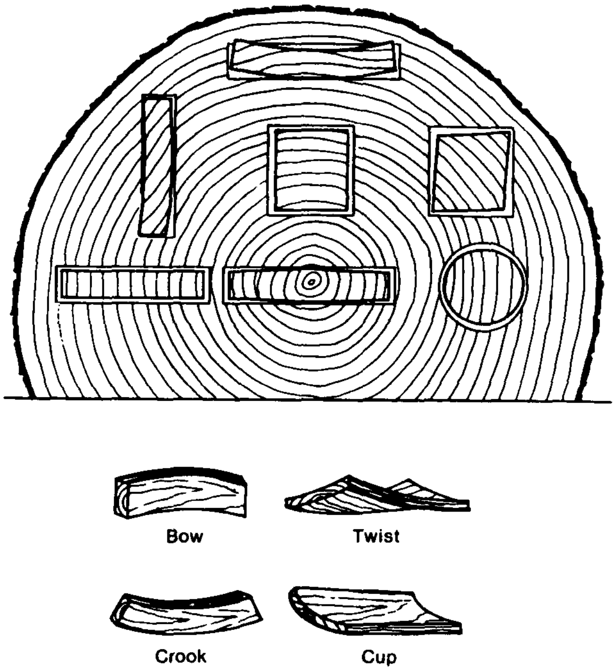

FIGURE 4 Characteristic shrinkage and distortion of wood as affected by direction of growth rings. Such distortion can result in warp, generally classified as bow, twist, crook, and cup.

D. Thermal Expansion

Thermal expansion of dry wood is positive in all directions; wood expands when heated and contracts when cooled. Wood that contains moisture reacts to temperature changes differently than dry wood.

The linear expansion coefficients of dry wood parallel to grain are generally independent of specific gravity and species and range from approximately 3×10^{-6} to 4.5×10^{-6} per °C. The linear expansion coefficients across the grain (tangential and radial) are in proportion to density and range from approximately 5 to 10 times greater than parallel to grain coefficients.

When moist wood is heated, it tends to expand because of normal thermal expansion and shrink because of moisture loss from increased temperature. Unless the initial moisture content of the wood is very low (3 to *4%),* the net dimensional change on heating is negative. Wood at intermediate moisture contents of approximately 8 to 20% will expand when first heated, then gradually shrink to a volume smaller than the initial volume as moisture is lost in the heated condition.

E. Pyrolytic Properties

Under appropriate conditions, wood will undergo thermal degradation or pyrolysis. The by-products of pyrolysis may burn, and if enough heat is generated and retained by the wood, the wood can be set on fire. In the presence of a pilot flame (independent source of ignition), the minimum rate of heating necessary for ignition is of the order of 0.3 calorie per square centimeter. In the absence of a pilot flame, the minimum rate of heating necessary for ignition is of the order of 0.6 calorie per square centimeter, nearly double the rate of the pilot flame situation.

Still, heavy timber construction deserves an extremely favorable fire-insurance rating because it will generally not produce sufficient heat energy to maintain combustion unless an external heat source is present. Timber will gradually produce a char layer from the residue of wood combustion. This char acts as a thermal insulator. On heavy timbers, this char layer will eventually inhibit combustion by establishing a thermal barrier between the uncharred wood (interior to char) and the heat of the fire (exterior to char). Heavy timber is virtually self-extinguishing, but steel, which has a thermal conductivity 100 times that of wood, will absorb heat until it reaches a temperature at which it yields under structural load without actually burning.

F. Density and Specific Gravity

The density of a material is the mass per unit volume at some specified condition. For a hydroscopic material such as wood, density depends on two factors: the weight of the wood structure and moisture retained in the wood. Wood density at various moisture contents can vary significantly and must be given relative to a specific condition to have practical meaning.

Specific gravity provides a relative measure of the amount of wood substance contained in a sample of wood. It is a dimensionless ratio of the weight of an ovendry volume of wood to the weight of an identical volume of water. In research activities, specific gravity may be reported on the basis of both weight and volume ovendry. For many engineering applications, the basis for specific gravity is generally the ovendry weight and volume at a moisture content of 12%. For example, a volume of wood at some specified moisture content with a specific gravity of 0.50 would have a density of 500 $\mathrm{kg/m^3}$.

G. Electrical Resistance

Wood is a good electrical insulator. However, significant variations in conductivity do exist. These variations in electrical resistance can be related to variations in grain orientation, temperature, and moisture content. The conductivity of wood in the longitudinal axis is approximately twice that in the radial or tangential axes. The electrical conductivity of wood generally doubles for each 10 °C increase in temperature. Generally, variations in conductivity related to wood density and species are considered minor.

The correlation between electrical resistivity and moisture content is the basis for electrical resistance-type moisture meters that estimate moisture content by measuring the resistance of the wood between two electrodes. Moisture content meters, as these instruments are commonly called, need to be calibrated for temperature and species and are effective only for moisture content ranges of 5 to *25%*. They are generally unreliable for high resistivities at moisture contents below 5 or 6%, for estimating the moisture content of green timber, or for estimating moisture content of treated timbers (most treatments alter conductivity).

H. Decay Resistance

Wood decay fungi and wood-destroying organisms require oxygen, appropriate temperature, moisture, and a food source. Wood will not decay if kept dry (moisture content less than 20%). On the other extremc, if continuously submerged in water at sufficient depths. wood will usually not decay. Whenever wood is intermediary to either of these two extremes, problems with wood decay can result. To avoid problems with decay where moisture cannot be controlled, the engineer or designer can use either naturally durable species or treated timber.

The natural durability of wood to the mechanisms and processes of deterioration is related to the anatomical characteristics and species of wood. In general, the outer zone or sapwood of all species has little resistance to deterioration and fails rapidly in adverse environments. For heartwood, natural durability depends on species. Heartwood forms as the living sapwood cells gradually die. In some species, the sugars present in the cells are converted to highly toxic extratives that are deposited in the wood cell wall. Many species produce durable heartwood, including western red cedar, redwood, and black locust; however, durability varies within a tree and between trees of a given species. To enhance durability, wood can be treated with an EPA-registered, toxic preservative chemical treatment.

1. Chemical Resistance

Wood is highly resistant to many chemicals, which gives it a significant advantage over many alternative building materials. Wood is often considered superior to alternative materials, such as concrete and steel, partly because of its resistance to mild acids (pH more than 2.0), acidic salt solutions, and corrosive agents. Generally, iron holds up better on exposure to alkaline solution than does wood, but wood can be treated with many of the common wood preservatives (e. g., creosote) to greatly enhance its performance in this respect.

Heartwood is far more durable than sapwood to chemical attack because heartwood is more resistant to penetration by liquids. Many preservative treatments, such as creosote or pentachlorophenol in heavy oil, can also significantly increase the ability of wood to resist liquid or chemical penetration, or both. Chemical solutions may induce two general types of action: normal reversible swelling by a liquid and irreversible chemical degradation. With the former, removal of the liquid will return wood to its original condition. With the latter, permanent changes occur within the wood structure from hydrolysis, oxidation, or delignification.

|||. Mechanical Properties

Mechanical properties are the characteristics of a material in response to externally applied forces. They include elastic properties, which characterize resistance to deformation and distortion, and strength properties, which characterize resistance to applied loads. Mechanical property values are given in terms of stress (force per unit area) and strain (deformation resulting from the applied stress). The mechanical property values of wood are obtained from laboratory tests of lumber of straight-grained clear wood samples (without natural defects that would reduce strength, such as knots, checks, splits, etc.).

A. Elastic Properties

Elastic properties relate the resistance of a material to deformation under an applied stress to the ability of the material to regain its original dimensions when the stress is removed. For a material with ideal elastic properties loaded below the proportional (elastic) limit, all deformation is recoverable and the body returns to its original shape when the stress is removed. Wood is not ideally elastic in that some deformation from loading is not immediately recovered when the load is removed; however, residual deformations are generally recoverable over a period of time. Although technically considered a viscoelastic material, wood is usually assumed to behave as an elastic material for most engineering applications.

For an isotropic material with equal property values in all directions, elastic properties are measured by three elastic constants: modulus of elasticity (E), modulus of rigidity (G), and Poisson's ratio (μ). The following equation shows the relationship:

$$\mu_{ij} = E_k/G_{ij}, \tag{2}$$

where i, j, and k represent the three principal axes. Because wood is orthotropic, 12 constants are required to measure elastic behavior: three moduli of elasticity, three moduli of rigidity, and six Poisson's ratios.

1. Modulus of Elasticity

Modulus of elasticity relates the stress applied along one axis to the strain occurring on the same axis. The three moduli of elasticity for wood are denoted E_L, E_R, and E_T to reflect the elastic moduli in the longitudinal, radial, and tangential directions, respectively. For example, EL relates the stress in the longitudinal direction to the strain in the longitudinal direction.

Elastic constants vary within and between species and with moisture content and specific gravity. The only constant that has been extensively derived from test data is E_L. Other constants may be available from limited test data but are most frequently developed from material relationships or by regression equations that predict behavior as a function of density. Relative values of elastic constants for clearwood of several common wood species are given in Table I.

2. Shear Modulus

Shear modulus relates shear stress to shear strain. The three shear moduli for wood are denoted G_{LR}, G_{LT}, and G_{RT} for the longitudinal-radial. longitudinal-tangential, and radial-tangential planes. respectively. For example, G_{LR} is the modulus of rigidity based on the shear strain in the LR plane and the shear stress in the LT and RT planes. The modulus of rigidity for several wood species and for each plane are given in Table 1.

3. Poisson's Ratio

Poisson's ratio relates the strain parallel to an applied stress to the accompanying strain occurring laterally. For wood, the six Poisson's ratios are denoted μ_{LR}, μ_{LT}, μ_{RL}, μ_{RT}, μ_{TL}, and μ_{TR}. The first subscript refers to the direction of applied stress; the second subscript refers to the direction of the accompanying lateral strain. For example, μ_{LR} is the Poisson's ratio for stress along the longitudinal axis and strain along the radial axis. Estimates of Poisson's ratios for several wood species and for each orientation are given in Table I.

B. Strength Properties

Strength properties me the ultimate resistance of a material to applied loads. With wood, strength varies significantly depending on species, loading condition, load duration, and a number of assorted material and environmental factors.

Because wood is anisotropic, mechanical properties also vary in the three principal axes. Property values in the longitudinal axis are generally significantly higher than those in the tangential or radial axes. Strength-related properties in the longitudinal axis are usually referred to as parallel-to-grain properties. For most engineering design purposes, simply differentiating between parallel- and perpendicular-to-grain properties is sufficient because the relative tangential and radial directions are randomized by the primary sawing process (i. e., conversion from logs to boards).

1. Compression

When a compression load is applied parallel to grain, it produces stress that deforms (shortens) wood cells along their longitudinal axis. When wood is stressed in compression parallel to grain, failure initially begins as the microfibrils begin to fold within the cell wall, thereby creating planes of weakness or instability within the cell wall. As stress in compression parallel to grain continues to increase, the wood-cells themselves fold into S shapes. forming visible wrinkles on the surface. Large deformations occur from the internal crushing of the complex cellular structure. The average strength of green clear wood specimens of Douglas-fir and loblolly pine in compression parallel to grain is approximately 26.1 and 24.2 MPa, respectively.

When a compression load is applied perpendicular to grain, it produces stress that deforms the wood cells perpendicular to their length. Once the hollow cell cavities are collapsed, wood is quite strong because no void space exists. In practice, compressive strength of wood perpendicular to grain is usually assumed to be exceeded when deformation exceeds *4%.* of the proportional limit stress. Using this convention, the average strength of green clear wood specimens of Douglas-fir and loblolly pine in compression perpendicular to grain is approximately 4.8 and 4.6 MPa, respectively.

Compression applied at an angle to the grain produces stresses that act both parallel and perpendicular

TABLE I

Elastic Ratios for Various Species

Species	Approximate specific gravity[a]	Approximate moisture content (percentage)	Modulus of elasticity ratio[b]		Ratio of modulus of rigidity to modulus of elasticity[c]			Poisson's ratio[d]					
			E_T/E_L	E_R/E_L	G_{LR}/E_L	G_{LT}/E_L	G_{RT}/E_L	μ_{LR}	μ_{LT}	μ_{RT}	μ_{TR}	μ_{RL}	μ_{TL}
Balsa	0.13	9	0.015	0.046	0.054	0.037	0.005	0.23	0.49	0.67	0.23	0.02	0.01
Birch, yellow	0.64	13	0.050	0.078	0.074	0.068	0.017	0.43	0.45	0.70	0.43	0.04	0.02
Douglas-fir	0.50	12	0.050	0.068	0.064	0.078	0.007	0.29	0.45	0.39	0.37	0.04	0.03
Spruce, Sitka	0.38	12	0.043	0.078	0.064	0.061	0.003	0.37	0.47	0.44	0.24	0.04	0.02
Sweetgum	0.53	11	0.050	0.115	0.089	0.061	0.021	0.32	0.40	0.68	0.31	0.04	0.02
Walnut, black	0.59	11	0.056	0.106	0.085	0.062	0.021	0.50	0.63	0.72	0.38	0.05	0.04
Yellow-poplar	0.38	11	0.043	0.092	0.075	0.069	0.011	0.32	0.39	0.70	0.33	0.03	0.02

[a] Based on ovendry weight and volume at the moisture content shown.

[b] E is modulus of elasticity; T, tangential axis, L, longitudinal axis, R, radial axis.

[c] G is modulus of ridigity.

[d] μ is Poisson's ratio.

to grain. The strength at any intermediate angle is intermediate to values of compression parallel and perpendicular to grain and is determined using Hankinson's formula.

2. Tension

Parallel to its grain, wood is very strong in tension. Failure occurs by a complex combination of two modes: cell-to-cell slippage and cell wall failure. Slippage occurs where two adjacent cells slide past one another. Cell wail failure involves rupture within the cell wall with little or no visible deformation prior to complete failure. Tensile strength parallel to grain for clear wood has been historically difficult to obtain; it is often conservatively estimated from bending test values because clear wood normally exhibits initial failure on the face stressed in tension.

In contrast to tension parallel to grain, wood is relatively weak when loaded in tension perpendicular to grain. Stresses in this direction act perpendicular to the cell lengths and produce splitting or cleavage along the grain, which can have a significant effect on structural integrity. Deformations are usually low prior to failure because of the geometry and structure of the cell wall cross-section. Strength in tension perpendicular to grain for clear green samples of Douglas-fir and loblolly pine average 2.1 and 1.8 MPa, respectively. However, because of the excessive variability associated with ultimate stress in tension perpendicular to grain. design situations that induce this stress should be avoided.

3. Bending

Flexural (bending) properties are critical. Bending stresses are induced when a material is used as a beam, such as in a floor or rafter system. The. bending strength of clear Dougias-fir and loblolly pine averages 52.6 and 50.3 MPa, respectively, while the modulus of elasticity averages 10.7 and 9.7 GPa, respectively. Because tensile and compressive strengths parallel to grain are different from each other, the strength in bending is less than in tension but more than in compression.

4. Shear

When used as a beam, wood is exposed to compression stress on one surface of the beam and tensile stress on the other. This opposition of stress results in a shearing action through the section of the beam. This parallel-to-grain shearing action is termed horizontal shear. The horizontal shear strength of clear Douglas-fir and loblolly pine averages 6.2 and 5.9 MPa, respectively. Conversely, when stress is applied perpendicular to the cell length in a plane parallel to grain, this action is termed rolling shear. Rolling shear stresses produce a tendency for the wood cells to roll over one another. In general, rolling shear strength values for clear specimens average 18 to 28% of the parallel-to-grain shear values.

5. Energy Absorption Resistance

Energy absorption or shock resistance is a function of the ability of a material to quickly absorb and then dissipate energy via deformation. Wood is remarkably resilient in this respect and is often a preferred material for shock loading. Several parameters are used to describe energy absorption depending on the eventual criteria of failure considered. Work to proportional limit, work to maximum load, and work to total failure (i. e., toughness) describe the energy absorption of wood materials at progressively more severe failure criteria.

6. Fatigue

The fatigue resistance of wood is sometimes an important consideration. Wood, like many fibrous materials, is quite resistant to fatigue (i. e., the effects of repeated loading). In many crystalline metals, repeated loadings of 1 to 10 million cycles at stress levels of 10 to 15%. of ultimate can induce fatigue-type failures. At comparable stress levels, the fatigue strength of wood is often several times that of most metals.

7. Hardness

Hardness represents the resistance of wood to indentation and marring. Hardness is comparatively measured by force required to embed a 11.3-mm ball one-half its diameter into the wood.

|V. Factors Affecting Properties of Wood

To this point, our discussions of wood properties have mostly been based on tests of straight-grained specimens of clear wood. Clear wood properties are important, but by no means do they totally represent the engineering performance of solid-sawn lumber, timber, or glulam (glued-laminated timber) containing knots, slope of grain, and other strength-reducing characteristics. To understand the properties of these end-use products, the user must appreciate

TABLE II

Mechanical Properties of Some Commercially Important Woods Grown in the United States[a]

Common name of species	Moisture condition	Specific gravity[b]	Static bending			Impact bending[d] (m)	Compression parallel to grain[e] (MPa)	Compression perpendicular to grain[f] (MPa)	Shear parallel to grain[g] (MPa)	Tension perpendicular to grain[h] (MPa)	Side hardness-load perpendicular to grain (kN)
			Modulus of rupture (MPa)	Modulus of elasticity[c] (GPa)	Work to maximum load (kJ/m^3)						
						Hardwoods					
Aspen,	Green	0.35	34.9	5.89	43.8	0.56	14.7	1.2	4.5	1.6	1.33
quaking	Dry	0.38	57.5	8.08	52.0	0.53	29.1	2.5	5.8	1.8	1.56
Cherry,	Green	0.47	54.8	8.97	87.6	0.84	24.2	2.5	7.7	3.9	2.94
black	Dry	0.50	84.2	10.20	78.1	0.74	48.7	4.7	11.6	3.8	4.23
Cottonwood,	Green	0.37	36.3	6.92	50.0	0.53	15.6	1.4	4.7	2.8	1.51
eastern	Dry	0.40	58.2	9.38	50.7	0.51	33.6	2.6	6.4	4.0	1.91
Elm,	Green	0.46	49.3	7.60	80.8	0.97	19.9	2.5	6.8	4.0	2.76
American	Dry	0.50	80.8	9.18	89.0	0.99	37.8	4.7	10.3	4.5	3.69
Hickory,	Green	0.64	75.3	10.75	162.3	1.88	31.4	5.8	0.4	—	—
shagbark	Dry	0.72	138.3	14.79	176.7	1.70	63.1	12.1	16.6	—	—
Maple											
Red	Green	0.49	52.7	9.52	78.1	0.81	22.5	2.7	7.9	—	3.11
	Dry	0.54	91.8	11.23	85.6	0.81	44.8	6.8	12.7	—	4.23
Sugar	Green	0.56	64.4	10.61	91.1	1.02	27.5	4.4	10.0	—	4.31
	Dry	0.63	108.2	12.53	113.0	0.99	53.6	10.1	16.0	—	6.45
Oak											
Northern	Green	0.56	56.8	9.24	90.4	1.12	23.6	4.2	8.3	5.1	4.45
red	Dry	0.63	97.9	12.46	99.3	1.09	46.3	6.9	12.2	5.5	5.74
White	Green	0.60	56.8	8.56	79.4	1.07	24.4	4.6	8.6	5.3	4.72
	Dry	0.68	104.1	12.19	101.3	0.94	0.9	7.3	13.7	5.5	6.05
Walnut,	Green	0.51	65.1	9.72	100.0	0.94	29.4	3.4	8.4	3.9	4.00
black	Dry	0.55	100.0	11.50	73.3	0.86	51.9	6.9	9.4	4.7	4.49
Yellow-	Green	0.40	41.1	8.35	51.4	0.66	18.2	1.8	5.4	3.5	1.96
poplar	Dry	0.42	69.2	10.82	60.3	0.61	37.9	3.4	8.1	3.7	2.40
						Softwoods					
Cedar,	Green	0.31	35.6	6.44	34.2	0.43	19.0	1.6	5.3	1.6	1.16
western red	Dry	0.32	51.4	7.60	39.7	0.43	31.2	3.1	6.8	1.5	1.56
Douglas-fir,[i]	Green	0.45	52.7	10.68	52.0	0.66	25.9	2.6	6.2	2.1	2.22
coast	Dry	0.48	84.9	13.35	67.8	0.79	49.5	5.5	7.7	2.3	3.16

Fir											
Balsam	Green	0.33	37.7	8.56	32.2	0.41	18.0	1.3	4.5	1.2	1.29
	Dry	0.35	63.0	9.93	34.9	0.51	36.2	2.8	6.5	1.2	1.78
White	Green	0.37	40.4	7.94	38.3	0.56	19.9	1.9	5.2	2.1	1.51
	Dry	0.39	67.1	10.27	49.3	0.51	39.7	3.6	7.5	2.1	2.14
Hemlock,	Green	0.42	45.2	8.97	47.2	0.56	23.0	1.9	5.9	2.0	1.82
western	Dry	0.45	77.4	11.16	56.8	0.58	49.3	3.8	8.8	2.3	2.40
Larch,	Green	0.48	52.7	10.00	70.5	0.74	25.7	2.7	6.0	2.3	2.27
western	Dry	0.52	89.0	12.80	86.3	0.89	52.2	6.4	9.3	2.9	3.69
Pine											
Eastern	Green	0.34	33.6	6.78	35.6	0.43	16.7	1.5	4.7	1.7	1.29
white	Dry	0.35	58.9	8.49	46.6	0.46	32.9	3.0	6.2	2.1	1.69
Loblolly	Green	0.47	50.0	9.59	56.2	0.76	24.0	2.7	5.9	1.8	2.00
	Dry	0.51	87.6	12.26	71.2	0.76	48.8	5.4	9.5	3.2	3.07
Ponderosa	Green	0.38	34.9	6.85	35.6	0.53	16.8	1.9	4.8	2.1	1.42
	Dry	0.40	64.4	8.83	48.6	0.48	36.4	4.0	7.7	2.9	2.05
Redwood											
Old-	Green	0.38	51.4	8.08	50.7	0.53	28.8	2.9	5.5	1.8	1.82
growth	Dry	0.40	68.5	9.18	47.2	0.48	42.1	4.8	6.4	1.6	2.14
Young-	Green	0.34	40.4	6.57	39.0	0.41	21.3	1.8	6.1	2.1	1.56
growth	Dry	0.35	54.1	7.53	35.6	0.38	35.6	3.6	7.6	1.7	1.87
Spruce											
Sitka	Green	0.37	39.0	8.42	43.1	0.61	18.3	1.9	5.2	1.7	1.56
	Dry	0.40	69.8	10.75	64.4	0.64	38.4	4.0	7.9	2.5	2.27
White	Green	0.33	34.2	7.81	41.1	0.56	16.1	1.4	4.4	1.5	1.42
	Dry	0.36	64.4	9.79	52.7	0.51	35.5	2.9	6.6	2.5	2.14

[a] Results of tests on small, clear, straight-grained specimens. Values in the first line for each species are from tests of green material; those in the second line are from tests of seasoned material adjusted to a 12% moisture content.

[b] Based on weight ovendry and volume at moisture content indicated.

[c] Measured from a simply supported, center-loaded beam, on a span-depth ratio of 14/1. The modulus can be corrected for the effect of shear deflection by increasing it 10%.

[d] Height of drop causing complete failure.

[e] Maximum crushing strength.

[f] Fiber stress at proportional limit.

[g] Maximum shearing strength.

[h] Maximum tensile strength.

[i] Douglas-fir in the States of Oregon and Washington west of the summit of the Cascade Mountains.

the impacts of several anatomical and processing-related factors. The user must also appreciate the interactive nature of environmental factors. This section will attempt to briefly relate the importance of many of these factors independently and in aggregate.

A. Anatomical Factors

The mechanical properties of wood vary between species; they are often compared via species averages (Table II). However, because mechanical properties vary within a species, it is incorrect to think that all material of Species A is stronger than material of Species B if, for example, average values are 10 to 15% different.

1. Specific Gravity and Density

The property values of wood increase with increasing specific gravity (SG). While density is a measure of weight per unit volume often reported with kilograms per cubic meter, SG is a dimensionless ratio of the density of wood at a specified moisture content to the density of water. Because changes in moisture contents result in dimensional changes, SG and density should be compared at the same moisture content. Specific gravity is an index of mechanical property values of wood free from defects; the higher the SG, the higher the appropriate property value. However, SG and density values for lumber are also affected by the presence of gums, resins, and extratives, which contribute little to mechanical properties.

2. Knots

A knot is that portion of a branch that has become incorporated in the bole of the tree. The influence of a knot on mechanical properties of a wood member is due to the interruption of continuity and change in direction of wood fibers associated with a knot. The influence of a knot depends on its size, its location, its shape, its soundness, and the type of stress measured.

Most mechanical property values are lower at sections containing knots. Knots generally have a greater effect on tensile strength than on compressive strength. For this reason, knots have their greatest influence in the tension zone when exposed to bending stress. The effects of knot size, type, and location are specifically addressed by the grading rules that specify limits for each commercially marketed species-size–grade combination.

3. Slope of Grain

The mechanical properties of wood are quite sensitive to fiber and ring orientation. For example, parallel-to-grain tensile or compressive strength property values are generally 10 to 20 times greater than those perpendicular to grain. Deviations from straight grain in a typical board are termed slope of grain or cross-grain. The terms relate the fiber direction to the edges of the piece. Any form of cross-grain can have detrimental effects on mechanical properties.

4. Juvenile Wood

During the first 5 to 20 years of growth, the immature cambial tissue produces wood cells with distinct variations in microfibril orientation throughout the important S_2 layer of the cell wall. This wood is referred to as juvenile wood. Juvenile wood exhibits excessive warpage because of anatomical differences within this S_2 layer of the cell wall. It also exhibits lower strength properties and becomes a problem within the wood industry because of the trend toward processing younger, smaller diameter trees as the larger diameter, old-growth stock becomes more difficult to obtain.

5. Creep

Wood is a viscoelastic material. Initially, it will act elastically, experiencing nearly full recovery of load-induced deformation upon stress removal. However, wood will experience nonrecoverable deformation upon extended loading. This deformation is known as creep. For example, the magnitude of additional creep-related deformation after a 10-year loading will roughly equal the initial deformation caused by that load. The rate of creep increases with increasing temperature and moisture content.

B. Environmental

1. Moisture Content

Mechanical property values of wood increase as wood dries from the fiber saturation point to 10 to 15% moisture content. For clear wood, mechanical property values continue to increase as wood dries below 10 to 15%. moisture content. For lumber, studies have shown that mechanical property values reach a maximum at about 10 to 15% moisture content. then begin to decrease with decreasing moisture content below 10 to 15%. For either product, the effects of moisture content are considered to be reversible in the absence of decay.

2. Temperature

Strength and stiffness decrease when wood is heated and increase when cooled. The temperature effect is immediate and, for the most part, reversible for short heating durations. However, if wood is exposed to elevated temperatures for an extended time, strength is permanently reduced because of wood substance degradation and a corresponding loss in weight. The magnitude of these permanent effects depends on moisture content, heating medium, temperature, exposure period, and to a lesser extent, species and specimen size. As a general rule, wood should not be exposed to temperatures above 65°C. The immediate effect of temperature interacts with the effect of moisture content so that neither effect can be completely understood without consideration of the other.

3. Decay and Insect Damage

Wood is conducive to decay and insect damage in moist, warm conditions. Decay within a structure cannot be tolerated because strength is rapidly reduced in even the early stages of decay. It has been estimated that a *5%* weight loss from decay can result in strength losses as high as 50%. If the warm, moist conditions required for decay cannot be controlled, then the use of naturally decay resistant wood species or chemical treatments are required to impede decay. Insects, such as termites and certain types of beetles, can be just as damaging to mechanical performance. Insect infestation can be controlled via mechanical barriers, naturally durable species, or chemical treatments.

V. Properties and Grades of Sawn Lumber

At first, the highest quality level of sawn lumber might seem desirable for all uses, and indeed it is needed for several uses. However, in most situations, such material would be prohibitively expensive and a wasteful use of our timber resource. In practice, the quality level needed for a function can be easily specified because lumber and timber are graded in an orderly system developed to serve the interests of the users and the producers.

The grading system is actually several systems, each designed for specific products. Hardwood lumber is mostly graded for remanufacture, with only small amounts graded for construction. Softwood is also graded for both remanufacture and construction, but primarily for construction.

In practice, an orderly, voluntary but circuitous system of responsibilities has evolved in the United **States** for the development, manufacture, and merchandising of most stress-graded lumber and timber. In general, stress-grading principles are developed from research findings and engineering concepts, often within committees and subcommittees of the American Society for Testing and Materials.

For lumber, the National Institute for Standards and Technology cooperates with producers, distributors, users, and regional grade-rules-writing agencies through the American Lumber Standard Committee (ALSC). The ALSC has assembled a voluntary softwood standard of manufacture, called the American Softwood Lumber Standard. The American Softwood Lumber Standard and its related National Grading Rule prescribe the ways in which stress-grading principles can be used to formulate grading rules for dimension lumber (nominal 2 to 4 in. thick). This lumber standard is the basis for commercially marketing structural lumber in the United States.

For timbers (more than 5 in. nominal), the National Grading Rule does not apply. Thus, each regional grade-rules-writing agency publishes grade rules for timbers following the general principles of the National Grading Rule, but each differs slightly in eventual grade requirements and names. For further specifics on the various characteristics for the individual species-grade combinations, contact the individual grade-rules-writing organizations directly. In North America, those agencies are National Lumber Grades Authority (Vancouver, BC, Canada), Northeastern Lumber Manufacturers Association (Cumberland, ME), Redwood Inspection Service (Mill Valley, CA), Southern Pine Inspection Bureau (Pensacola, FL), West Coast Lumber Inspection Bureau (Portland, OR), and Western Wood Products Association (Portland, OR). [See FOREST TREE, GENETIC IMPROVEMENT.]

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