Chapter 2

Structure of Wood

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Contents

The fibrous nature of wood strongly influences how it is used. Wood is primarily composed of hollow, elongate, spindle-shaped cells that are arranged parallel to each other along the trunk of a tree. When lumber and other products are cut from the tree, the characteristics of these fibrous cells and their arrangement affect such properties as strength and shrinkage as well as the grain pattern of the wood. This chapter briefly describes some elements of wood structure.

Bark, Wood, Branches, and Cambium

A cross section of a tree (Fig. 2–1) shows the following well-defined features (from outside to center): bark, which may be divided into an outer corky dead part (A), whose thickness varies greatly with species and age of trees, and an inner thin living part (B), which carries food from the leaves to growing parts of the tree; wood, which in merchantable trees of most species is clearly differentiated into sapwood (D) and heartwood (E); and pith (F), a small core of tissue located at the center of tree stems, branches, and twigs about which initial wood growth takes place. Sapwood contains both living and dead tissue and carries sap from the roots to the leaves. Heartwood is formed by a gradual change in the sapwood and is inactive. The wood rays (G), horizontally oriented tissue through the radial plane of the tree, vary in size from one cell wide and a few cells high to more than 15 cells wide and several centimeters high. The rays connect various layers from pith to bark for storage and transfer of food. The cambium layer (C), which is inside the inner bark and forms wood and bark cells, can be seen only with a microscope.

As the tree grows in height, branching is initiated by lateral bud development. The lateral branches are intergrown with the wood of the trunk as long as they are alive. After a branch dies, the trunk continues to increase in diameter and surrounds that portion of the branch projecting from the trunk when the branch died. If the dead branches drop from the tree, the dead stubs become overgrown and clear wood is formed.

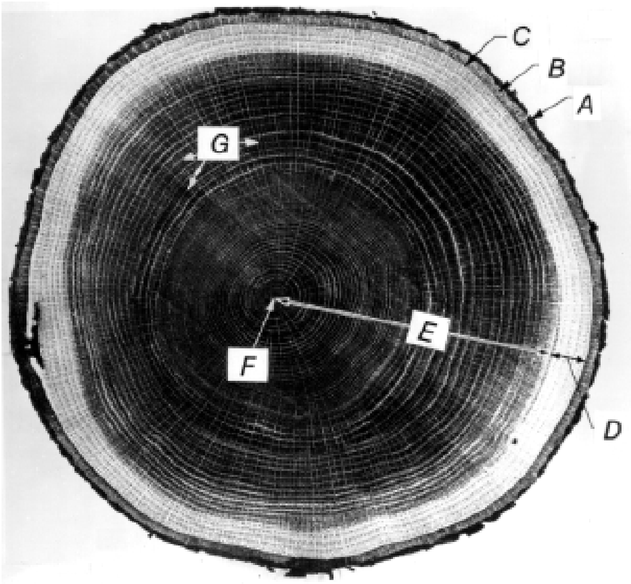

Figure 2–1. Cross section of white oak tree trunk: (A) outer bark (dry dead tissue), (B) inner bark (living tissue), (C) cambium, (D) sapwood, (E) heartwood, (F) pith, and (G) wood rays.

Most growth in thickness of bark and wood is caused by cell division in the cambium (Fig. 2–1C). No growth in diameter takes place in wood outside the cambial zone; new growth is purely the addition and growth of new cells, not the further development of old ones. New wood cells are formed on the inside of the cambium and new bark cells on the outside. Thus, new wood is laid down to the outside of old wood and the diameter of the woody trunk increases.

In most species, the existing bark is pushed outward by the formation of new bark, and the outer bark layers become stretched, cracked, and ridged and are finally sloughed off.

Sapwood and Heartwood

Sapwood is located between the cambium and heartwood (Fig. 2–1D). Sapwood contains both living and dead cells and functions primarily in the storage of food; in the outer layers near the cambium, sapwood handles the transport of water or sap. The sapwood may vary in thickness and number of growth rings. Sapwood commonly ranges from 4 to 6 cm (1-1/2 to 2 in.) in radial thickness. In certain species, such as catalpa and black locust, the sapwood contains few growth rings and usually does not exceed 1 cm (1/2 in.) in thickness. The maples, hickories, ashes, some southern pines, and ponderosa pine of North America and cativo (*Prioria copaifera*), ehie (*Guibourtia ehie*), and courbaril (*Hymenaea courbaril*) of tropical origin may have sapwood 8 to 15 cm (3 to 6 in.) or more in thickness, especially in second-growth trees. As a rule, the more vigorously growing trees have wider sapwood. Many second-growth trees of merchantable size consist mostly of sapwood.

In general, heartwood consists of inactive cells that do not function in either water conduction or food storage. The transition from sapwood to heartwood is accompanied by an increase in extractive content. Frequently, these extractives darken the heartwood and give species such as black walnut and cherry their characteristic color. Lighter colored heartwood occurs in North American species such as the spruces (except Sitka spruce), hemlocks, true firs, basswood, cottonwood, and buckeye, and in tropical species such as ceiba (*Ceiba pentandra*), obeche (*Triplochiton scleroxylon*), and ramin (*Gonystylus bancanus*). In some species, such as black locust, western redcedar, and redwood, heartwood extractives make the wood resistant to fungi or insect attack. All dark-colored heartwood is not resistant to decay, and some nearly colorless heartwood is decay resistant, as in northern white-cedar. However, none of the sapwood of any species is resistant to decay. Heartwood extractives may also affect wood by (a) reducing permeability, making the heartwood slower to dry and more difficult to impregnate with chemical preservatives, (b) increasing stability in changing moisture conditions, and (c) increasing weight (slightly). However, as sapwood changes to heartwood, no cells are added or taken away, nor do any cells change shape. The basic strength of the wood is essentially not affected by the transition from sapwood cells to heartwood cells.

In some species, such as the ashes, hickories, and certain oaks, the pores (vessels) become plugged to a greater or lesser extent with ingrowths known as tyloses. Heartwood in which the pores are tightly plugged by tyloses, as in white oak, is suitable for tight cooperage, because the tyloses prevent the passage of liquid through the pores. Tyloses also make impregnation of the wood with liquid preservatives difficult.

Growth Rings

In most species in temperate climates, the difference between wood that is formed early in a growing season and that formed later is sufficient to produce well-marked annual growth rings (Fig. 2–2). The age of a tree at the stump or the age at any cross section of the trunk may be determined by counting these rings. However, if the growth in diameter is interrupted, by drought or defoliation by insects for example, more than one ring may be formed in the same season. In such an event, the inner rings usually do not have sharply defined boundaries and are termed false rings. Trees that have only very small crowns or that have accidentally lost most of their foliage may form an incomplete growth layer, sometimes called a discontinuous ring.

The inner part of the growth ring formed first in the growing season is called earlywood and the outer part formed later in the growing season, latewood. Actual time of formation of these two parts of a ring may vary with environmental and weather conditions. Earlywood is characterized by cells with relatively large cavities and thin walls. Latewood cells have smaller cavities and thicker walls. The transition from earlywood to latewood may be gradual or abrupt, depending on

Figure 2–2. Cross section of ponderosa pine log showing growth rings. Light bands are earlywood, dark bands latewood. An annual (growth) ring is composed of an inner earlywood zone and outer latewood zone.

the kind of wood and the growing conditions at the time it was formed.

Growth rings are most readily seen in species with sharp contrast between latewood formed in one year and earlywood formed in the following year, such as in the native ring-porous hardwoods ash and oak, and in softwoods like southern pines. In some other species, such as water tupelo, aspen, and sweetgum, differentiation of earlywood and latewood is slight and the annual growth rings are difficult to recognize. In many tropical regions, growth may be practically continuous throughout the year, and no well-defined growth rings are formed.

When growth rings are prominent, as in most softwoods and ring-porous hardwoods, earlywood differs markedly from latewood in physical properties. Earlywood is lighter in weight, softer, and weaker than latewood. Because of the greater density of latewood, the proportion of latewood is sometimes used to judge the strength of the wood. This method is useful with such species as the southern pines, Douglas-fir, and the ring-porous hardwoods (ash, hickory, and oak).

Wood Cells

Wood cells—the structural elements of wood tissue—are of various sizes and shapes and are quite firmly cemented together. Dry wood cells may be empty or partly filled with deposits, such as gums and resins, or with tyloses. The majority of wood cells are considerably elongated and pointed at the ends; these cells are customarily called fibers or tracheids. The length of wood fibers is highly variable within a tree and among species. Hardwood fibers average about 1 mm (1/25 in.) in length; softwood fibers range from 3 to 8 mm (1/8 to 1/3 in.) in length.

In addition to fibers, hardwoods have cells of relatively large diameter known as vessels or pores. These cells form the main conduits in the movement of sap. Softwoods do not contain vessels for conducting sap longitudinally in the tree; this function is performed by the tracheids.

Both hardwoods and softwoods have cells (usually grouped into structures or tissues) that are oriented horizontally in the direction from pith toward bark. These groups of cells conduct sap radially across the grain and are called rays or wood rays (Fig. 2–1G). The rays are most easily seen on edge-grained or quartersawn surfaces, and they vary greatly in size in different species. In oaks and sycamores, the rays are conspicuous and add to the decorative features of the wood. Rays also represent planes of weakness along which seasoning checks readily develop.

Another type of wood cells, known as longitudinal or axial parenchyma cells, function mainly in the storage of food.

Chemical Composition

Dry wood is primarily composed of cellulose, lignin, hemicelluloses, and minor amounts (5% to 10%) of extraneous materials. Cellulose, the major component, constitutes approximately 50% of wood substance by weight. It is a high-molecular-weight linear polymer consisting of chains of 1 to more than 4 β-linked glucose monomers. During growth of the tree, the cellulose molecules are arranged into ordered strands called fibrils, which in turn are organized into the larger structural elements that make up the cell wall of wood fibers. Most of the cell wall cellulose is crystalline. Delignified wood fibers, which consist mostly of cellulose, have great commercial value when formed into paper. Delignified fibers may also be chemically altered to form textiles, films, lacquers, and explosives.

Lignin constitutes 23% to 33% of the wood substance in softwoods and 16% to 25% in hardwoods. Although lignin occurs in wood throughout the cell wall, it is concentrated toward the outside of the cells and between cells. Lignin is often called the cementing agent that binds individual cells together. Lignin is a three-dimensional phenylpropanol polymer, and its structure and distribution in wood are still not fully understood. On a commercial scale, it is necessary to remove lignin from wood to make high-grade paper or other paper products.

Theoretically, lignin might be converted to a variety of chemical products, but in commercial practice a large percentage of the lignin removed from wood during pulping operations is a troublesome byproduct, which is often burned for heat and recovery of pulping chemicals. One sizable commercial use for lignin is in the formulation of oil-well drilling muds. Lignin is also used in rubber compounding and concrete mixes. Lesser amounts are processed to yield vanillin for flavoring purposes and to produce solvents. Current research is examining the potential of using lignin in the manufacture of wood adhesives.

The hemicelluloses are associated with cellulose and are branched, low-molecular-weight polymers composed of several different kinds of pentose and hexose sugar monomers. The relative amounts of these sugars vary markedly with species. Hemicelluloses play an important role in fiber-to-fiber bonding in the papermaking process. The component sugars of hemicellulose are of potential interest for conversion into chemical products.

Unlike the major constituents of wood, extraneous materials are not structural components. Both organic and inorganic extraneous materials are found in wood. The organic component takes the form of extractives, which contribute to such wood properties as color, odor, taste, decay resistance, density, hygroscopicity, and flammability. Extractives include tannins and other polyphenolics, coloring matter, essential oils, fats, resins, waxes, gum starch, and simple metabolic intermediates. This component is termed extractives because it can be removed from wood by extraction with solvents, such as water, alcohol, acetone, benzene, or ether. Extractives may constitute roughly 5% to 30% of the wood substance, depending on such factors as species, growth conditions, and time of year when the tree is cut.

The inorganic component of extraneous material generally constitutes 0.2% to 1.0% of the wood substance, although greater values are occasionally reported. Calcium, potassium, and magnesium are the more abundant elemental constituents. Trace amounts (<100 parts per million) of phosphorus, sodium, iron, silicon, manganese, copper, zinc, and perhaps a few other elements are usually present.

Valuable nonfibrous products produced from wood include naval stores, pulp byproducts, vanillin, ethyl alcohol, charcoal, extractives, and products made from bark.

Species Identification

Many species of wood have unique physical, mechanical, or chemical properties. Efficient utilization dictates that species should be matched to end-use requirements through an understanding of their properties. This requires identification of the species in wood form, independent of bark, foliage, and other characteristics of the tree.

General wood identification can often be made quickly on the basis of readily visible characteristics such as color, odor, density, presence of pitch, or grain pattern. Where more positive identification is required, a laboratory investigation must be made of the microscopic anatomy of the wood. Identifying characteristics are described in publications such as the *Textbook of Wood Technology* by Panshin and de Zeeuw and *Identifying Wood: Accurate Results With Simple Tools* by R.B. Hoadley.

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Chapter 4

Mechanical Properties of Wood

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The mechanical properties presented in this chapter were obtained from tests of small pieces of wood termed “clear” and “straight grained” because they did not contain characteristics such as knots, cross grain, checks, and splits. These test pieces did have anatomical characteristics such as growth rings that occurred in consistent patterns within each piece. Clear wood specimens are usually considered “homogeneous” in wood mechanics.

Many of the mechanical properties of wood tabulated in this chapter were derived from extensive sampling and analysis procedures. These properties are represented as the average mechanical properties of the species. Some properties, such as tension parallel to the grain, and all properties for some imported species are based on a more limited number of specimens that were not subjected to the same sampling and analysis procedures. The appropriateness of these latter properties to represent the average properties of a species is uncertain; nevertheless, the properties represent the best information available.

Variability, or variation in properties, is common to all materials. Because wood is a natural material and the tree is subject to many constantly changing influences (such as moisture, soil conditions, and growing space), wood properties vary considerably, even in clear material. This chapter provides information, where possible, on the nature and magnitude of variability in properties.

This chapter also includes a discussion of the effect of growth features, such as knots and slope of grain, on clear wood properties. The effects of manufacturing and service environments on mechanical properties are discussed, and their effects on clear wood and material containing growth features are compared. Chapter 6 discusses how these research results have been implemented in engineering standards.

Orthotropic Nature of Wood

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: longitudinal, radial, and tangential. The longitudinal axis *L* is parallel to the fiber (grain); the radial axis *R* is normal to the growth rings (perpendicular to the grain in the radial direction); and

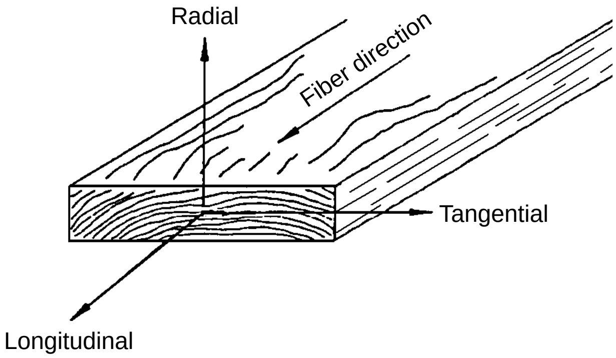

Figure 4–1. Three principal axes of wood with respect to grain direction and growth rings.

the tangential axis *T* is perpendicular to the grain but tangent to the growth rings. These axes are shown in Figure 4–1.

Elastic Properties

Twelve constants (nine are independent) are needed to describe the elastic behavior of wood: three moduli of elasticity *E*, three moduli of rigidity *G*, and six Poisson's ratios μ. The moduli of elasticity and Poisson's ratios are related by expressions of the form

$$\frac{\mu_{ij}}{E_i} = \frac{\mu_{ji}}{E_j}, \quad i \neq j \quad i,j = L,R,T \qquad (4\text{–}1)$$

General relations between stress and strain for a homogeneous orthotropic material can be found in texts on anisotropic elasticity.

Modulus of Elasticity

Elasticity implies that deformations produced by low stress are completely recoverable after loads are removed. When loaded to higher stress levels, plastic deformation or failure occurs. The three moduli of elasticity, which are denoted by E_L, E_R, and E_T, respectively, are the elastic moduli along the longitudinal, radial, and tangential axes of wood. These moduli are usually obtained from compression tests; however, data for E_R and E_T are not extensive. Average values of E_R and E_T for samples from a few species are presented in Table 4–1 as ratios with E_L; the Poisson's ratios are shown in Table 4–2. The elastic ratios, as well as the elastic constants themselves, vary within and between species and with moisture content and specific gravity.

The modulus of elasticity determined from bending, E_L, rather than from an axial test, may be the only modulus of elasticity available for a species. Average E_L values obtained from bending tests are given in Tables 4–3 to 4–5. Representative coefficients of variation of E_L determined with bending tests for clear wood are reported in Table 4–6. As tabulated, E_L includes an effect of shear deflection; E_L from bending can be increased by 10% to remove this effect approximately.

Table 4–1. Elastic ratios for various species at approximately 12% moisture content[a]

Species	E_T/E_L	E_R/E_L	G_{LR}/E_L	G_{LT}/E_L	G_{RT}/E_L
Hardwoods					
Ash, white	0.080	0.125	0.109	0.077	—
Balsa	0.015	0.046	0.054	0.037	0.005
Basswood	0.027	0.066	0.056	0.046	—
Birch, yellow	0.050	0.078	0.074	0.068	0.017
Cherry, black	0.086	0.197	0.147	0.097	—
Cottonwood, eastern	0.047	0.083	0.076	0.052	—
Mahogany, African	0.050	0.111	0.088	0.059	0.021
Mahogany, Honduras	0.064	0.107	0.066	0.086	0.028
Maple, sugar	0.065	0.132	0.111	0.063	—
Maple, red	0.067	0.140	0.133	0.074	—
Oak, red	0.082	0.154	0.089	0.081	—
Oak, white	0.072	0.163	0.086	—	—
Sweet gum	0.050	0.115	0.089	0.061	0.021
Walnut, black	0.056	0.106	0.085	0.062	0.021
Yellow-poplar	0.043	0.092	0.075	0.069	0.011
Softwoods					
Baldcypress	0.039	0.084	0.063	0.054	0.007
Cedar, northern white	0.081	0.183	0.210	0.187	0.015
Cedar, western red	0.055	0.081	0.087	0.086	0.005
Douglas-fir	0.050	0.068	0.064	0.078	0.007
Fir, subalpine	0.039	0.102	0.070	0.058	0.006
Hemlock, western	0.031	0.058	0.038	0.032	0.003
Larch, western	0.065	0.079	0.063	0.069	0.007
Pine					
Loblolly	0.078	0.113	0.082	0.081	0.013
Lodgepole	0.068	0.102	0.049	0.046	0.005
Longleaf	0.055	0.102	0.071	0.060	0.012
Pond	0.041	0.071	0.050	0.045	0.009
Ponderosa	0.083	0.122	0.138	0.115	0.017
Red	0.044	0.088	0.096	0.081	0.011
Slash	0.045	0.074	0.055	0.053	0.010
Sugar	0.087	0.131	0.124	0.113	0.019
Western white	0.038	0.078	0.052	0.048	0.005
Redwood	0.089	0.087	0.066	0.077	0.011
Spruce, Sitka	0.043	0.078	0.064	0.061	0.003
Spruce, Engelmann	0.059	0.128	0.124	0.120	0.010

[a] E_L may be approximated by increasing modulus of elasticity values in Table 4–3 by 10%.

This adjusted bending E_L can be used to determine E_R and E_T based on the ratios in Table 4–1.

Poisson's Ratio

When a member is loaded axially, the deformation perpendicular to the direction of the load is proportional to the deformation parallel to the direction of the load. The ratio of the transverse to axial strain is called Poisson's ratio. The Poisson's ratios are denoted by μ_{LR}, μ_{RL}, μ_{LT}, μ_{TL}, μ_{RT}, and μ_{TR}. The first letter of the subscript refers to direction of applied stress and the second letter to direction of lateral deformation. For example, μ_{LR} is the Poisson's ratio for deformation along the radial axis caused by stress along the longitudinal axis. Average values of Poisson's ratios for samples of a few species are given in Table 4–2. Values for μ_{RL} and μ_{TL} are less precisely determined than are those for the other Poisson's ratios. Poisson's ratios vary within and between species and are affected by moisture content and specific gravity.

Table 4–2. Poisson's ratios for various species at approximately 12% moisture content

Species	μ_{LR}	μ_{LT}	μ_{RT}	μ_{TR}	μ_{RL}	μ_{TL}
Hardwoods						
Ash, white	0.371	0.440	0.684	0.360	0.059	0.051
Aspen, quaking	0.489	0.374	—	0.496	0.054	0.022
Balsa	0.229	0.488	0.665	0.231	0.018	0.009
Basswood	0.364	0.406	0.912	0.346	0.034	0.022
Birch, yellow	0.426	0.451	0.697	0.426	0.043	0.024
Cherry, black	0.392	0.428	0.695	0.282	0.086	0.048
Cottonwood, eastern	0.344	0.420	0.875	0.292	0.043	0.018
Mahogany, African	0.297	0.641	0.604	0.264	0.033	0.032
Mahogany, Honduras	0.314	0.533	0.600	0.326	0.033	0.034
Maple, sugar	0.424	0.476	0.774	0.349	0.065	0.037
Maple, red	0.434	0.509	0.762	0.354	0.063	0.044
Oak, red	0.350	0.448	0.560	0.292	0.064	0.033
Oak, white	0.369	0.428	0.618	0.300	0.074	0.036
Sweet gum	0.325	0.403	0.682	0.309	0.044	0.023
Walnut, black	0.495	0.632	0.718	0.378	0.052	0.035
Yellow-poplar	0.318	0.392	0.703	0.329	0.030	0.019
Softwoods						
Baldcypress	0.338	0.326	0.411	0.356	—	—
Cedar, northern white	0.337	0.340	0.458	0.345	—	—
Cedar, western red	0.378	0.296	0.484	0.403	—	—
Douglas-fir	0.292	0.449	0.390	0.374	0.036	0.029
Fir, subalpine	0.341	0.332	0.437	0.336	—	—
Hemlock, western	0.485	0.423	0.442	0.382	—	—
Larch, western	0.355	0.276	0.389	0.352	—	—
Pine						
Loblolly	0.328	0.292	0.382	0.362	—	—
Lodgepole	0.316	0.347	0.469	0.381	—	—
Longleaf	0.332	0.365	0.384	0.342	—	—
Pond	0.280	0.364	0.389	0.320	—	—
Ponderosa	0.337	0.400	0.426	0.359	—	—
Red	0.347	0.315	0.408	0.308	—	—
Slash	0.392	0.444	0.447	0.387	—	—
Sugar	0.356	0.349	0.428	0.358	—	—
Western white	0.329	0.344	0.410	0.334	—	—
Redwood	0.360	0.346	0.373	0.400	—	—
Spruce, Sitka	0.372	0.467	0.435	0.245	0.040	0.025
Spruce, Engelmann	0.422	0.462	0.530	0.255	0.083	0.058

Modulus of Rigidity

The modulus of rigidity, also called shear modulus, indicates the resistance to deflection of a member caused by shear stresses. The three moduli of rigidity denoted by G_{LR}, G_{LT}, and G_{RT} are the elastic constants in the *LR*, *LT*, and *RT* planes, respectively. For example, G_{LR} is the modulus of rigidity based on shear strain in the *LR* plane and shear stresses in the *LT* and *RT* planes. Average values of shear moduli for samples of a few species expressed as ratios with E_L are given in Table 4–1. As with moduli of elasticity, the moduli of rigidity vary within and between species and with moisture content and specific gravity.

Strength Properties

Common Properties

Mechanical properties most commonly measured and represented as "strength properties" for design include modulus of rupture in bending, maximum stress in compression parallel to grain, compressive stress perpendicular to grain, and shear strength parallel to grain. Additional measurements are often made to evaluate work to maximum load in bending, impact bending strength, tensile strength perpendicular to grain, and hardness. These properties, grouped according to the broad forest tree categories of hardwood and softwood (not correlated with hardness or softness), are given in Tables 4–3 to 4–5 for many of the commercially important species. Average coefficients of variation for these properties from a limited sampling of specimens are reported in Table 4–6.

Modulus of rupture—Reflects the maximum load-carrying capacity of a member in bending and is proportional to 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 computed is valid only to the elastic limit.

Work to maximum load in bending—Ability to absorb shock with some permanent deformation and more or less injury to a specimen. Work to maximum load is a measure of the combined strength and toughness of wood under bending stresses.

Compressive strength parallel to grain—Maximum stress sustained by a compression parallel-to-grain specimen having a ratio of length to least dimension of less than 11.

Compressive stress perpendicular to grain—Reported as stress at proportional limit. There is no clearly defined ultimate stress for this property.

Shear strength parallel to grain—Ability to resist internal slipping of one part upon another along the grain. Values presented are average strength in radial and tangential shear planes.

Impact bending—In the impact bending test, a hammer of given weight is dropped upon a beam from successively increased heights until rupture occurs or the beam deflects 152 mm (6 in.) or more. The height of the maximum drop, or the drop that causes failure, is a comparative value that represents the ability of wood to absorb shocks that cause stresses beyond the proportional limit.

Tensile strength perpendicular to grain—Resistance of wood to forces acting across the grain that tend to split a member. Values presented are the average of radial and tangential observations.

Hardness—Generally defined as resistance to indentation using a modified Janka hardness test, measured by the load required to embed a 11.28-mm (0.444-in.) ball to one-half its diameter. Values presented are the average of radial and tangential penetrations.

Tensile strength parallel to grain—Maximum tensile stress sustained in direction parallel to grain. Relatively few data are available on the tensile strength of various species of clear wood parallel to grain. Table 4–7 lists average tensile strength values for a limited number of specimens of a few species. In the absence of sufficient tension test data, modulus of rupture values are sometimes substituted for tensile strength of small, clear, straight-grained pieces of wood. The modulus of rupture is considered to be a low or conservative estimate of tensile strength for clear specimens (this is not true for lumber).

Table 4–3a. Strength properties of some commercially important woods grown in the United States (metric)[a]

Common species names	Moisture content	Specific gravity[b]	Static bending: Modulus of rupture (kPa)	Static bending: Modulus of elasticity[c] (MPa)	Static bending: Work to maximum load (kJ/m³)	Impact bending (mm)	Compression parallel to grain (kPa)	Compression perpendicular to grain (kPa)	Shear parallel to grain (kPa)	Tension perpendicular to grain (kPa)	Side hardness (N)
Hardwoods											
Alder, red	Green	0.37	45,000	8,100	55	560	20,400	1,700	5,300	2,700	2,000
	12%	0.41	68,000	9,500	58	510	40,100	3,000	7,400	2,900	2,600
Ash											
Black	Green	0.45	41,000	7,200	83	840	15,900	2,400	5,900	3,400	2,300
	12%	0.49	87,000	11,000	103	890	41,200	5,200	10,800	4,800	3,800
Blue	Green	0.53	66,000	8,500	101	—	24,800	5,600	10,600	—	—
	12%	0.58	95,000	9,700	99	—	48,100	9,800	14,000	—	—
Green	Green	0.53	66,000	9,700	81	890	29,000	5,000	8,700	4,100	3,900
	12%	0.56	97,000	11,400	92	810	48,800	9,000	13,200	4,800	5,300
Oregon	Green	0.50	52,000	7,800	84	990	24,200	3,700	8,200	4,100	3,500
	12%	0.55	88,000	9,400	99	840	41,600	8,600	12,300	5,000	5,200
White	Green	0.55	66,000	9,900	108	970	27,500	4,600	9,300	4,100	4,300
	12%	0.60	103,000	12,000	115	1,090	51,100	8,000	13,200	6,500	5,900
Aspen											
Bigtooth	Green	0.36	37,000	7,700	39	—	17,200	1,400	5,000	—	—
	12%	0.39	63,000	9,900	53	—	36,500	3,100	7,400	—	—
Quaking	Green	0.35	35,000	5,900	44	560	14,800	1,200	4,600	1,600	1,300
	12%	0.38	58,000	8,100	52	530	29,300	2,600	5,900	1,800	1,600
Basswood, American	Green	0.32	34,000	7,200	37	410	15,300	1,200	4,100	1,900	1,100
	12%	0.37	60,000	10,100	50	410	32,600	2,600	6,800	2,400	1,800
Beech, American	Green	0.56	59,000	9,500	82	1,090	24,500	3,700	8,900	5,000	3,800
	12%	0.64	103,000	11,900	104	1,040	50,300	7,000	13,900	7,000	5,800
Birch											
Paper	Green	0.48	44,000	8,100	112	1,240	16,300	1,900	5,800	2,600	2,500
	12%	0.55	85,000	11,000	110	860	39,200	4,100	8,300	—	4,000
Sweet	Green	0.60	65,000	11,400	108	1,220	25,800	3,200	8,500	3,000	4,300
	12%	0.65	117,000	15,000	124	1,190	58,900	7,400	15,400	6,600	6,500
Yellow	Green	0.55	57,000	10,300	111	1,220	23,300	3,000	7,700	3,000	3,600
	12%	0.62	114,000	13,900	143	1,400	56,300	6,700	13,000	6,300	5,600
Butternut	Green	0.36	37,000	6,700	57	610	16,700	1,500	5,200	3,000	1,700
	12%	0.38	56,000	8,100	57	610	36,200	3,200	8,100	3,000	2,200
Cherry, black	Green	0.47	55,000	9,000	88	840	24,400	2,500	7,800	3,900	2,900
	12%	0.50	85,000	10,300	79	740	49,000	4,800	11,700	3,900	4,200
Chestnut, American	Green	0.40	39,000	6,400	48	610	17,000	2,100	5,500	3,000	1,900
	12%	0.43	59,000	8,500	45	480	36,700	4,300	7,400	3,200	2,400
Cottonwood											
Balsam poplar	Green	0.31	27,000	5,200	29	—	11,700	1,000	3,400	—	—
	12%	0.34	47,000	7,600	34	—	27,700	2,100	5,400	—	—
Black	Green	0.31	34,000	7,400	34	510	15,200	1,100	4,200	1,900	1,100
	12%	0.35	59,000	8,800	46	560	31,000	2,100	7,200	2,300	1,600
Eastern	Green	0.37	37,000	7,000	50	530	15,700	1,400	4,700	2,800	1,500
	12%	0.40	59,000	9,400	51	510	33,900	2,600	6,400	4,000	1,900
Elm											
American	Green	0.46	50,000	7,700	81	970	20,100	2,500	6,900	4,100	2,800
	12%	0.50	81,000	9,200	90	990	38,100	4,800	10,400	4,600	3,700
Rock	Green	0.57	66,000	8,200	137	1,370	26,100	4,200	8,800	—	—
	12%	0.63	102,000	10,600	132	1,420	48,600	8,500	13,200	—	—
Slippery	Green	0.48	55,000	8,500	106	1,190	22,900	2,900	7,700	4,400	2,900
	12%	0.53	90,000	10,300	117	1,140	43,900	5,700	11,200	3,700	3,800
Hackberry	Green	0.49	45,000	6,600	100	1,220	18,300	2,800	7,400	4,300	3,100
	12%	0.53	76,000	8,200	88	1,090	37,500	6,100	11,000	4,000	3,900

Table 4–5b. Mechanical properties of some woods imported into the United States other than Canadian imports (inch–pound)[a]—con.

Common and botanical names of species	Moisture content	Specific gravity	Static bending: Modulus of rupture (lbf/in²)	Static bending: Modulus of elasticity ($\times 10^6$ lbf/in²)	Static bending: Work to maximum load (in-lbf/in³)	Compression parallel to grain (lbf/in²)	Shear parallel to grain (lbf/in²)	Side hardness (lbf)	Sample origin[b]
Shorea (Shorea spp.,	Green	0.68	11,700	2.1	—	5,380	1,440	1,350	AS
bullau group)	12%		18,800	2.61	—	10,180	2,190	1,780	
Shorea, lauan–meranti group									
Dark red meranti	Green	0.46	9,400	1.5	8.6	4,720	1,110	700	AS
	12%		12,700	1.77	13.8	7,360	1,450	780	
Light red meranti	Green	0.34	6,600	1.04	6.2	3,330	710	440	AS
	12%		9,500	1.23	8.6	5,920	970	460	
White meranti	Green	0.55	9,800	1.3	8.3	5,490	1,320	1,000	AS
	15%		12,400	1.49	11.4	6,350	1,540	1,140	
Yellow meranti	Green	0.46	8,000	1.3	8.1	3,880	1,030	750	AS
	12%		11,400	1.55	10.1	5,900	1,520	770	
Spanish-cedar (*Cedrela* spp.)	Green	0.41	7,500	1.31	7.1	3,370	990	550	AM
	12%	—	11,500	1.44	9.4	6,210	1,100	600	
Sucupira (*Bowdichia* spp.)	Green	0.74	17,200	2.27	—	9,730	—	—	AM
	15%		19,400	—	—	11,100	—	—	
Sucupira (*Diplotropis purpurea*)	Green	0.78	17,400	2.68	13	8,020	1,800	1,980	AM
	12%		20,600	2.87	14.8	12,140	1,960	2,140	
Teak (*Tectona grandis*)	Green	0.55	11,600	1.37	13.4	5,960	1,290	930	AS
	12%		14,600	1.55	12	8,410	1,890	1,000	
Tornillo (*Cedrelinga*	Green	0.45	8,400	—	—	4,100	1,170	870	AM
cateniformis)	12%	—	—	—	—	—	—	—	
Wallaba (*Eperua* spp.)	Green	0.78	14,300	2.33	—	8,040	—	1,540	AM
	12%	—	19,100	2.28	—	10,760	—	2,040	

[a]Results of tests on small, clear, straight-grained specimens. Property values were taken from world literature (not obtained from experiments conducted at the Forest Products Laboratory). Other species may be reported in the world literature, as well as additional data on many of these species. Some property values have been adjusted to 12% moisture content.
[b]AF is Africa; AM, America; AS, Asia.

Table 4–6. Average coefficients of variation for some mechanical properties of clear wood

Property	Coefficient of variation[a] (%)
Static bending	
Modulus of rupture	16
Modulus of elasticity	22
Work to maximum load	34
Impact bending	25
Compression parallel to grain	18
Compression perpendicular to grain	28
Shear parallel to grain, maximum shearing strength	14
Tension parallel to grain	25
Side hardness	20
Toughness	34
Specific gravity	10

[a]Values based on results of tests of green wood from approximately 50 species. Values for wood adjusted to 12% moisture content may be assumed to be approximately of the same magnitude.

Table 4–7. Average parallel-to-grain tensile strength of some wood species[a]

Species	Tensile strength (kPa (lb/in²))	
Hardwoods		
Beech, American	86,200	(12,500)
Elm, cedar	120,700	(17,500)
Maple, sugar	108,200	(15,700)
Oak		
Overcup	77,900	(11,300)
Pin	112,400	(16,300)
Poplar, balsam	51,000	(7,400)
Sweetgum	93,800	(13,600)
Willow, black	73,100	(10,600)
Yellow-poplar	109,600	(15,900)
Softwoods		
Baldcypress	58,600	(8,500)
Cedar		
Port-Orford	78,600	(11,400)
Western redcedar	45,500	(6,600)
Douglas-fir, interior north	107,600	(15,600)
Fir		
California red	77,900	(11,300)
Pacific silver	95,100	(13,800)
Hemlock, western	89,600	(13,000)
Larch, western	111,700	(16,200)
Pine		
Eastern white	73,100	(10,600)
Loblolly	80,000	(11,600)
Ponderosa	57,900	(8,400)
Virginia	94,500	(13,700)
Redwood		
Virgin	64,800	(9,400)
Young growth	62,700	(9,100)
Spruce		
Engelmann	84,800	(12,300)
Sitka	59,300	(8,600)

[a]Results of tests on small, clear, straight-grained specimens tested green. For hardwood species, strength of specimens tested at 12% moisture content averages about 32% higher; for softwoods, about 13% higher.

Table 4–8. Average toughness values for a few hardwood species[a]

Species	Moisture content	Specific gravity	Toughness: Radial (J (in-lbf))		Toughness: Tangential (J (in-lbf))	
Birch, yellow	12%	0.65	8,100	(500)	10,100	(620)
Hickory (mockernut, pignut, sand)	Green	0.64	11,400	(700)	11,700	(720)
	12%	0.71	10,100	(620)	10,700	(660)
Maple, sugar	14%	0.64	6,000	(370)	5,900	(360)
Oak, red						
Pin	12%	0.64	7,000	(430)	7,000	(430)
Scarlet	11%	0.66	8,300	(510)	7,200	(440)
Oak, white						
Overcup	Green	0.56	11,900	(730)	11,100	(680)
	13%	0.62	5,500	(340)	5,000	(310)
Sweetgum	Green	0.48	5,500	(340)	5,400	(330)
	13%	0.51	4,200	(260)	4,200	(260)
Willow, black	Green	0.38	5,000	(310)	5,900	(360)
	11%	0.4	3,400	(210)	3,700	(230)
Yellow-poplar	Green	0.43	5,200	(320)	4,900	(300)
	12%	0.45	3,600	(220)	3,400	(210)

Less Common Properties

Strength properties less commonly measured in clear wood include torsion, toughness, rolling shear, and fracture toughness. Other properties involving time under load include creep, creep rupture or duration of load, and fatigue strength.

Torsion strength—Resistance to twisting about a longitudinal axis. For solid wood members, torsional shear strength may be taken as shear strength parallel to grain. Two-thirds of the value for torsional shear strength may be used as an estimate of the torsional shear stress at the proportional limit.

Toughness—Energy required to cause rapid complete failure in a centrally loaded bending specimen. Tables 4–8 and 4–9 give average toughness values for samples of a few hardwood and softwood species. Average coefficients of variation for toughness as determined from approximately 50 species are shown in Table 4–6.

Creep and duration of load—Time-dependent deformation of wood under load. If the load is sufficiently high and the duration of load is long, failure (creep–rupture) will eventually occur. The time required to reach rupture is commonly called duration of load. Duration of load is an important factor in setting design values for wood. Creep and duration of load are described in later sections of this chapter.

Fatigue—Resistance to failure under specific combinations of cyclic loading conditions: frequency and number of cycles, maximum stress, ratio of maximum to minimum stress, and other less-important factors. The main factors affecting fatigue in wood are discussed later in this chapter. The discussion also includes interpretation of fatigue data and information on fatigue as a function of the service environment.

Rolling shear strength—Shear strength of wood where shearing force is in a longitudinal plane and is acting perpendicular to the grain. Few test values of rolling shear in solid wood have been reported. In limited tests, rolling shear strength averaged 18% to 28% of parallel-to-grain shear values. Rolling shear strength is about the same in the longitudinal–radial and longitudinal–tangential planes.

Fracture toughness—Ability of wood to withstand flaws that initiate failure. Measurement of fracture toughness helps identify the length of critical flaws that initiate failure in materials.

To date there is no standard test method for determining fracture toughness in wood. Three types of stress fields, and associated stress intensity factors, can be defined at a crack tip: opening mode (I), forward shear mode (II), and transverse shear mode (III) (Fig. 4–2a). A crack may lie in one of these

Table 4–9. Average toughness values for a few softwood species[a]

Species	Moisture content	Specific gravity	Toughness Radial (J (in-lbf))		Toughness Tangential (J (in-lbf))	
Cedar						
Western red	9%	0.33	1,500	(90)	2,100	(130)
Yellow	10%	0.48	3,400	(210)	3,700	(230)
Douglas-fir						
Coast	Green	0.44	3,400	(210)	5,900	(360)
	12%	0.47	3,300	(200)	5,900	(360)
Interior west	Green	0.48	3,300	(200)	4,900	(300)
	13%	0.51	3,400	(210)	5,500	(340)
Interior north	Green	0.43	2,800	(170)	3,900	(240)
	14%	0.46	2,600	(160)	4,100	(250)
Interior south	Green	0.38	2,100	(130)	2,900	(180)
	14%	0.4	2,000	(120)	2,900	(180)
Fir						
California red	Green	0.36	2,100	(130)	2,900	(180)
	12%	0.39	2,000	(120)	2,800	(170)
Noble	Green	0.36	—	—	3,900	(240)
	12%	0.39	—	—	3,600	(220)
Pacific silver	Green	0.37	2,400	(150)	3,700	(230)
	13%	0.4	2,800	(170)	4,200	(260)
White	Green	0.36	2,300	(140)	3,600	(220)
	13%	0.38	2,100	(130)	3,300	(200)
Hemlock						
Mountain	Green	0.41	4,100	(250)	4,600	(280)
	14%	0.44	2,300	(140)	2,800	(170)
Western	Green	0.38	2,400	(150)	2,800	(170)
	12%	0.41	2,300	(140)	3,400	(210)
Larch, western	Green	0.51	4,400	(270)	6,500	(400)
	12%	0.55	3,400	(210)	5,500	(340)
Pine						
Eastern white	Green	0.33	2,000	(120)	2,600	(160)
	12%	0.34	1,800	(110)	2,000	(120)
Jack	Green	0.41	3,300	(200)	6,200	(380)
	12%	0.42	2,300	(140)	3,900	(240)
Loblolly	Green	0.48	5,000	(310)	6,200	(380)
	12%	0.51	2,600	(160)	4,200	(260)
Lodgepole	Green	0.38	2,600	(160)	3,400	(210)
Ponderosa	Green	0.38	3,100	(190)	4,400	(270)
	11%	0.43	2,400	(150)	3,100	(190)
Red	Green	0.4	3,400	(210)	5,700	(350)
	12%	0.43	2,600	(160)	4,700	(290)
Shortleaf	Green	0.47	4,700	(290)	6,500	(400)
	13%	0.5	2,400	(150)	3,700	(230)
Slash	Green	0.55	5,700	(350)	7,300	(450)
	12%	0.59	3,400	(210)	5,200	(320)
Virginia	Green	0.45	5,500	(340)	7,600	(470)
	12%	0.49	2,800	(170)	4,100	(250)
Redwood						
Old-growth	Green	0.39	1,800	(110)	3,300	(200)
	11%	0.39	1,500	(90)	2,300	(140)
Young-growth	Green	0.33	1,800	(110)	2,300	(140)
	12%	0.34	1,500	(90)	1,800	(110)
Spruce, Engelmann	Green	0.34	2,400	(150)	3,100	(190)
	12%	0.35	1,800	(110)	2,900	(180)

[a]Results of tests on small, clear, straight-grained specimens.

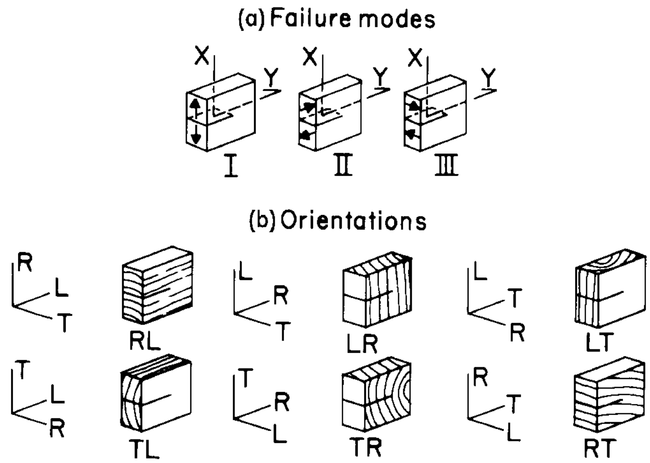

Figure 4–2. Possible crack propagation systems for wood.

three planes and may propagate in one of two directions in each plane. This gives rise to six crack-propagation systems (*RL*, *TL*, *LR*, *TR*, *LT*, and *RT*) (Fig. 4–2b). Of these crack-propagation systems, four systems are of practical importance: *RL*, *TL*, *TR*, and *RT*. Each of these four systems allow for propagation of a crack along the lower strength path parallel to the grain. The *RL* and *TL* orientations in wood (where *R* or *T* is perpendicular to the crack plane and *L* is the direction in which the crack propagates) will predominate as a result of the low strength and stiffness of wood perpendicular to the grain. It is therefore one of these two orientations that is most often tested. Values for Mode I fracture toughness range from 220 to 550 $\text{kPa}\sqrt{\text{m}}$ (200 to 500 $\text{lbf}/\text{in}^2\sqrt{\text{in.}}$) and for Mode II range from 1,650 to 2,400 $\text{kPa}\sqrt{\text{m}}$ (1,500 to 2,200 $\text{lbf}/\text{in}^2\sqrt{\text{in.}}$). Table 4–10 summarizes selected mode I and mode II test results at 10% to 12% moisture content available in the literature. The limited information available on moisture content effects on fracture toughness suggests that fracture toughness is either insensitive to moisture content or increases as the material dries, reaching a maximum between 6% and 15% moisture content; fracture toughness then decreases with further drying.

Vibration Properties

The vibration properties of primary interest in structural materials are speed of sound and internal friction (damping capacity).

Speed of Sound

The speed of sound in a structural material is a function of the modulus of elasticity and density. In wood, the speed of sound also varies with grain direction because the transverse modulus of elasticity is much less than the longitudinal value (as little as 1/20); the speed of sound across the grain is about one-fifth to one-third of the longitudinal value. For example, a piece of wood with a longitudinal modulus of elasticity of 12.4 GPa (1.8×10^6 lbf/in^2) and density of

Table 4–10. Summary of selected fracture toughness results

	Fracture toughness ($kPa\sqrt{m}$ ($lbf/in^2\sqrt{in.}$))			
	Mode I		Mode II	
Species	*TL*	*RL*	*TL*	*RL*
Douglas-fir	320 (290)	360 (330)		2,230 (2,030)
Western hemlock	375 (340)		2,240 (2,040)	
Pine				
Western white	250 (225)	260 (240)		
Scots	440 (400)	500 (455)	2,050 (1,860)	
Southern	375 (340)		2,070 (1,880)	
Ponderosa	290 (265)			
Red spruce	420 (380)		2,190 (1,990)	1,665 (1,510)
Northern red oak	410 (370)			
Sugar maple	480 (430)			
Yellow-poplar	517 (470)			

480 kg/m^3 (30 lb/ft^3) would have a speed of sound in the longitudinal direction of about 3,800 m/s (12,500 ft/s). In the transverse direction, modulus of elasticity would be about 690 MPa (100×10^3 lbf/in^2) and the speed of sound approximately 890 m/s (2,900 ft/s).

The speed of sound decreases with increasing temperature or moisture content in proportion to the influence of these variables on modulus of elasticity and density. The speed of sound decreases slightly with increasing frequency and amplitude of vibration, although for most common applications this effect is too small to be significant. There is no recognized independent effect of species on the speed of sound. Variability in the speed of sound in wood is directly related to the variability of modulus of elasticity and density.

Internal Friction

When solid material is strained, some mechanical energy is dissipated as heat. Internal friction is the term used to denote the mechanism that causes this energy dissipation. The internal friction mechanism in wood is a complex function of temperature and moisture content. In general, there is a value of moisture content at which internal friction is minimum. On either side of this minimum, internal friction increases as moisture content varies down to zero or up to the fiber saturation point. The moisture content at which minimum internal friction occurs varies with temperature. At room temperature (23ºC (73ºF)), the minimum occurs at about 6% moisture content; at −20ºC (−4ºF), it occurs at about 14% moisture content, and at 70ºC (158ºF), at about 4%. At 90ºC (194ºF), the minimum is not well defined and occurs near zero moisture content.

Similarly, there are temperatures at which internal friction is minimum, and the temperatures of minimum internal friction vary with moisture content. The temperatures of minimum internal friction are higher as the moisture content is decreased. For temperatures above 0ºC (32ºF) and moisture content greater than about 10%, internal friction increases strongly as temperature increases, with a strong positive interaction with moisture content. For very dry wood, there is a general tendency for internal friction to decrease as the temperature increases.

The value of internal friction, expressed by logarithmic decrement, ranges from about 0.1 for hot, moist wood to less than 0.02 for hot, dry wood. Cool wood, regardless of moisture content, would have an intermediate value.

Mechanical Properties of Clear Straight-Grained Wood

The mechanical properties listed in Table 4–1 through Table 4–9 are based on a variety of sampling methods. Generally, the most extensive sampling is represented in Tables 4–3 and 4–4. The values in Table 4–3 are averages derived for a number of species grown in the United States. The tabulated value is an estimate of the average clear wood property of the species. Many values were obtained from test specimens taken at a height of 2.4 to 5 m (8 to 16 ft) above the stump of the tree. Values reported in Table 4–4 represent estimates of the average clear wood properties of species grown in Canada and commonly imported into the United States.

Methods of data collection and analysis changed over the years during which the data in Tables 4–3 and 4–4 were collected. In addition, the character of some forests has changed with time. Because not all the species were reevaluated to reflect these changes, the appropriateness of the data should be reviewed when used for critical applications such as stress grades of lumber.

Values reported in Table 4–5 were collected from the world literature; thus, the appropriateness of these properties to represent a species is not known. The properties reported in Tables 4–1, 4–2, 4–5, 4–7, 4–8, 4–9 and 4–10 may not necessarily represent average species characteristics because of inadequate sampling; however, they do suggest the relative influence of species and other specimen parameters on the mechanical behavior recorded.

Variability in properties can be important in both production and consumption of wood products. The fact that a piece may be stronger, harder, or stiffer than the average is often of less concern to the user than if the piece is weaker; however, this may not be true if lightweight material is selected for a specific purpose or if harder or tougher material is difficult to work. Some indication of the spread of property values is therefore desirable. Average coefficients of variation for many mechanical properties are presented in Table 4–6.

The mechanical properties reported in the tables are significantly affected by specimen moisture content at time of test. Some tables include properties that were evaluated at differing moisture levels; these moisture levels are reported. As indicated in the tables, many of the dry test data were adjusted to a common moisture content base of 12%.

Specific gravity is reported in many tables because this property is used as an index of clear wood mechanical properties. The specific gravity values given in Tables 4–3 and 4–4 represent the estimated average clear wood specific gravity of the species. In the other tables, the specific gravity values represent only the specimens tested. The variability of specific gravity, represented by the coefficient of variation derived from tests on 50 species, is included in Table 4–6.

Mechanical and physical properties as measured and reported often reflect not only the characteristics of the wood but also the influence of the shape and size of the test specimen and the test mode. The test methods used to establish properties in Tables 4–3, 4–4, 4–7, 4–8 and 4–9 are based on standard procedures (ASTM D143). The test methods for properties presented in other tables are referenced in the selected bibliography at the end of this chapter.

Common names of species listed in the tables conform to standard nomenclature of the U.S. Department of Agriculture, Forest Service. Other names may be used locally for a species. Also, one common name may be applied to groups of species for marketing.

Natural Characteristics Affecting Mechanical Properties

Clear straight-grained wood is used for determining fundamental mechanical properties; however, because of natural growth characteristics of trees, wood products vary in specific gravity, may contain cross grain, or may have knots and localized slope of grain. Natural defects such as pitch pockets may occur as a result of biological or climatic elements influencing the living tree. These wood characteristics must be taken into account in assessing actual properties or estimating the actual performance of wood products.

Specific Gravity

The substance of which wood is composed is actually heavier than water; its specific gravity is about 1.5 regardless of wood species. In spite of this, the dry wood of most species floats in water, and it is thus 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 other species and therefore higher specific gravity. Thus, specific gravity is an excellent index of the amount of wood substance contained in a piece of wood; it is a good index of mechanical properties as long as the wood is clear, straight grained, and free from defects. However, specific gravity values also reflect the presence of gums, resins, and extractives, which contribute little to mechanical properties.

Approximate relationships between various mechanical properties and specific gravity for clear straight-grained wood of hardwoods and softwoods are given in Table 4–11 as power functions. Those relationships are based on average values for the 43 softwood and 66 hardwood species presented in Table 4–3. The average data vary around the relationships, so that the relationships do not accurately predict individual average species values or an individual specimen value. In fact, mechanical properties within a species tend to be linearly, rather than curvilinearly, related to specific gravity; where data are available for individual species, linear analysis is suggested.

Knots

A knot is that portion of a branch that has become incorporated in the bole of a tree. The influence of a knot on the mechanical properties of a wood member is due to the interruption of continuity and change in the direction of wood fibers associated with the knot. The influence of knots depends on their size, location, shape, and soundness; attendant local slope of grain; and type of stress to which the wood member is subjected.

The shape (form) of a knot on a sawn surface depends upon the direction of the exposing cut. A nearly round knot is produced when lumber is sawn from a log and a branch is sawn through at right angles to its length (as in a flatsawn board). An oval knot is produced if the saw cut is diagonal to the branch length (as in a bastard-sawn board) and a "spiked" knot when the cut is lengthwise to the branch (as in a quartersawn board).

Knots are further classified as intergrown or encased (Fig. 4–3). As long as a limb remains alive, there is continuous growth at the junction of the limb and the bole of the tree, and the resulting knot is called intergrown. After the branch has died, additional growth on the trunk encloses the dead limb, resulting in an encased knot; bole fibers are not continuous with the fibers of the encased knot. Encased knots and knotholes tend to be accompanied by less cross-grain than are intergrown knots and are therefore generally less problematic with regard to most mechanical properties.

Most mechanical properties are lower in sections containing knots than in clear straight-grained wood because (a) the clear wood is displaced by the knot, (b) the fibers around the knot are distorted, resulting in cross grain, (c) the discontinuity of wood fiber leads to stress concentrations, and (d) checking often occurs around the knots during drying. Hardness and strength in compression perpendicular to the grain are exceptions, where knots may be objectionable only in that they cause nonuniform wear or nonuniform stress distributions at contact surfaces.

Knots have a much greater effect on strength in axial tension than in axial short-column compression, and the effects on bending are somewhat less than those in axial tension.

Table 4–11a. Functions relating mechanical properties to specific gravity of clear, straight-grained wood (metric)

	Specific gravity–strength relationship			
	Green wood		Wood at 12% moisture content	
Property[a]	Softwoods	Hardwoods	Softwoods	Hardwoods
Static bending				
MOR (kPa)	109,600 $G^{1.01}$	118,700 $G^{1.16}$	170,700 $G^{1.01}$	171,300 $G^{0.13}$
MOE (MPa)	16,100 $G^{0.76}$	13,900 $G^{0.72}$	20,500 $G^{0.84}$	16,500 $G^{0.7}$
WML (kJ/m^3)	147 $G^{1.21}$	229 $G^{1.52}$	179 $G^{1.34}$	219 $G^{1.54}$
Impact bending (N)	353 $G^{1.35}$	422 $G^{1.39}$	346 $G^{1.39}$	423 $G^{1.65}$
Compression parallel (kPa)	49,700 $G^{0.94}$	49,000 $G^{1.11}$	93,700 $G^{0.97}$	76,000 $G^{0.89}$
Compression perpendicular (kPa)	8,800 $G^{1.53}$	18,500 $G^{2.48}$	16,500 $G^{1.57}$	21,600 $G^{2.09}$
Shear parallel (kPa)	11,000 $G^{0.73}$	17,800 $G^{1.24}$	16,600 $G^{0.85}$	21,900 $G^{1.13}$
Tension perpendicular (kPa)	3,800 $G^{0.78}$	10,500 $G^{1.37}$	6,000 $G^{1.11}$	10,100 $G^{1.3}$
Side hardness (N)	6,230 $G^{1.41}$	16,550 $G^{2.31}$	85,900 $G^{1.5}$	15,300 $G^{2.09}$

[a]Compression parallel to grain is maximum crushing strength; compression perpendicular to grain is fiber stress at proportional limit. MOR is modulus of rupture; MOE, modulus of elasticity; and WML, work to maximum load. For green wood, use specific gravity based on ovendry weight and green volume; for dry wood, use specific gravity based on ovendry weight and volume at 12% moisture content.

Table 4–11b. Functions relating mechanical properties to specific gravity of clear, straight-grained wood (inch–pound)

	Specific gravity–strength relationship			
	Green wood		Wood at 12% moisture content	
Property[a]	Softwoods	Hardwoods	Softwoods	Hardwoods
Static bending				
MOR (lb/in^2)	15,890 $G^{1.01}$	17,210 $G^{1.16}$	24,760 $G^{1.01}$	24,850 $G^{0.13}$
MOE ($\times 10^6$ lb/in^2)	2.33 $G^{0.76}$	2.02 $G^{0.72}$	2.97 $G^{0.84}$	2.39 $G^{0.7}$
WML (in-lbf/in^3)	21.33 $G^{1.21}$	33.2 $G^{1.52}$	25.9 $G^{1.34}$	31.8 $G^{1.54}$
Impact bending (lbf)	79.28 $G^{1.35}$	94.9 $G^{1.39}$	77.7 $G^{1.39}$	95.1 $G^{1.65}$
Compression parallel (lb/in^2)	7,210 $G^{0.94}$	7,110 $G^{1.11}$	13,590 $G^{0.97}$	11,030 $G^{0.89}$
Compression perpendicular (lb/in^2)	1,270 $G^{1.53}$	2,680 $G^{2.48}$	2,390 $G^{1.57}$	3,130 $G^{2.09}$
Shear parallel (lb/in^2)	1,590 $G^{0.73}$	2,580 $G^{1.24}$	2,410 $G^{0.85}$	3,170 $G^{1.13}$
Tension perpendicular (lb/in^2)	550 $G^{0.78}$	1,520 $G^{1.37}$	870 $G^{1.11}$	1,460 $G^{1.3}$
Side hardness (lbf)	1,400 $G^{1.41}$	3,720 $G^{2.31}$	1,930 $G^{1.5}$	3,440 $G^{2.09}$

[a]Compression parallel to grain is maximum crushing strength; compression perpendicular to grain is fiber stress at proportional limit. MOR is modulus of rupture; MOE, modulus of elasticity; and WML, work to maximum load. For green wood, use specific gravity based on ovendry weight and green volume; for dry wood, use specific gravity based on ovendry weight and volume at 12% moisture content.

For this reason, in a simply supported beam, a knot on the lower side (subjected to tensile stresses) has a greater effect on the load the beam will support than does a knot on the upper side (subjected to compressive stresses).

In long columns, knots are important because they affect stiffness. In short or intermediate columns, the reduction in strength caused by knots is approximately proportional to their size; however, large knots have a somewhat greater relative effect than do small knots.

Knots in round timbers, such as poles and piles, have less effect on strength than do knots in sawn timbers. Although the grain is irregular around knots in both forms of timber, the angle of the grain to the surface is smaller in naturally round timber than in sawn timber. Furthermore, in round timbers there is no discontinuity in wood fibers, which results from sawing through both local and general slope of grain.

The effects of knots in structural lumber are discussed in Chapter 6.

Slope of Grain

In some wood product applications, the directions of important stresses may not coincide with the natural axes of fiber orientation in the wood. This may occur by choice in design, from the way the wood was removed from the log, or because of grain irregularities that occurred while the tree was growing.

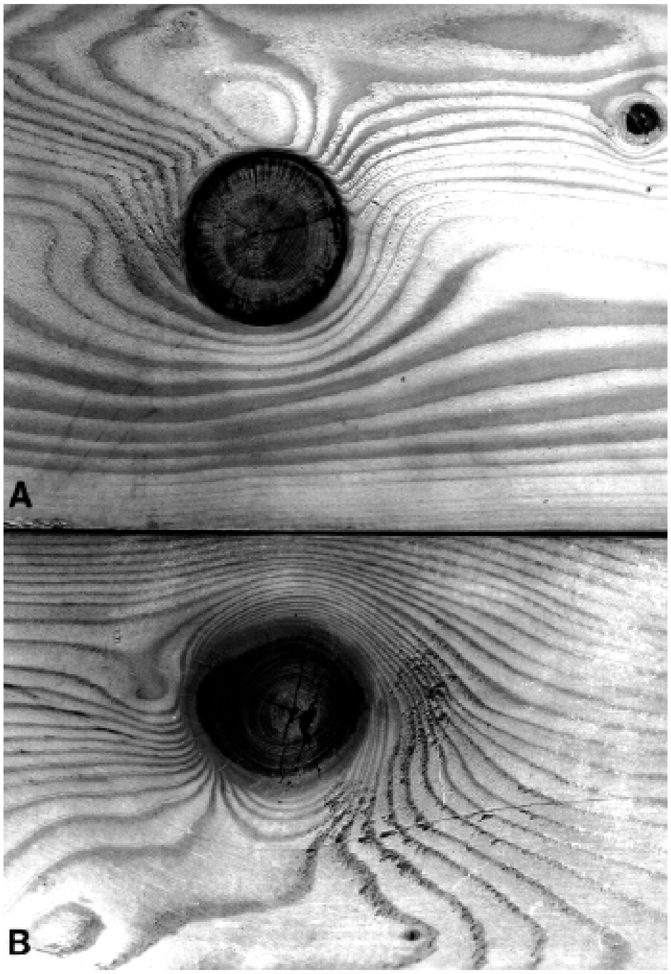

Figure 4–3. Types of knots. A, encased knot; B, intergrown.

Elastic properties in directions other than along the natural axes can be obtained from elastic theory. Strength properties in directions ranging from parallel to perpendicular to the fibers can be approximated using a Hankinson-type formula (Bodig and Jayne 1982):

$$N = \frac{PQ}{P\sin^n \theta + Q\cos^n \theta} \qquad (4\text{–}2)$$

where N is strength at angle θ from fiber direction, Q strength perpendicular to grain, P strength parallel to grain, and n an empirically determined constant.

This formula has been used for modulus of elasticity as well as strength properties. Values of n and associated ratios of Q/P tabulated from available literature are as follows:

Property	*n*	*Q/P*
Tensile strength	1.5–2	0.04–0.07
Compression strength	2–2.5	0.03–0.40
Bending strength	1.5–2	0.04–0.10
Modulus of elasticity	2	0.04–0.12
Toughness	1.5–2	0.06–0.10

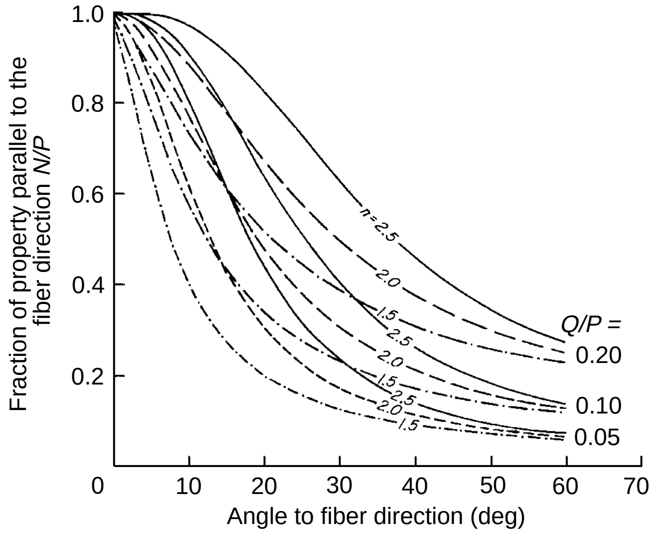

Figure 4–4. Effect of grain angle on mechanical property of clear wood according to Hankinson-type formula. *Q/P* is ratio of mechanical property across the grain (*Q*) to that parallel to the grain (*P*); *n* is an empirically determined constant.

The Hankinson-type formula can be graphically depicted as a function of Q/P and n. Figure 4–4 shows the strength in any direction expressed as a fraction of the strength parallel to fiber direction, plotted against angle to the fiber direction θ. The plot is for a range of values of Q/P and n.

The term slope of grain relates the fiber direction to the edges of a piece. Slope of grain is usually expressed by the ratio between 25 mm (1 in.) of the grain from the edge or long axis of the piece and the distance in millimeters (inches) within which this deviation occurs (tan θ). The effect of grain slope on some properties of wood, as determined from tests, is shown in Table 4–12. The values for modulus of rupture fall very close to the curve in Figure 4–4 for $Q/P = 0.1$ and $n = 1.5$. Similarly, the impact bending values fall close to the curve for $Q/P = 0.05$ and $n = 1.5$, and the compression values for the curve for $Q/P = 0.1$, $n = 2.5$.

The term cross grain indicates the condition measured by slope of grain. Two important forms of cross grain are spiral and diagonal (Fig. 4–5). Other types are wavy, dipped, interlocked, and curly.

Spiral grain is caused by winding or spiral growth of wood fibers about the bole of the tree instead of vertical growth. In sawn products, spiral grain can be defined as fibers lying in the tangential plane of the growth rings, rather than parallel to the longitudinal axis of the product (see Fig. 4–5 for a simple case). Spiral grain in sawn products often goes undetected by ordinary visual inspection. The best test for spiral grain is to split a sample section from the piece in the radial direction. A visual method of determining the presence of spiral grain is to note the alignment of pores, rays, and resin ducts on a flatsawn face. Drying checks on a flatsawn surface follow the fibers and indicate the slope of the fiber. Relative

Table 4–12. Strength of wood members with various grain slopes compared with strength of a straight-grained member[a]

Maximum slope of grain in member	Modulus of rupture (%)	Impact bending (%)	Compression parallel to grain (%)
Straight-grained	100	100	100
1 in 25	96	95	100
1 in 20	93	90	100
1 in 15	89	81	100
1 in 10	81	62	99
1 in 5	55	36	93

[a]Impact bending is height of drop causing complete failure (0.71-kg (50-lb) hammer); compression parallel to grain is maximum crushing strength.

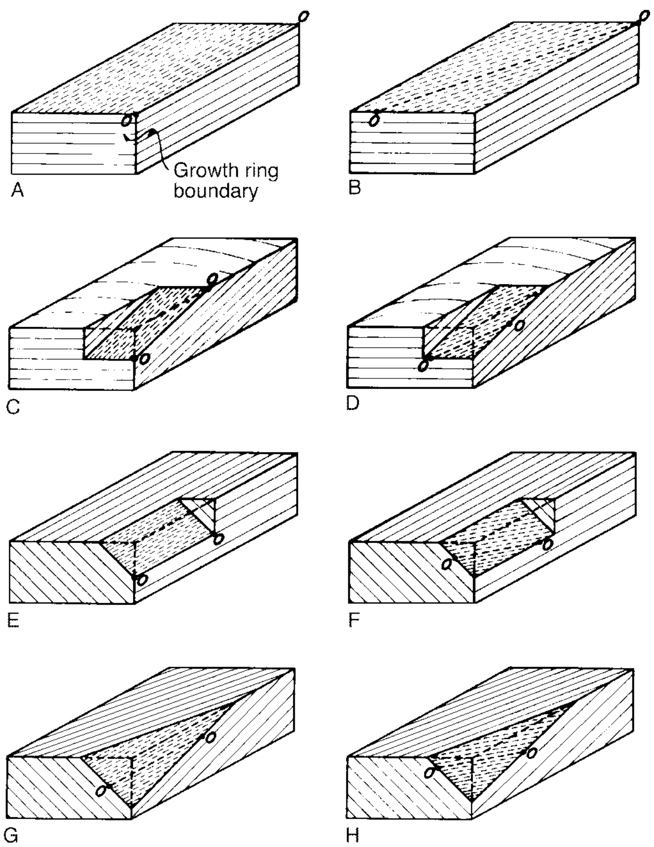

Figure 4–5. Relationship of fiber orientation (O-O) to axes, as shown by schematic of wood specimens containing straight grain and cross grain. Specimens A through D have radial and tangential surfaces; E through H do not. Specimens A and E contain no cross grain; B, D, F, and H have spiral grain; C, D, G, and H have diagonal grain.

change in electrical capacitance is an effective technique for measuring slope of grain.

Diagonal grain is cross grain caused by growth rings that are not parallel to one or both surfaces of the sawn piece. Diagonal grain is produced by sawing a log with pronounced taper parallel to the axis (pith) of the tree. Diagonal grain also occurs in lumber sawn from crooked logs or logs with butt swell.

Cross grain can be quite localized as a result of the disturbance of a growth pattern by a branch. This condition, termed local slope of grain, may be present even though the branch (knot) may have been removed by sawing. The degree of local cross grain may often be difficult to determine. Any form of cross grain can have a deleterious effect on mechanical properties or machining characteristics.

Spiral and diagonal grain can combine to produce a more complex cross grain. To determine net cross grain, regardless of origin, fiber slopes on the contiguous surface of a piece must be measured and combined. The combined slope of grain is determined by taking the square root of the sum of the squares of the two slopes. For example, assume that the spiral grain slope on the flat-grained surface of Figure 4–5D is 1 in 12 and the diagonal-grain slope is 1 in 18. The combined slope is

$$\sqrt{(1/18)^2 + (1/12)^2} = 1/10$$

or a slope of 1 in 10.

A regular reversal of right and left spiraling of grain in a tree stem produces the condition known as interlocked grain. Interlocked grain occurs in some hardwood species (Ch. 3, Table 3–9) and markedly increases resistance to splitting in the radial plane. Interlocked grain decreases both the static bending strength and stiffness of clear wood specimens. The data from tests of domestic hardwoods shown in Table 4–3 do not include pieces that exhibited interlocked grain. Some mechanical property values in Table 4–5 are based on specimens with interlocked grain because that is a characteristic of some species. The presence of interlocked grain alters the relationship between bending strength and compressive strength of lumber cut from tropical hardwoods.

Annual Ring Orientation

Stresses perpendicular to the fiber (grain) direction may be at any angle from 0° (T) to 90° (R) to the growth rings (Fig. 4–6). Perpendicular-to-grain properties depend somewhat upon orientation of annual rings with respect to the direction of stress. The compression perpendicular-to-grain values in Table 4–3 were derived from tests in which the load was applied parallel to the growth rings (T direction); shear parallel-to-grain and tension perpendicular-to-grain values are averages of equal numbers of specimens with 0° and 90° growth ring orientations. In some species, there is no difference in 0° and 90° orientation properties. Other species exhibit slightly higher shear parallel or tension perpendicular-to-grain properties for the 0° orientation than for

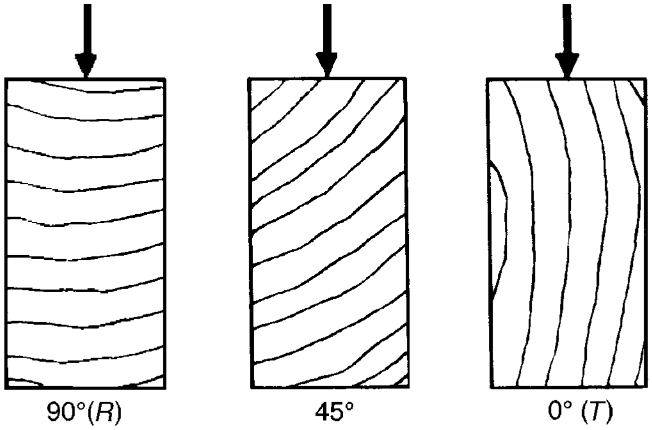

Figure 4–6. Direction of load in relation to direction of annual growth rings: 90° or perpendicular (*R*), 45°, 0° or parallel (*T*).

the 90° orientation; the converse is true for about an equal number of species.

The effects of intermediate annual ring orientations have been studied in a limited way. Modulus of elasticity, compressive perpendicular-to-grain stress at the proportional limit, and tensile strength perpendicular to the grain tend to be about the same at 45° and 0°, but for some species these values are 40% to 60% lower at the 45° orientation. For those species with lower properties at 45° ring orientation, properties tend to be about equal at 0° and 90° orientations. For species with about equal properties at 0° and 45° orientations, properties tend to be higher at the 90° orientation.

Reaction Wood

Abnormal woody tissue is frequently associated with leaning boles and crooked limbs of both conifers and hardwoods. It is generally believed that such wood is formed as a natural response of the tree to return its limbs or bole to a more normal position, hence the term reaction wood. In softwoods, the abnormal tissue is called compression wood; it is common to all softwood species and is found on the lower side of the limb or inclined bole. In hardwoods, the abnormal tissue is known as tension wood; it is located on the upper side of the inclined member, although in some instances it is distributed irregularly around the cross section. Reaction wood is more prevalent in some species than in others.

Many of the anatomical, chemical, physical, and mechanical properties of reaction wood differ distinctly from those of normal wood. Perhaps most evident is the increase in density compared with that of normal wood. The specific gravity of compression wood is commonly 30% to 40% greater than that of normal wood; the specific gravity of tension wood commonly ranges between 5% and 10% greater than that of normal wood, but it may be as much as 30% greater.

Compression wood is usually somewhat darker than normal wood because of the greater proportion of latewood, and it frequently has a relatively lifeless appearance, especially in woods in which the transition from earlywood to latewood is abrupt. Because compression wood is more opaque than normal wood, intermediate stages of compression wood can be detected by transmitting light through thin cross sections; however, borderline forms of compression wood that merge with normal wood can commonly be detected only by microscopic examination.

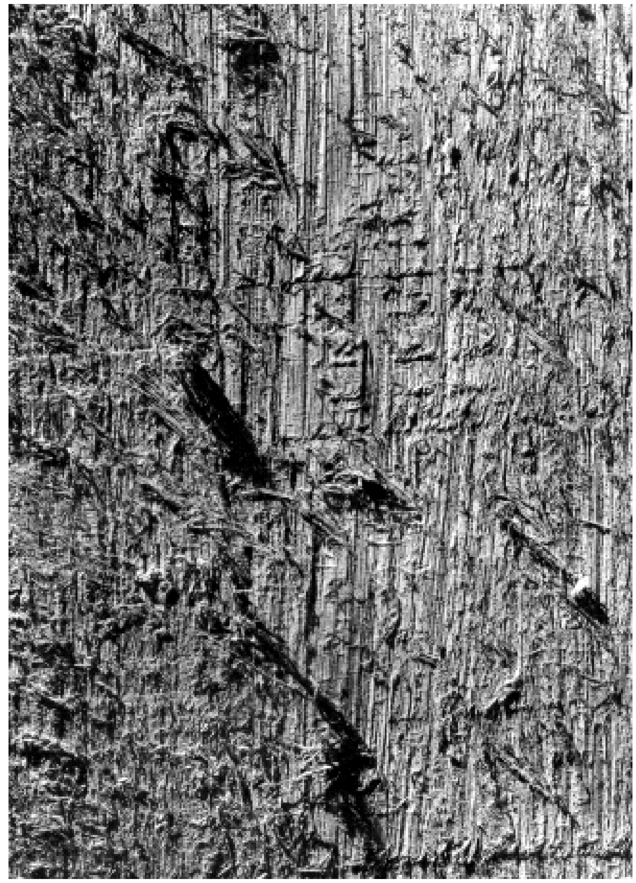

Figure 4–7. Projecting tension wood fibers on sawn surface of mahogany board.

Tension wood is more difficult to detect than is compression wood. However, eccentric growth as seen on the transverse section suggests its presence. Also, because it is difficult to cleanly cut the tough tension wood fibers, the surfaces of sawn boards are “woolly,” especially when the boards are sawn in the green condition (Fig. 4–7). In some species, tension wood may be evident on a smooth surface as areas of contrasting colors. Examples of this are the silvery appearance of tension wood in sugar maple and the darker color of tension wood in mahogany.

Reaction wood, particularly compression wood in the green condition, may be stronger than normal wood. However, compared with normal wood with similar specific gravity, reaction wood is definitely weaker. Possible exceptions to this are compression parallel-to-grain properties of compression wood and impact bending properties of tension wood.

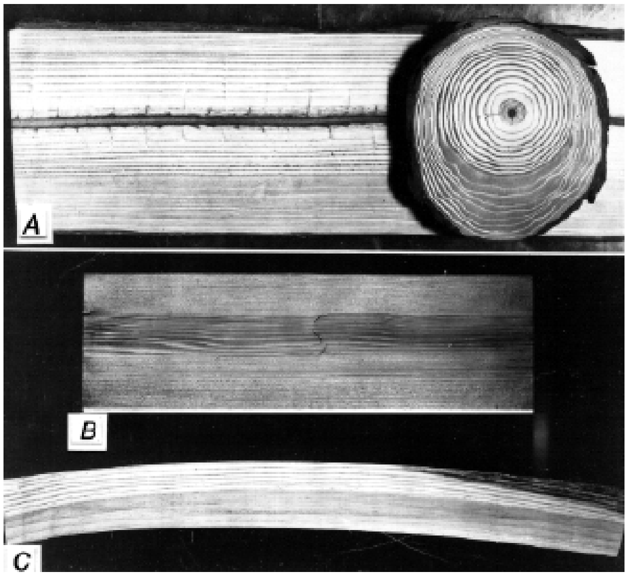

Figure 4–8. Effects of compression wood. A, eccentric growth about pith in cross section containing compression wood—dark area in lower third of cross section is compression wood; B, axial tension break caused by excessive longitudinal shrinkage of compression wood; C, warp caused by excessive longitudinal shrinkage.

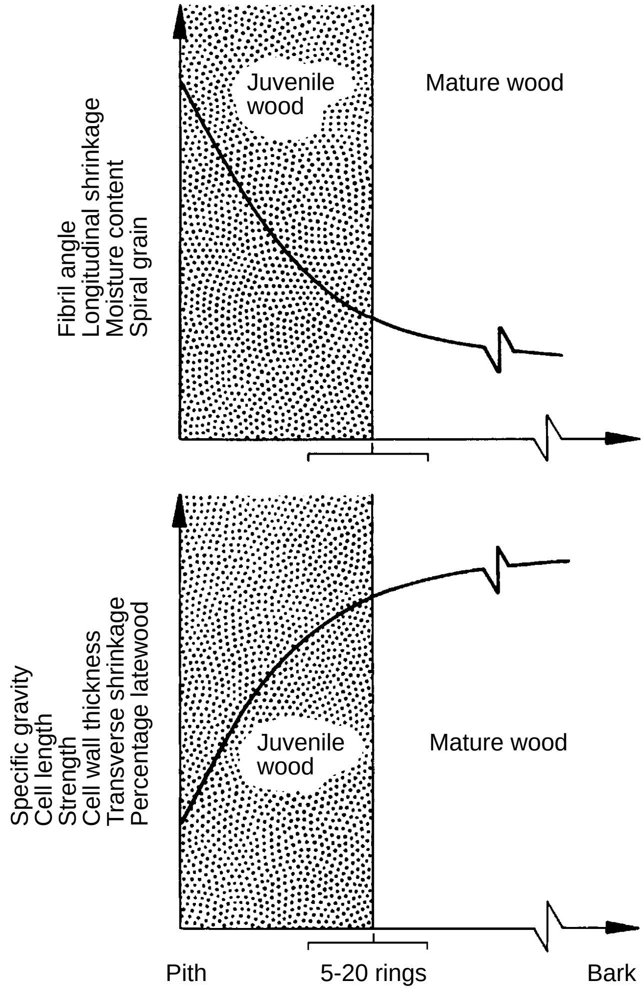

Figure 4–9. Properties of juvenile wood.

Because of the abnormal properties of reaction wood, it may be desirable to eliminate this wood from raw material. In logs, compression wood is characterized by eccentric growth about the pith and the large proportion of latewood at the point of greatest eccentricity (Fig. 4–8A). Fortunately, pronounced compression wood in lumber can generally be detected by ordinary visual examination.

Compression and tension wood undergo extensive longitudinal shrinkage when subjected to moisture loss below the fiber saturation point. Longitudinal shrinkage in compression wood may be up to 10 times that in normal wood and in tension wood, perhaps up to 5 times that in normal wood. When reaction wood and normal wood are present in the same board, unequal longitudinal shrinkage causes internal stresses that result in warping. In extreme cases, unequal longitudinal shrinkage results in axial tension failure over a portion of the cross section of the lumber (Fig. 4–8B). Warp sometimes occurs in rough lumber but more often in planed, ripped, or resawn lumber (Fig. 4–8C).

Juvenile Wood

Juvenile wood is the wood produced near the pith of the tree; for softwoods, it is usually defined as the material 5 to 20 rings from the pith depending on species. Juvenile wood has considerably different physical and anatomical properties than that of mature wood (Fig. 4–9). In clear wood, the properties that have been found to influence mechanical behavior include fibril angle, cell length, and specific gravity, the latter a composite of percentage of latewood, cell wall thickness, and lumen diameter. Juvenile wood has a high fibril angle (angle between longitudinal axis of wood cell and cellulose fibrils), which causes longitudinal shrinkage that may be more than 10 times that of mature wood. Compression wood and spiral grain are also more prevalent in juvenile wood than in mature wood and contribute to longitudinal shrinkage. In structural lumber, the ratio of modulus of rupture, ultimate tensile stress, and modulus of elasticity for juvenile to mature wood ranges from 0.5 to 0.9, 0.5 to 0.95, and 0.45 to 0.75, respectively. Changes in shear strength resulting from increases in juvenile wood content can be adequately predicted by monitoring changes in density alone for all annual ring orientations. The same is true for perpendicular-to-grain compressive strength when the load is applied in the tangential direction. Compressive strength perpendicular-to-grain for loads applied in the radial direction, however, is more sensitive to changes in juvenile wood content and may be up to eight times less than that suggested by changes in density alone. The juvenile wood to mature wood ratio is lower for higher grades of lumber than for lower grades, which indicates that juvenile wood has greater influence in reducing the mechanical properties of high-grade structural lumber. Only a limited amount of research has been done on juvenile wood in hardwood species.

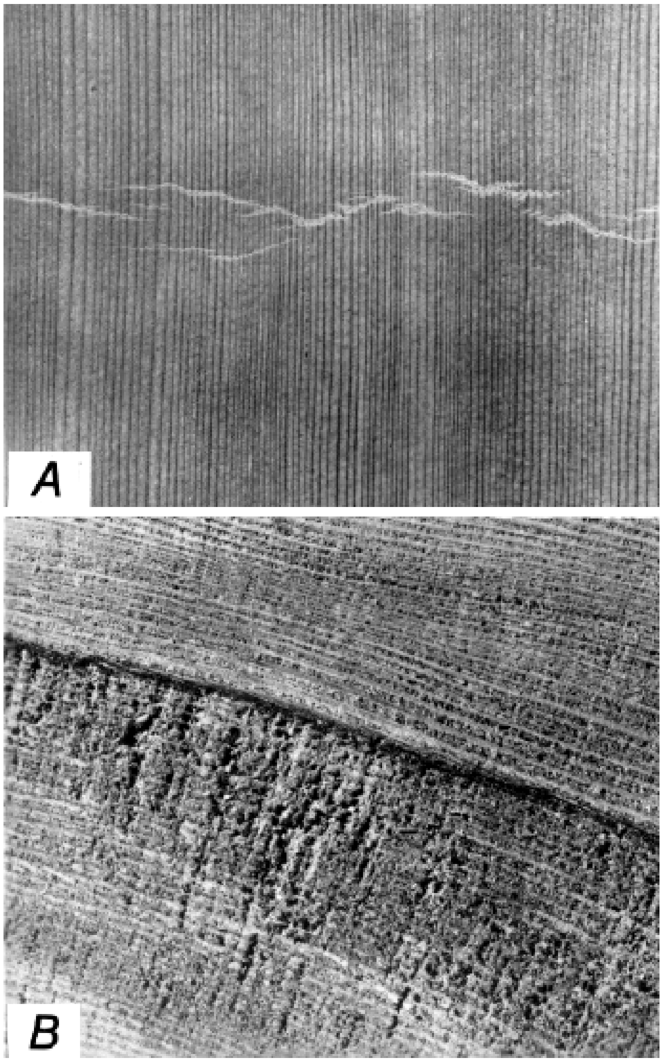

Figure 4–10. Compression failures. A, compression failure shown by irregular lines across grain; B, fiber breakage in end-grain surfaces of spruce lumber caused by compression failures below dark line.

Compression Failures

Excessive compressive stresses along the grain that produce minute compression failures can be caused by excessive bending of standing trees from wind or snow; felling of trees across boulders, logs, or irregularities in the ground; or rough handling of logs or lumber. Compression failures should not be confused with compression wood. In some instances, compression failures are visible on the surface of a board as minute lines or zones formed by crumpling or buckling of cells (Fig. 4–10A), although the failures usually appear as white lines or may even be invisible to the naked eye. The presence of compression failures may be indicated by fiber breakage on end grain (Fig. 4–10B). Since compression failures are often difficult to detect with the unaided eye, special efforts, including optimum lighting, may be required for detection. The most difficult cases are detected only by microscopic examination.

Products containing visible compression failures have low strength properties, especially in tensile strength and shock resistance. The tensile strength of wood containing compression failures may be as low as one-third the strength of matched clear wood. Even slight compression failures, visible only under a microscope, may seriously reduce strength and cause brittle fracture. Because of the low strength associated with compression failures, many safety codes require certain structural members, such as ladder rails and scaffold planks, to be entirely free of such failures.

Pitch Pockets

A pitch pocket is a well-defined opening that contains free resin. The pocket extends parallel to the annual rings; it is almost flat on the pith side and curved on the bark side. Pitch pockets are confined to such species as the pines, spruces, Douglas-fir, tamarack, and western larch.

The effect of pitch pockets on strength depends upon their number, size, and location in the piece. A large number of pitch pockets indicates a lack of bond between annual growth layers, and a piece with pitch pockets should be inspected for shake or separation along the grain.

Bird Peck

Maple, hickory, white ash, and a number of other species are often damaged by small holes made by woodpeckers. These bird pecks often occur in horizontal rows, sometimes encircling the tree, and a brown or black discoloration known as a mineral streak originates from each hole. Holes for tapping maple trees are also a source of mineral streaks. The streaks are caused by oxidation and other chemical changes in the wood. Bird pecks and mineral streaks are not generally important in regard to strength of structural lumber, although they do impair the appearance of the wood.

Extractives

Many wood species contain removable extraneous materials or extractives that do not degrade the cellulose–lignin structure of the wood. These extractives are especially abundant in species such as larch, redwood, western redcedar, and black locust.

A small decrease in modulus of rupture and strength in compression parallel to grain has been measured for some species after the extractives have been removed. The extent to which extractives influence strength is apparently a function of the amount of extractives, the moisture content of the piece, and the mechanical property under consideration.

Properties of Timber From Dead Trees

Timber from trees killed by insects, blight, wind, or fire may be as good for any structural purpose as that from live trees, provided further insect attack, staining, decay, or drying degrade has not occurred. In a living tree, the heartwood is entirely dead and only a comparatively few sapwood cells are alive. Therefore, most wood is dead when cut, regardless of whether the tree itself is living or not. However, if a tree stands on the stump too long after its death, the sapwood is likely to decay or to be attacked severely by wood-boring insects, and eventually the heartwood will be similarly affected. Such deterioration also occurs in logs that have been cut from live trees and improperly cared for afterwards. Because of variations in climatic and other factors that affect deterioration, the time that dead timber may stand or lie in the forest without serious deterioration varies.

Tests on wood from trees that had stood as long as 15 years after being killed by fire demonstrated that this wood was as sound and strong as wood from live trees. Also, the heartwood of logs of some more durable species has been found to be thoroughly sound after lying in the forest for many years.

On the other hand, in nonresistant species, decay may cause great loss of strength within a very brief time, both in trees standing dead on the stump and in logs cut from live trees and allowed to lie on the ground. The important consideration is not whether the trees from which wood products are cut are alive or dead, but whether the products themselves are free from decay or other degrading factors that would render them unsuitable for use.

Effects of Manufacturing and Service Environments

Moisture Content

Many mechanical properties are affected by changes in moisture content below the fiber saturation point. Most properties reported in Tables 4–3, 4–4, and 4–5 increase with decrease in moisture content. The relationship that describes these changes in clear wood property at about 21ºC (70ºF) is

$$P = P_{12}\left(\frac{P_{12}}{P_g}\right)^{\left(\frac{12-M}{M_p-12}\right)} \qquad (4–3)$$

where P is the property at moisture content M (%), P_{12} the same property at 12% MC, P_g the same property for green wood, and M_p moisture content at the intersection of a horizontal line representing the strength of green wood and an inclined line representing the logarithm of the strength–moisture content relationship for dry wood. This assumed linear relationship results in an M_p value that is slightly less than the fiber saturation point. Table 4–13 gives values of M_p for a few species; for other species, M_p = 25 may be assumed.

Average property values of P_{12} and P_g are given for many species in Tables 4–3 to 4–5. The formula for moisture content adjustment is not recommended for work to maximum load, impact bending, and tension perpendicular to grain. These properties are known to be erratic in their response to moisture content change.

The formula can be used to estimate a property at any moisture content below M_p from the species data given. For example, suppose you want to find the modulus of rupture of white ash at 8% moisture content. Using information from Tables 4–3a and 4–13,

$$P_8 = 103{,}000\left[\frac{103{,}000}{66{,}000}\right]^{4/12} = 119{,}500 \text{ kPa}$$

Care should be exercised when adjusting properties below 12% moisture. Although most properties will continue to increase while wood is dried to very low moisture content levels, for most species some properties may reach a maximum value and then decrease with further drying (Fig. 4–11). For clear Southern Pine, the moisture content at which a maximum property has been observed is given in Table 4–14.

Table 4–13. Intersection moisture content values for selected species[a]

Species	M_p (%)
Ash, white	24
Birch, yellow	27
Chestnut, American	24
Douglas-fir	24
Hemlock, western	28
Larch, western	28
Pine, loblolly	21
Pine, longleaf	21
Pine, red	24
Redwood	21
Spruce, red	27
Spruce, Sitka	27
Tamarack	24

[a]Intersection moisture content is point at which mechanical properties begin to change when wood is dried from the green condition.

This increase in mechanical properties with drying assumes small, clear specimens in a drying process in which no deterioration of the product (degrade) occurs. For 51-mm- (2-in.-) thick lumber containing knots, the increase in property with decreasing moisture content is dependent upon lumber quality. Clear, straight-grained lumber may show increases in properties with decreasing moisture content that approximate those of small, clear specimens. However, as the frequency and size of knots increase, the reduction in strength resulting from the knots begins to negate the increase in property in the clear wood portion of the lumber. Very low quality lumber, which has many large knots, may be insensitive to changes in moisture content. Figures 4–12 and 4–13 illustrate the effect of moisture content on the properties of lumber as a function of initial lumber strength (Green and others 1989). Application of these results in adjusting allowable properties of lumber is discussed in Chapter 6.

Additional information on influences of moisture content on dimensional stability is included in Chapter 12.

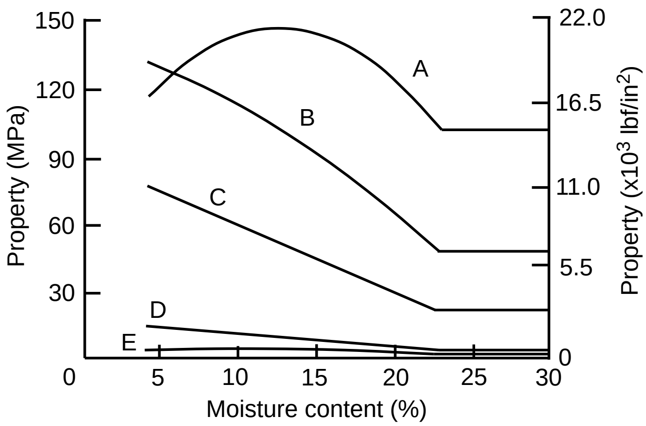

Figure 4–11. Effect of moisture content on wood strength properties. A, tension parallel to grain; B, bending; C, compression parallel to grain; D, compression perpendicular to grain; and E, tension perpendicular to grain.

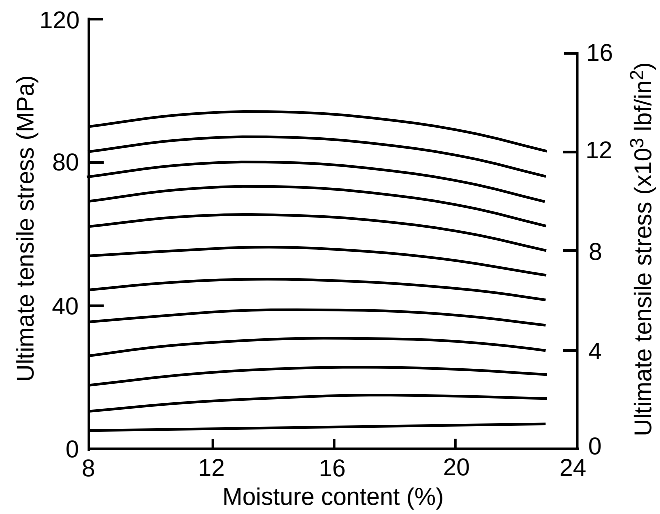

Figure 4–12. Effect of moisture content on tensile strength of lumber parallel to grain.

Table 4–14. Moisture content for maximum property value in drying clear Southern Pine from green to 4% moisture content

Property	Moisture content at which peak property occurs (%)
Ultimate tensile stress parallel to grain	12.6
Ultimate tensile stress perpendicular to grain	10.2
MOE tension perpendicular to grain	4.3
MOE compression parallel to grain	4.3
Modulus of rigidity, G_{RT}	10.0

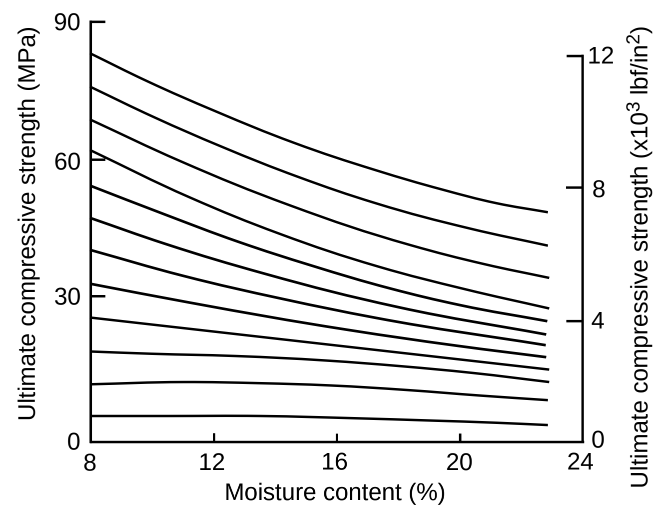

Figure 4–13. Effect of moisture content on compressive strength of lumber parallel to grain.

Temperature

Reversible Effects

In general, the mechanical properties of wood decrease when heated and increase when cooled. At a constant moisture content and below approximately 150ºC (302ºF), mechanical properties are approximately linearly related to temperature. The change in properties that occurs when wood is quickly heated or cooled and then tested at that condition is termed an immediate effect. At temperatures below 100ºC (212ºF), the immediate effect is essentially reversible; that is, the property will return to the value at the original temperature if the temperature change is rapid.

Figure 4–14 illustrates the immediate effect of temperature on modulus of elasticity parallel to grain, modulus of rupture, and compression parallel to grain, 20°C (68°F), based on a composite of results for clear, defect-free wood. This figure represents an interpretation of data from several investigators. The width of the bands illustrates variability between and within reported trends.

Table 4–15 lists changes in clear wood properties at −50°C (−58°F) and 50°C (122°F) relative to those at 20°C (68°F) for a number of moisture conditions. The large changes at −50°C (−58°F) for green wood (at fiber saturation point or wetter) reflect the presence of ice in the wood cell cavities.

The strength of dry lumber, at about 12% moisture content, may change little as temperature increases from −29°C (−20°F) to 38°C (100°F). For green lumber, strength generally decreases with increasing temperature. However, for temperatures between about 7°C (45°F) and 38°C (100°F), the changes may not differ significantly from those at room temperature. Table 4–16 provides equations that have been

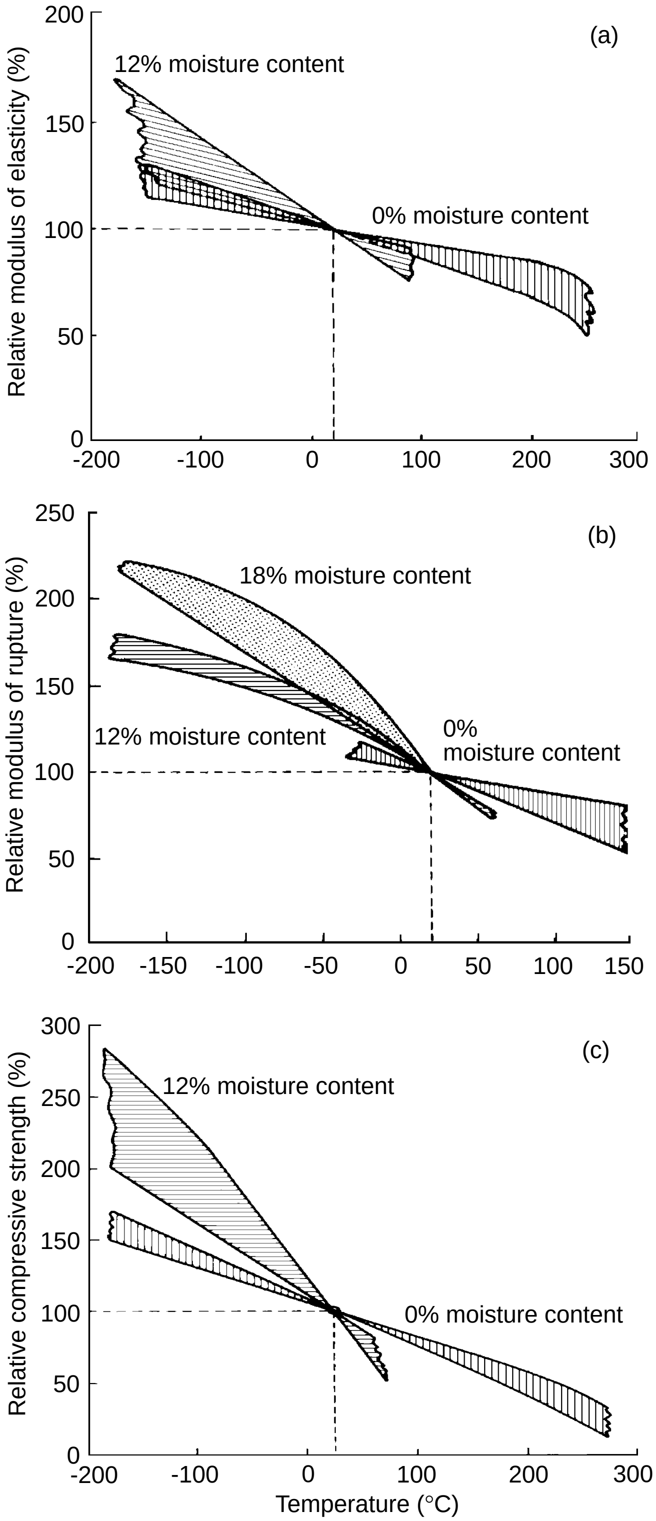

Figure 4–14. Immediate effect of temperature at two moisture content levels relative to value at 20°C (68°F) for clear, defect-free wood: (a) modulus of elasticity parallel to grain, (b) modulus of rupture in bending, (c) compressive strength parallel to grain. The plot is a composite of results from several studies. Variability in reported trends is illustrated by width of bands.

Table 4–15. Approximate middle-trend effects of temperature on mechanical properties of clear wood at various moisture conditions

Property	Moisture condition[a] (%)	Relative change in mechanical property from 20°C (68°F) at –50°C (–58°F) (%)	Relative change in mechanical property from 20°C (68°F) at +50°C (+122°F) (%)
MOE parallel to grain	0	+11	–6
	12	+17	–7
	>FSP	+50	—
MOE perpendicular to grain	6	—	–20
	12	—	–35
	≥20	—	–38
Shear modulus	>FSP	—	–25
Bending strength	≤4	+18	–10
	11–15	+35	–20
	18–20	+60	–25
	>FSP	+110	–25
Tensile strength parallel to grain	0–12	—	–4
Compressive strength parallel to grain	0	+20	–10
	12–45	+50	–25
Shear strength parallel to grain	>FSP	—	–25
Tensile strength perpendicular to grain	4–6	—	–10
	11–16	—	–20
	≥18	—	–30
Compressive strength perpendicular to grain at proportional limit	0–6	—	–20
	≥10	—	–35

[a]FSP indicates moisture content greater than fiber saturation point.

used to adjust some lumber properties for the reversible effects of temperature.

Irreversible Effects

In addition to the reversible effect of temperature on wood, there is an irreversible effect at elevated temperature. This permanent effect is one of degradation of wood substance, which results in loss of weight and strength. The loss depends on factors that include moisture content, heating medium, temperature, exposure period, and to some extent, species and size of piece involved.

The permanent decrease of modulus of rupture caused by heating in steam and water is shown as a function of temperature and heating time in Figure 4–15, based on tests of clear pieces of Douglas-fir and Sitka spruce. In the same studies, heating in water affected work to maximum load more than modulus of rupture (Fig. 4–16). The effect of heating dry wood (0% moisture content) on modulus of rupture and modulus of elasticity is shown in Figures 4–17 and 4–18, respectively, as derived from tests on four softwoods and two hardwoods.

Table 4–16. Percentage change in bending properties of lumber with change in temperature[a]

Property	Lumber grade[b]	Moisture content	$((P–P_{70}) / P_{70})100 = A + BT + CT^2$			Temperature range	
			A	B	C	T_{min}	T_{max}
MOE	All	Green	22.0350	–0.4578	0	0	32
		Green	13.1215	–0.1793	0	32	150
		12%	7.8553	–0.1108	0	–15	150
MOR	SS	Green	34.13	–0.937	0.0043	–20	46
		Green	0	0	0	46	100
		12%	0	0	0	–20	100
	No. 2 or less	Green	56.89	–1.562	0.0072	–20	46
		Green	0	0	0	46	100
		Dry	0	0	0	–20	100

[a]For equation, P is property at temperature T in °F; P_{70}, property at 21°C (70°F).
[b]SS is Select Structural.

Figure 4–19 illustrates the permanent loss in bending strength of Spruce–Pine–Fir standard 38- by 89-mm (nominal 2- by 4-in.) lumber heated at 66°C (150°F) and about 12% moisture content. During this same period, modulus of elasticity barely changed. Most in-service exposures at 66°C (150°F) would be expected to result in much lower moisture content levels. Additional results for other lumber products and exposure conditions will be reported as Forest Products Laboratory studies progress.

The permanent property losses discussed here are based on tests conducted after the specimens were cooled to room temperature and conditioned to a range of 7% to 12% moisture content. If specimens are tested hot, the percentage of strength reduction resulting from permanent effects is based on values already reduced by the immediate effects. Repeated exposure to elevated temperature has a cumulative effect on wood properties. For example, at a given temperature the property loss will be about the same after six 1-month exposure as it would be after a single 6-month exposure.

The shape and size of wood pieces are important in analyzing the influence of temperature. If exposure is for only a short time, so that the inner parts of a large piece do not reach the temperature of the surrounding medium, the immediate effect on strength of the inner parts will be less than that for the outer parts. However, the type of loading must be considered. If the member is to be stressed in bending, the outer fibers of a piece will be subjected to the greatest stress and will ordinarily govern the ultimate strength of the piece; hence, under this loading condition, the fact that the inner part is at a lower temperature may be of little significance.

For extended noncyclic exposures, it can be assumed that the entire piece reaches the temperature of the heating medium and will therefore be subject to permanent strength losses throughout the volume of the piece, regardless of size and mode of stress application. However, in ordinary construction wood often will not reach the daily temperature extremes of the air around it; thus, long-term effects should be based on the accumulated temperature experience of critical structural parts.

Time Under Load

Rate of Loading

Mechanical property values, as given in Tables 4–3, 4–4, and 4–5, are usually referred to as static strength values. Static strength tests are typically conducted at a rate of loading or rate of deformation to attain maximum load in about 5 min. Higher values of strength are obtained for wood loaded at a more rapid rate and lower values are obtained at slower rates. For example, the load required to produce failure in a wood member in 1 s is approximately 10% higher than that obtained in a standard static strength test. Over several orders of magnitude of rate of loading, strength is approximately an exponential function of rate. See Chapter 6 for application to treated woods.

Figure 4–20 illustrates how strength decreases with time to maximum load. The variability in the trend shown is based on results from several studies pertaining to bending, compression, and shear.

Creep and Relaxation

When initially loaded, a wood member deforms elastically. If the load is maintained, additional time-dependent deformation occurs. This is called creep. Creep occurs at even very low stresses, and it will continue over a period of years. For sufficiently high stresses, failure eventually occurs. This failure phenomenon, called duration of load (or creep rupture), is discussed in the next section.

At typical design levels and use environments, after several years the additional deformation caused by creep may approximately equal the initial, instantaneous elastic deformation. For illustration, a creep curve based on creep as a function of initial deflection (relative creep) at several stress levels is shown in Figure 4–21; creep is greater under higher stresses than under lower ones.

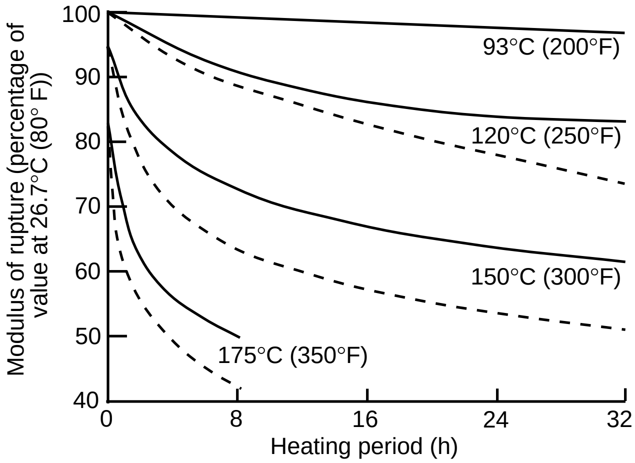

Figure 4–15. Permanent effect of heating in water (solid line) and steam (dashed line) on modulus of rupture of clear, defect-free wood. All data based on tests of Douglas-fir and Sitka spruce at room temperature.

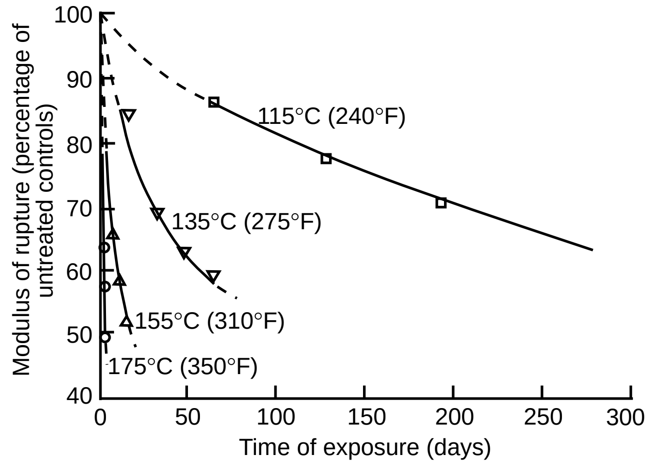

Figure 4–17. Permanent effect of oven heating at four temperatures on modulus of rupture, based on clear pieces of four softwood and two hardwood species. All tests conducted at room temperature.

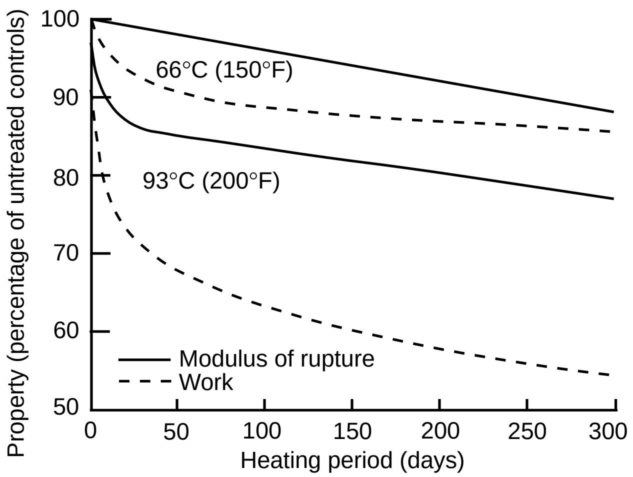

Figure 4–16. Permanent effect of heating in water on work to maximum load and modulus of rupture of clear, defect-free wood. All data based on tests of Douglas-fir and Sitka spruce at room temperature.

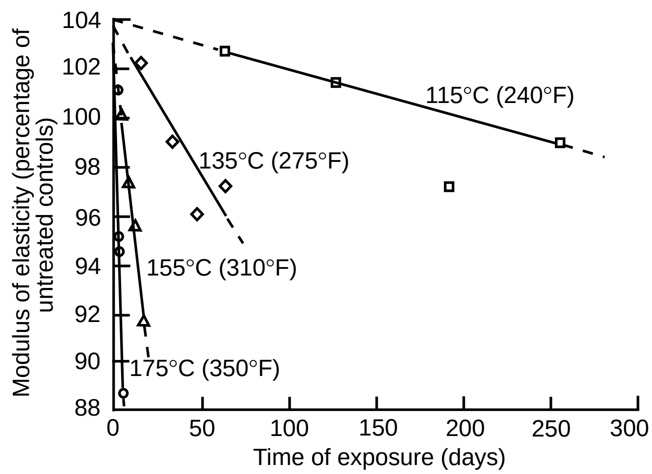

Figure 4–18. Permanent effect of oven heating at four temperatures on modulus of elasticity, based on clear pieces of four softwood and two hardwood species. All tests conducted at room temperature.

Ordinary climatic variations in temperature and humidity will cause creep to increase. An increase of about 28°C (50°F) in temperature can cause a two- to threefold increase in creep. Green wood may creep four to six times the initial deformation as it dries under load.

Unloading a member results in immediate and complete recovery of the original elastic deformation and after time, a recovery of approximately one-half the creep at deformation as well. Fluctuations in temperature and humidity increase the magnitude of the recovered deformation.

Relative creep at low stress levels is similar in bending, tension, or compression parallel to grain, although it may be somewhat less in tension than in bending or compression under varying moisture conditions. Relative creep across the grain is qualitatively similar to, but likely to be greater than, creep parallel to the grain. The creep behavior of all species studied is approximately the same.

If instead of controlling load or stress, a constant deformation is imposed and maintained on a wood member, the initial stress relaxes at a decreasing rate to about 60% to 70% of its original value within a few months. This reduction of stress with time is commonly called relaxation.

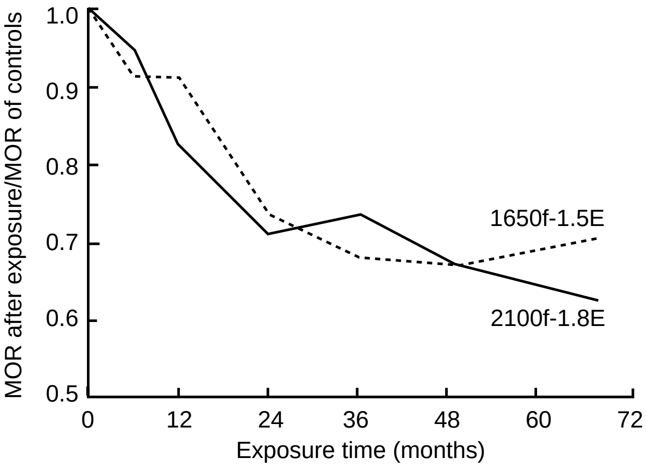

Figure 4–19. Permanent effect of heating at 66°C (150°F) on modulus of rupture for two grades of machine-stress-rated Spruce–Pine–Fir lumber at 12% moisture content. All tests conducted at room temperature.

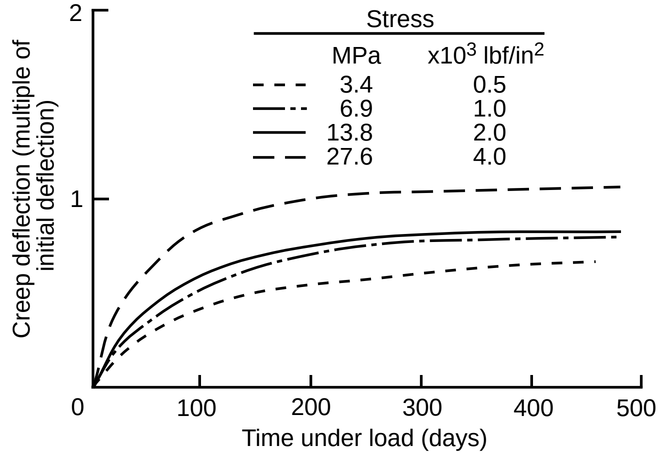

Figure 4–21. Influence of four levels of stress on creep (Kingston 1962).

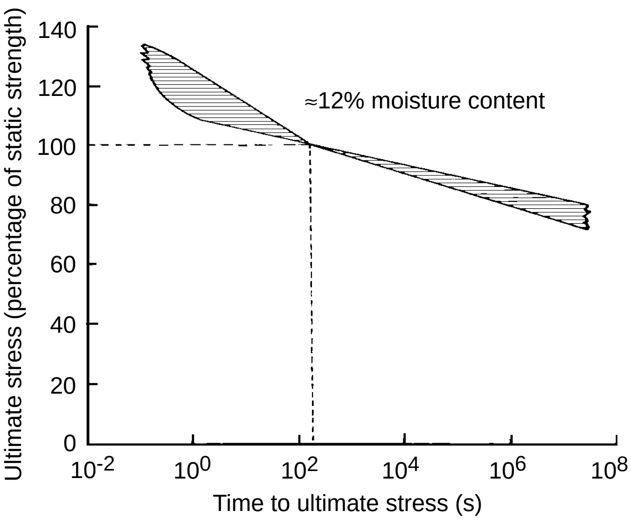

Figure 4–20. Relationship of ultimate stress at short-time loading to that at 5-min loading, based on composite of results from rate-of-load studies on bending, compression, and shear parallel to grain. Variability in reported trends is indicated by width of band.

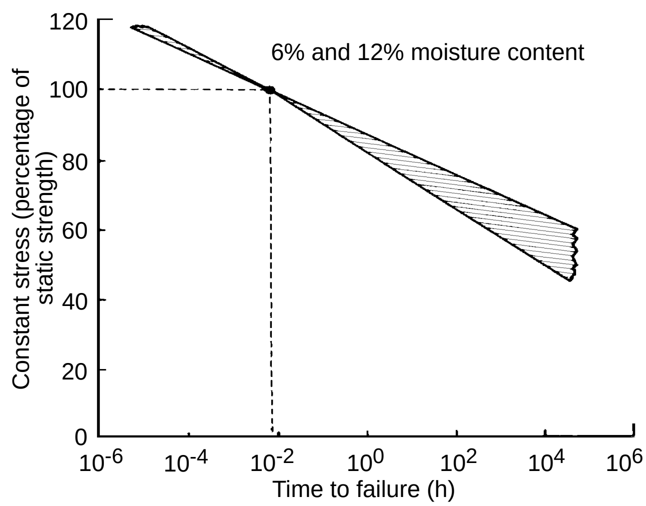

Figure 4–22. Relationship between stress due to constant load and time to failure for small clear wood specimens, based on 28 s at 100% stress. The figure is a composite of trends from several studies; most studies involved bending but some involved compression parallel to grain and bending perpendicular to grain. Variability in reported trends is indicated by width of band.

In limited bending tests carried out between approximately 18°C (64°F) and 49°C (120°F) over 2 to 3 months, the curve of stress as a function of time that expresses relaxation is approximately the mirror image of the creep curve (deformation as a function of time). These tests were carried out at initial stresses up to about 50% of the bending strength of the wood. As with creep, relaxation is markedly affected by fluctuations in temperature and humidity.

Duration of Load

The duration of load, or the time during which a load acts on a wood member either continuously or intermittently, is an important factor in determining the load that the member can safely carry. The duration of load may be affected by changes in temperature and relative humidity.

The constant stress that a wood member can sustain is approximately an exponential function of time to failure, as illustrated in Figure 4–22. This relationship is a composite of results of studies on small, clear wood specimens, conducted at constant temperature and relative humidity.

For a member that continuously carries a load for a long period, the load required to produce failure is much less than that determined from the strength properties in Tables 4–3 to 4–5. Based on Figure 4–22, a wood member under the continuous action of bending stress for 10 years may carry only 60% (or perhaps less) of the load required to produce failure in the same specimen loaded in a standard bending strength test of only a few minutes duration. Conversely, if the duration of load is very short, the load-carrying capacity may be higher than that determined from strength properties given in the tables.

Time under intermittent loading has a cumulative effect. In tests where a constant load was periodically placed on a beam and then removed, the cumulative time the load was actually applied to the beam before failure was essentially equal to the time to failure for a similar beam under the same load applied continuously.

The time to failure under continuous or intermittent loading is looked upon as a creep–rupture process; a member has to undergo substantial deformation before failure. Deformation at failure is approximately the same for duration of load tests as for standard strength tests.

Changes in climatic conditions increase the rate of creep and shorten the duration during which a member can support a given load. This effect can be substantial for very small wood specimens under large cyclic changes in temperature and relative humidity. Fortunately, changes in temperature and relative humidity are moderate for wood in the typical service environment.

Fatigue

In engineering, the term fatigue is defined as the progressive damage that occurs in a material subjected to cyclic loading. This loading may be repeated (stresses of the same sign; that is, always compression or always tension) or reversed (stresses of alternating compression and tension). When sufficiently high and repetitious, cyclic loading stresses can result in fatigue failure.

Fatigue life is a term used to define the number of cycles that are sustained before failure. Fatigue strength, the maximum stress attained in the stress cycle used to determine fatigue life, is approximately exponentially related to fatigue life; that is, fatigue strength decreases approximately linearly as the logarithm of number of cycles increases. Fatigue strength and fatigue life also depend on several other factors: frequency of cycling; repetition or reversal of loading; range factor (ratio of minimum to maximum stress per cycle); and other factors such as temperature, moisture content, and specimen size. Negative range factors imply repeated reversing loads, whereas positive range factors imply nonreversing loads.

Results from several fatigue studies on wood are given in Table 4–17. Most of these results are for repeated loading with a range ratio of 0.1, meaning that the minimum stress per cycle is 10% of the maximum stress. The maximum stress per cycle, expressed as a percentage of estimated static strength, is associated with the fatigue life given in millions of cycles. The first three lines of data, which list the same cyclic frequency (30 Hz), demonstrate the effect of range ratio on fatigue strength (maximum fatigue stress that can be maintained for a given fatigue life); fatigue bending strength decreases as range ratio decreases. Third-point bending results show the effect of small knots or slope of grain on fatigue strength at a range ratio of 0.1 and frequency of 8.33 Hz. Fatigue strength is lower for wood containing small knots or a 1-in-12 slope of grain than for clear straight-grained wood and even lower for wood containing a combination of small knots and a 1-in-12 slope of grain. Fatigue strength is the same for a scarf joint in tension as for tension parallel to the grain, but a little lower for a finger joint in tension. Fatigue strength is slightly lower in shear than in tension parallel to the grain. Other comparisons do not have much meaning because range ratios or cyclic frequency differ; however, fatigue strength is high in compression parallel to the grain compared with other properties. Little is known about other factors that may affect fatigue strength in wood.

Table 4–17. Summary of reported results on cyclic fatigue[a]

Property	Range ratio	Cyclic frequency (Hz)	Maximum stress per cycle[b] (%)	Approximate fatigue life (×10^6 cycles)
Bending, clear, straight grain				
Cantilever	0.45	30	45	30
Cantilever	0	30	40	30
Cantilever	–1.0	30	30	30
Center-point	–1.0	40	30	4
Rotational	–1.0	—	28	30
Third-point	0.1	8-1/3	60	2
Bending, third-point				
Small knots	0.1	8-1/3	50	2
Clear, 1:12 slope of grain	0.1	8-1/3	50	2
Small knots, 1:12 slope of grain	0.1	8-1/3	40	2
Tension parallel to grain				
Clear, straight grain	0.1	15	50	30
Clear, straight grain	0	40	60	3.5
Scarf joint	0.1	15	50	30
Finger joint	0.1	15	40	30
Compression parallel to grain				
Clear, straight grain	0.1	40	75	3.5
Shear parallel to grain				
Glue-laminated	0.1	15	45	30

[a]Initial moisture content about 12% to 15%.
[b]Percentage of estimated static strength.

Creep, temperature rise, and loss of moisture content occur in tests of wood for fatigue strength. At stresses that cause failure in about 106 cycles at 40 Hz, a temperature rise of

15°C (27°F) has been reported for parallel-to-grain compression fatigue (range ratio slightly greater than zero), parallel-to-grain tension fatigue (range ratio = 0), and reversed bending fatigue (range ratio = –1). The rate of temperature rise is high initially but then diminishes to moderate; a moderate rate of temperature rise remains more or less constant during a large percentage of fatigue life. During the latter stages of fatigue life, the rate of temperature rise increases until failure occurs. Smaller rises in temperature would be expected for slower cyclic loading or lower stresses. Decreases in moisture content are probably related to temperature rise.

Aging

In relatively dry and moderate temperature conditions where wood is protected from deteriorating influences such as decay, the mechanical properties of wood show little change with time. Test results for very old timbers suggest that significant losses in clear wood strength occur only after several centuries of normal aging conditions. The soundness of centuries-old wood in some standing trees (redwood, for example) also attests to the durability of wood.

Exposure to Chemicals

The effect of chemical solutions on mechanical properties depends on the specific type of chemical. Nonswelling liquids, such as petroleum oils and creosote, have no appreciable effect on properties. Properties are lowered in the presence of water, alcohol, or other wood-swelling organic liquids even though these liquids do not chemically degrade the wood substance. The loss in properties depends largely on the amount of swelling, and this loss is regained upon removal of the swelling liquid. Anhydrous ammonia markedly reduces the strength and stiffness of wood, but these properties are regained to a great extent when the ammonia is removed. Heartwood generally is less affected than sapwood because it is more impermeable. Accordingly, wood treatments that retard liquid penetration usually enhance natural resistance to chemicals.

Chemical solutions that decompose wood substance (by hydrolysis or oxidation) have a permanent effect on strength. The following generalizations summarize the effect of chemicals:

- Some species are quite resistant to attack by dilute mineral and organic acids.
- Oxidizing acids such as nitric acid degrade wood more than do nonoxidizing acids.
- Alkaline solutions are more destructive than are acidic solutions.
- Hardwoods are more susceptible to attack by both acids and alkalis than are softwoods.
- Heartwood is less susceptible to attack by both acids and alkalis than is sapwood.

Because both species and application are extremely important, reference to industrial sources with a specific history of use is recommended where possible. For example, large cypress tanks have survived long continuous use where exposure conditions involved mixed acids at the boiling point. Wood is also used extensively in cooling towers because of its superior resistance to mild acids and solutions of acidic salts.

Chemical Treatment

Wood is often treated with chemicals to enhance its fire performance or decay resistance in service. Each set of treatment chemicals and processes has a unique effect on the mechanical properties of the treated wood.

Fire-retardant treatments and treatment methods distinctly reduce the mechanical properties of wood. Some fire-retardant-treated products have experienced significant in-service degradation on exposure to elevated temperatures when used as plywood roof sheathing or roof-truss lumber. New performance requirements within standards set by the American Standards for Testing and Materials (ASTM) and American Wood Preservers' Association (AWPA) preclude commercialization of inadequately performing fire-retardant-treated products.

Although preservative treatments and treatment methods generally reduce the mechanical properties of wood, any initial loss in strength from treatment must be balanced against the progressive loss of strength from decay when untreated wood is placed in wet conditions. The effects of preservative treatments on mechanical properties are directly related to wood quality, size, and various pretreatment, treatment, and post-treatment processing factors. The key factors include preservative chemistry or chemical type, preservative retention, initial kiln-drying temperature, post-treatment drying temperature, and pretreatment incising (if required). North American design guidelines address the effects of incising on mechanical properties of refractory wood species and the short-term duration-of-load adjustments for all treated lumber. These guidelines are described in Chapter 6.

Oil-Type Preservatives

Oil-type preservatives cause no appreciable strength loss because they do not chemically react with wood cell wall components. However, treatment with oil-type preservatives can adversely affect strength if extreme in-retort seasoning parameters are used (for example, Boultonizing, steaming, or vapor drying conditions) or if excessive temperatures or pressures are used during the treating process. To preclude strength loss, the user should follow specific treatment processing requirements as described in the treatment standards.

Waterborne Preservatives

Waterborne preservative treatments can reduce the mechanical properties of wood. Treatment standards include specific processing requirements intended to prevent or limit strength reductions resulting from the chemicals and the waterborne preservative treatment process. The effects of waterborne preservative treatment on mechanical properties are related to species, mechanical properties, preservative chemistry or type, preservative retention, post-treatment drying temperature, size and grade of material, product type, initial kiln-drying temperature, incising, and both temperature and moisture in service.

Species—The magnitude of the effect of various waterborne preservatives on mechanical properties does not appear to vary greatly between different species.

Mechanical property—Waterborne preservatives affect each mechanical property differently. If treated according to AWPA standards, the effects are as follows: modulus of elasticity (MOE), compressive strength parallel to grain, and compressive stress perpendicular to grain are unaffected or slightly increased; modulus of rupture (MOR) and tensile strength parallel to grain are reduced from 0% to 20%, depending on chemical retention and severity of redrying temperature; and energy-related properties (for example, work to maximum load and impact strength) are reduced from 10% to 50%.

Preservative chemistry or type—Waterborne preservative chemical systems differ in regard to their effect on strength, but the magnitude of these differences is slight compared with the effects of treatment processing factors. Chemistry-related differences seem to be related to the reactivity of the waterborne preservative and the temperature during the fixation/precipitation reaction with wood.

Retention—Waterborne preservative retention levels of ≤16 kg/m^3 (≤1.0 lb/ft^3) have no effect on MOE or compressive strength parallel to grain and a slight negative effect (−5% to −10%) on tensile or bending strength. However, energy-related properties are often reduced from 15% to 30%. At a retention level of 40 kg/m^3 (2.5 lb/ft^3), MOR and energy-related properties are further reduced.

Post-treatment drying temperature—Air drying after treatment causes no significant reduction in the static strength of wood treated with waterborne preservative at a retention level of 16 kg/m^3 (1.0 lb/ft^3). However, energy-related properties are reduced. The post-treatment redrying temperature used for material treated with waterborne preservative has been found to be critical when temperatures exceed 75 °C (167 °F). Redrying limitations in treatment standards have precluded the need for an across-the-board design adjustment factor for waterborne-preservative-treated lumber in engineering design standards. The limitation on post-treatment kiln-drying temperature is set at 74°C (165°F).

Size of material—Generally, larger material, specifically thicker, appears to undergo less reduction in strength than does smaller material. Recalling that preservative treatments usually penetrate the treated material to a depth of only 6 to 51 mm (0.25 to 2.0 in.), depending on species and other factors, the difference in size effect appears to be a function of the product's surface-to-volume ratio, which affects the relative ratio of treatment-induced weight gain to original wood weight.

Grade of material—The effect of waterborne preservative treatment is a quality-dependent phenomenon. Higher grades of wood are more affected than lower grades. When viewed over a range of quality levels, higher quality lumber is reduced in strength to a proportionately greater extent than is lower quality lumber.

Product type—The magnitude of the treatment effect on strength for laminated veneer lumber conforms closely to effects noted for higher grades of solid-sawn lumber. The effects of waterborne preservative treatment on plywood seem comparable to that on lumber. Fiber-based composite products may be reduced in strength to a greater extent than is lumber. This additional effect on fiber-based composites may be more a function of internal bond damage caused by waterborne-treatment-induced swelling rather than actual chemical hydrolysis.

Initial kiln-drying temperature—Although initial kiln drying of some lumber species at 100°C to 116°C (212°F to 240°F) for short durations has little effect on structural properties, such drying results in more hydrolytic degradation of the cell wall than does drying at lower temperature kiln schedules. Subsequent preservative treatment and redrying of material initially dried at high temperatures causes additional hydrolytic degradation. When the material is subsequently treated, initial kiln drying at 113°C (235°F) has been shown to result in greater reductions over the entire bending and tensile strength distributions than does initial kiln drying at 91°C (196°F). Because Southern Pine lumber, the most widely treated product, is most often initially kiln dried at dry-bulb temperatures near or above 113°C (235°F), treatment standards have imposed a maximum redrying temperature limit of 74°C (165°F) to preclude the cumulative effect of thermal processing.

Incising—Incising, a pretreatment mechanical process in which small slits (incisions) are punched in the surface of the wood product, is used to improve preservative penetration and distribution in difficult-to-treat species. Incising may reduce strength; however, because the increase in treatability provides a substantial increase in biological performance, this strength loss must be balanced against the progressive loss in strength of untreated wood from the incidence of decay. Most incising patterns induce some strength loss, and the magnitude of this effect is related to the size of material being incised and the incision depth and density (that is, number of incisions per unit area). In less than 50 mm (2 in.) thick, dry lumber, incising and preservative treatment induces losses in MOE of 5% to 15% and in static strength properties of 20% to 30%. Incising and treating timbers or tie stock at an incision density of ≤1,500 incisions/m^2 (≤140 incisions/ft^2) and to a depth of 19 mm (0.75 in.) reduces strength by 5% to 10%.

In-service temperature—Both fire-retardant and preservative treatments accelerate the thermal degradation of bending strength of lumber when exposed to temperatures above 54˚C (130˚F).

In-service moisture content—Current design values apply to material dried to ≤19% maximum (15% average) moisture content or to green material. No differences in strength have been found between treated and untreated material when tested green or at moisture contents above 12%. When very dry treated lumber of high grade was tested at 10% moisture content, its bending strength was reduced compared with that of matched dry untreated lumber.

Duration of load—When subjected to impact loads, wood treated with chromated copper arsenate (CCA) does not exhibit the same increase in strength as that exhibited by untreated wood. However, when loaded over a long period, treated and untreated wood behave similarly.

Polymerization

Wood is also sometimes impregnated with monomers, such as methyl methacrylate, which are subsequently polymerized. Many of the mechanical properties of the resultant wood–plastic composite are higher than those of the original wood, generally as a result of filling the void spaces in the wood structure with plastic. The polymerization process and both the chemical nature and quantity of monomers influence composite properties.

Nuclear Radiation

Wood is occasionally subjected to nuclear radiation. Examples are wooden structures closely associated with nuclear reactors, the polymerization of wood with plastic using nuclear radiation, and nondestructive estimation of wood density and moisture content. Very large doses of gamma rays or neutrons can cause substantial degradation of wood. In general, irradiation with gamma rays in doses up to about 1 megarad has little effect on the strength properties of wood. As dosage exceeds 1 megarad, tensile strength parallel to grain and toughness decrease. At a dosage of 300 megarads, tensile strength is reduced about 90%. Gamma rays also affect compressive strength parallel to grain at a dosage above 1 megarad, but higher dosage has a greater effect on tensile strength than on compressive strength; only approximately one-third of compressive strength is lost when the total dose is 300 megarads. Effects of gamma rays on bending and shear strength are intermediate between the effects on tensile and compressive strength.

Mold and Stain Fungi

Mold and stain fungi do not seriously affect most mechanical properties of wood because such fungi feed on substances within the cell cavity or attached to the cell wall rather than on the structural wall itself. The duration of infection and the species of fungi involved are important factors in determining the extent of degradation.

Although low levels of biological stain cause little loss in strength, heavy staining may reduce specific gravity by 1% to 2%, surface hardness by 2% to 10%, bending and crushing strength by 1% to 5%, and toughness or shock resistance by 15% to 30%. Although molds and stains usually do not have a major effect on strength, conditions that favor these organisms also promote the development of wood-destroying (decay) fungi and soft-rot fungi (Ch. 13). Pieces with mold and stain should be examined closely for decay if they are used for structural purposes.

Decay

Unlike mold and stain fungi, wood-destroying (decay) fungi seriously reduce strength by metabolizing the cellulose fraction of wood that gives wood its strength.

Early stages of decay are virtually impossible to detect. For example, brown-rot fungi may reduce mechanical properties in excess of 10% before a measurable weight loss is observed and before decay is visible. When weight loss reaches 5% to 10%, mechanical properties are reduced from 20% to 80%. Decay has the greatest effect on toughness, impact bending, and work to maximum load in bending, the least effect on shear and hardness, and an intermediate effect on other properties. Thus, when strength is important, adequate measures should be taken to (a) prevent decay before it occurs, (b) control incipient decay by remedial measures (Ch. 13), or (c) replace any wood member in which decay is evident or believed to exist in a critical section. Decay can be prevented from starting or progressing if wood is kept dry (below 20% moisture content).

No method is known for estimating the amount of reduction in strength from the appearance of decayed wood. Therefore, when strength is an important consideration, the safe procedure is to discard every piece that contains even a small amount of decay. An exception may be pieces in which decay occurs in a knot but does not extend into the surrounding wood.

Insect Damage

Insect damage may occur in standing trees, logs, and undried (unseasoned) or dried (seasoned) lumber. Although damage is difficult to control in the standing tree, insect damage can be eliminated to a great extent by proper control methods. Insect holes are generally classified as pinholes, grub holes, and powderpost holes. Because of their irregular burrows, powderpost larvae may destroy most of a piece's interior while only small holes appear on the surface, and the strength of the piece may be reduced virtually to zero. No method is known for estimating the reduction in strength from the appearance of insect-damaged wood. When strength is an important consideration, the safe procedure is to eliminate pieces containing insect holes.

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