Chapter 4

Mechanical Properties of Wood

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Mechanical properties discussed in this chapter have been 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 do contain wood structure characteristics such as growth rings that occur in consistent patterns within the 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 and are used to derive allowable properties for design. Some properties, such as tension, and all properties for some imported species are based on a more limited number of specimens not subject to the same sampling and analysis procedures. The appropriateness of these latter properties to represent the average properties of a species is uncertain; nevertheless, they 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 numerous 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.

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 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:

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

General relations between stress and strain for a homogeneous, orthotropic material can be found in texts on anisotropic elasticity. Regression equations that may be used to predict some elastic parameters as a function of density have been developed.

Modulus of Elasticity

The three moduli of elasticity denoted by E_L, E_R, and E_T are, respectively, the elastic moduli along 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 ratios, as well as the three elastic constants themselves, vary within and between species and with moisture content and specific gravity.

E_L determined from bending, rather than from an axial test, may be the only *E* available for a species. Average values of E_L obtained from bending tests are given in tables 4−2, 4−3, and 4−4. A representative coefficient of variation of E_L determined with bending tests for clear wood is reported in table 4−5. E_L as tabulated includes an effect of shear deflection. E_L from bending can be increased by 10 percent to approximately remove this effect. This adjusted bending E_L can be used to determine E_R and E_T based on ratios in table 4−1.

Modulus of Rigidity

The three moduli of rigidity denoted by G_{LR}, G_{LT}, 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.

Poisson's Ratio

The six Poisson's ratios are denoted by μ_{LR}, μ_{RL}, μ_{LT}, μ_{TL}, μ_{RT}, μ_{TR}. The first letter of the subscript refers to direction of applied stress and the second letter refers to direction

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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 4−1. 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 slightly by moisture content.

Strength Properties

Common Properties

Strength values most commonly measured and represented as "strength properties" for design include the modulus of rupture in bending, the maximum stress in compression parallel to the grain, compressive strength perpendicular to the grain, and shear strength parallel to the grain. Additional measurements often made include work to maximum load in bending, impact bending strength, tensile strength perpendicular to the 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 4−2, 4−3, and 4−4 for many of the commercially important species. Coefficients of variation for these properties from a limited sampling of specimens are reported in table 4−5.

Modulus of Rupture

Modulus of rupture in bending reflects the maximum load-carrying capacity of a member and is proportional to the maximum moment borne by a specimen. It 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 proportional limit.

Work to Maximum Load in Bending

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

Maximum Crushing Strength

Maximum crushing strength is the maximum stress sustained by a compression parallel-to-grain specimen having a ratio of length to least dimension of less than 11.

Compression Perpendicular to Grain

Strength in compression perpendicular to grain is reported as the stress at the proportional limit because there is no clearly defined ultimate stress for this property.

Shear Strength Parallel to Grain

Shear strength is a measure of ability to resist internal slipping of one part upon another along the grain. Values presented are the average of radial and tangential shear.

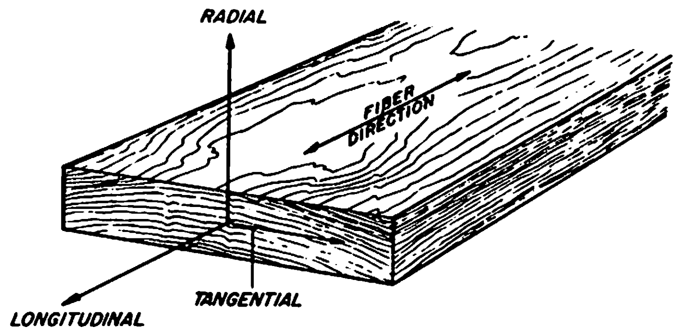

Figure 4−1—The three principal axes of wood with respect to grain direction and growth rings. (M140 728)

Impact Bending

In the impact bending test, a hammer of given weight is dropped upon a beam from successively increased heights until complete rupture occurs. The height of the maximum drop, or the drop that causes failure, is a comparative figure representing the ability of wood to absorb shocks that cause stresses beyond the proportional limit.

Tensile Strength Perpendicular to Grain

Tensile strength perpendicular to the grain is a measure of the 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

Hardness represents the resistance of wood to wear and marring. It is measured by the load required to embed a 0.444-inch ball to one-half its diameter in the wood. Values presented are the average of radial and tangential penetrations.

Tension Parallel to Grain

Relatively few data are available on the tensile strength of various species parallel to grain. Table 4−6 lists average tensile strength values for a limited number of specimens of a few species. In the absence of sufficient tension test data, the 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 these specimens. Chapter 6 should be consulted for discussion of the tensile properties of structural members.

Less Common Properties

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

Torsion

For solid wood members, the torsional shear strength may be taken as the shear strength parallel to the grain. Two-thirds of this value may be used as the torsional shear stress at the proportional limit.

Toughness

Toughness represents the energy required to cause complete failure rapidly in a centrally loaded bending specimen. Table 4–7 gives average toughness values for samples of a few hardwood and softwood species. Table 4–5 records the average coefficient of variation for toughness as determined from approximately 50 species.

Creep and Creep-Rupture

Wood is known to creep under load. If the load is sufficiently high and acts long enough, failure (creep-rupture) will eventually occur. Duration of stress is commonly used as the term for time before rupture. Duration of stress is an important factor in setting design values for wood. Creep and duration of stress are described in later sections of this chapter.

Fatigue

Fatigue strength is that property which provides resistance to failure under specific combinations of cyclic loading conditions: frequency and number of cycles, the maximum stress, the ratio of maximum to minimum stress, and other factors of less importance. The main factors affecting fatigue in wood are discussed later in this chapter. Interpretation of fatigue data and a discussion of fatigue as a function of the service environment are also included.

Rolling Shear Strength

The term "rolling shear" describes the shear strength of wood where the shearing force is in any longitudinal plane and is acting perpendicular to the grain. Test procedures for rolling shear in solid wood are of recent origin; few test values have been reported. In limited tests, rolling shear strengths averaged 18 to 28 percent of the parallel-to-grain shear values. Rolling shear strength is about the same in the longitudinal-radial plane as in the longitudinal-tangential plane.

Vibration Properties

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

Speed of Sound

The speed of sound in a structural material varies directly with the square root of modulus of elasticity and inversely with the square root of density. In wood, the speed of sound also varies strongly 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 1,800,000 pounds per square inch (psi) and a density of 30 pounds per cubic foot would have a speed of sound in the longitudinal direction of about 150,000 inches per second. In the transverse direction, its modulus of elasticity would be about 100,000 psi and the speed of sound approximately 35,000 inches per second.

The speed of sound decreases with increasing temperature or moisture content in proportion to the influence of these variables on the 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 the minimum internal friction occurs varies with temperature. At room temperature (23 °C), the minimum occurs at about 6 percent moisture content; at −20 °C, it occurs at about 14 percent moisture content; and at 70 °C, at about 4 percent. At 90 °C 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 0 °C, and moisture contents greater than about 10 percent, 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.

Summary Tables on Mechanical Properties of Clear Straight-Grained Wood

The mechanical properties listed in tables 4−1 through 4−7 are based on a variety of sampling methods. Generally, the most extensive sampling is represented in tables 4−2, 4−3, and 4−4. The values in table 4−2 are averages derived for a number of species grown in the United States. The table value is an estimate of the average clear wood property of the species. Many of the values were obtained from test specimens taken at heights between 8 and 16 feet above the stump of the tree. Values reported in table 4−3 represent estimates of the average clear wood properties of species grown in Canada and commonly imported into the United States, while those in table 4−4 represent estimates of average properties of species imported from other countries.

Methods of data collection and analysis have changed over the years during which the data in tables 4−2 and 4−3 have been collected. In addition, the character of some forests changes with time. Because not all of the species have been 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 4−4 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, 4−6, 4−7, and 4−13 may not necessarily represent average species characteristics because of inadequate sampling; 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. Often the fact that a piece may be stronger, harder, or stiffer than the average is of less concern to the user than if it is weaker; however, this may not be true if lightweight material is selected for a specific purpose or if harder or tougher material is hard to work. It is desirable, therefore, that some indication of the spread of property values be known. Average coefficients of variation for many mechanical properties are presented in table 4−5.

The mechanical properties reported in the tables are significantly affected by the moisture content of the specimens at the time of test. Some tables include properties evaluated at differing moisture levels; these moisture levels are reported. As indicated in the tables, many of the dry test data have been adjusted to a common moisture content base of 12 percent. The differences in properties displayed in the tables as a result of differing moisture levels are not necessarily consistent for larger wood pieces such as lumber. Guidelines for adjusting clear wood properties to arrive at allowable properties for lumber are discussed in chapter 6, "Lumber Stress Grades and Allowable Properties."

Specific gravity is reported in many of the tables because it is used as an index of clear wood mechanical properties. The specific gravity values given in tables 4−2 and 4−3 represent the estimated average clear wood specific gravity of the species. In the other tables, the specific gravity represents 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 4−5.

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 test specimen and the mode of test. The methods of test used to establish properties in tables 4−2, 4−3, 4−6, and 4−7 are based on standard procedures, ASTM D 143. The methods of test for properties presented in other tables are referenced in the selected references at the end of this chapter.

Common names of species listed in the tables conform to standard nomenclature of the USDA, 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 have knots and localized slope of grain. Natural defects such as pitch pockets may occur due to biological or climatic elements acting on the living tree. These wood characteristics must be taken into account in assessing actual properties or estimating actual performance of wood products.

Specific Gravity

The substance of which wood is composed is actually heavier than water, its specific gravity being about 1.5 regardless of the species of wood. 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 others and therefore to have higher specific gravity. Specific gravity thus is an excellent index of the amount of wood substance a piece of wood contains; it is a good index of mechanical properties so 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.

(Text continues on page 4-27.)

Table 4 – 1—*Elastic ratios for various species*

Species	Approximate specific gravity[1]	Approximate moisture content	Modulus of elasticity ratios		Ratio of modulus of rigidity to modulus of elasticity			Poisson's ratios					
			E_T/E_L	E_R/E_L	G_{LR}/E_L	G_{LT}/E_L	G_{RT}/E_L	μ_{LR}	μ_{LT}	μ_{RT}	μ_{TR}	μ_{RL}	μ_{TL}
		Pct											
Balsa	0.13	9	0.015	0.046	0.054	0.037	0.005	0.23	0.49	0.67	0.23	0.02	0.01
Birch, yellow	.64	13	.050	.078	.074	.068	.017	.43	.45	.70	.43	.04	.02
Douglas-fir	.50	12	.050	.068	.064	.078	.007	.29	.45	.39	.37	.04	.03
Spruce, Sitka	.38	12	.043	.078	.064	.061	.003	.37	.47	.44	.24	.04	.02
Sweetgum	.53	11	.050	.115	.089	.061	.021	.32	.40	.68	.31	.04	.02
Walnut, black	.59	11	.056	.106	.085	.062	.021	.50	.63	.72	.38	.05	.04
Yellow-poplar	.38	11	.043	.092	.075	.069	.011	.32	.39	.70	.33	.03	.02

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

Table 4-2—*Mechanical properties[1] of some commercially important woods grown in the United States*

Common names of species	Moisture condition	Specific gravity[2]	Static bending — Modulus of rupture	Static bending — Modulus of elasticity[3]	Static bending — Work to maximum load	Impact bending—height of drop causing complete failure[4]	Compression parallel to grain—maximum crushing strength	Compression perpendicular to grain—fiber stress at proportional limit	Shear parallel to grain—maximum shearing strength	Tension perpendicular to grain—maximum tensile strength	Side hardness—load perpendicular to grain
			Psi	*Million psi*	*In-lb per in³*	*In*	*Psi*	*Psi*	*Psi*	*Psi*	*Lb*
					HARDWOODS						
Alder, red	Green	0.37	6,500	1.17	8.0	22	2,960	250	770	390	440
	Dry	.41	9,800	1.38	8.4	20	5,820	440	1,080	420	590
Ash:											
Black	Green	.45	6,000	1.04	12.1	33	2,300	350	860	490	520
	Dry	.49	12,600	1.60	14.9	35	5,970	760	1,570	700	850
Blue	Green	.53	9,600	1.24	14.7	—	4,180	810	1,540	—	—
	Dry	.58	13,800	1.40	14.4	—	6,980	1,420	2,030	—	—
Green	Green	.53	9,500	1.40	11.8	35	4,200	730	1,260	590	870
	Dry	.56	14,100	1.66	13.4	32	7,080	1,310	1,910	700	1,200
Oregon	Green	.50	7,600	1.13	12.2	39	3,510	530	1,190	590	790
	Dry	.55	12,700	1.36	14.4	33	6,040	1,250	1,790	720	1,160
White	Green	.55	9,500	1.44	15.7	38	3,990	670	1,350	590	960
	Dry	.60	15,000	1.74	16.6	43	7,410	1,160	1,910	940	1,320
Aspen:											
Bigtooth	Green	.36	5,400	1.12	5.7	—	2,500	210	730	—	—
	Dry	.39	9,100	1.43	7.7	—	5,300	450	1,080	—	—
Quaking	Green	.35	5,100	.86	6.4	22	2,140	180	660	230	300
	Dry	.38	8,400	1.18	7.6	21	4,250	370	850	260	350
Basswood, American	Green	.32	5,000	1.04	5.3	16	2,220	170	600	280	250
	Dry	.37	8,700	1.46	7.2	16	4,730	370	990	350	410
Beech, American	Green	.56	8,600	1.38	11.9	43	3,550	540	1,290	720	850
	Dry	.64	14,900	1.72	15.1	41	7,300	1,010	2,010	1,010	1,300
Birch:											
Paper	Green	.48	6,400	1.17	16.2	49	2,360	270	840	380	560
	Dry	.55	12,300	1.59	16.0	34	5,690	600	1,210	—	910
Sweet	Green	.60	9,400	1.65	15.7	48	3,740	470	1,240	430	970
	Dry	.65	16,900	2.17	18.0	47	8,540	1,080	2,240	950	1,470
Yellow	Green	.55	8,300	1.50	16.1	48	3,380	430	1,110	430	780
	Dry	.62	16,600	2.01	20.8	55	8,170	970	1,880	920	1,260

Table 4-2—*Mechanical properties*[1] *of some commercially important woods grown in the United States*—Continued

Common names of species	Moisture condition	Specific gravity[2]	Static bending: Modulus of rupture	Static bending: Modulus of elasticity[3]	Static bending: Work to maximum load	Impact bending—height of drop causing complete failure[4]	Compression parallel to grain—maximum crushing strength	Compression perpendicular to grain—fiber stress at proportional limit	Shear parallel to grain—maximum shearing strength	Tension perpendicular to grain—maximum tensile strength	Side hardness—load perpendicular to grain
			Psi	*Million psi*	*In-lb per in³*	*In*	*Psi*	*Psi*	*Psi*	*Psi*	*Lb*
					HARDWOODS—continued						
Butternut	Green	.36	5,400	.97	8.2	24	2,420	220	760	430	390
	Dry	.38	8,100	1.18	8.2	24	5,110	460	1,170	440	490
Cherry, black	Green	.47	8,000	1.31	12.8	33	3,540	360	1,130	570	660
	Dry	.50	12,300	1.49	11.4	29	7,110	690	1,700	560	950
Chestnut, American	Green	.40	5,600	.93	7.0	24	2,470	310	800	440	420
	Dry	.43	8,600	1.23	6.5	19	5,320	620	1,080	460	540
Cottonwood:											
Balsam poplar	Green	.31	3,900	.75	4.2	—	1,690	140	500	—	—
	Dry	.34	6,800	1.10	5.0	—	4,020	300	790	—	—
Black	Green	.31	4,900	1.08	5.0	20	2,200	160	610	270	250
	Dry	.35	8,500	1.27	6.7	22	4,500	300	1,040	330	350
Eastern	Green	.37	5,300	1.01	7.3	21	2,280	200	680	410	340
	Dry	.40	8,500	1.37	7.4	20	4,910	380	930	580	430
Elm:											
American	Green	.46	7,200	1.11	11.8	38	2,910	360	1,000	590	620
	Dry	.50	11,800	1.34	13.0	39	5,520	690	1,510	660	830
Rock	Green	.57	9,500	1.19	19.8	54	3,780	610	1,270	—	940
	Dry	.63	14,800	1.54	19.2	56	7,050	1,230	1,920	—	1,320
Slippery	Green	.48	8,000	1.23	15.4	47	3,320	420	1,110	640	660
	Dry	.53	13,000	1.49	16.9	45	6,360	820	1,630	530	860
Hackberry	Green	.49	6,500	.95	14.5	48	2,650	400	1,070	630	700
	Dry	.53	11,000	1.19	12.8	43	5,440	890	1,590	580	880
Hickory, pecan:											
Bitternut	Green	.60	10,300	1.40	20.0	66	4,570	800	1,240	—	—
	Dry	.66	17,100	1.79	18.2	66	9,040	1,680	—	—	—
Nutmeg	Green	.56	9,100	1.29	22.8	54	3,980	760	1,030	—	—
	Dry	.60	16,600	1.70	25.1	—	6,910	1,570	—	—	—
Pecan	Green	.60	9,800	1.37	14.6	53	3,990	780	1,480	680	1,310
	Dry	.66	13,700	1.73	13.8	44	7,850	1,720	2,080	—	1,820
Water	Green	.61	10,700	1.56	18.8	56	4,660	880	1,440	—	—
	Dry	.62	17,800	2.02	19.3	53	8,600	1,550	—	—	—

Table 4–2—*Mechanical properties[1] of some commercially important woods grown in the United States*—**Continued**

Common names of species	Moisture condition	Specific gravity[2]	Static bending: Modulus of rupture	Static bending: Modulus of elasticity[3]	Static bending: Work to maximum load	Impact bending—height of drop causing complete failure[4]	Compression parallel to grain—maximum crushing strength	Compression perpendicular to grain—fiber stress at proportional limit	Shear parallel to grain—maximum shearing strength	Tension perpendicular to grain—maximum tensile strength	Side hardness—load perpendicular to grain
			Psi	*Million psi*	*In-lb per in³*	*In*	*Psi*	*Psi*	*Psi*	*Psi*	*Lb*
					HARDWOODS—continued						
Hickory, true:											
Mockernut	Green	.64	11,100	1.57	26.1	88	4,480	810	1,280	—	—
	Dry	.72	19,200	2.22	22.6	77	8,940	1,730	1,740	—	—
Pignut	Green	.66	11,700	1.65	31.7	89	4,810	920	1,370	—	—
	Dry	.75	20,100	2.26	30.4	74	9,190	1,980	2,150	—	—
Shagbark	Green	.64	11,000	1.57	23.7	74	4,580	840	1,520	—	—
	Dry	.72	20,200	2.16	25.8	67	9,210	1,760	2,430	—	—
Shellbark	Green	.62	10,500	1.34	29.9	104	3,920	810	1,190	—	—
	Dry	.69	18,100	1.89	23.6	88	8,000	1,800	2,110	—	—
Honeylocust	Green	.60	10,200	1.29	12.6	47	4,420	1,150	1,660	930	1,390
	Dry	—	14,700	1.63	13.3	47	7,500	1,840	2,250	900	1,580
Locust, black	Green	.66	13,800	1.85	15.4	44	6,800	1,160	1,760	770	1,570
	Dry	.69	19,400	2.05	18.4	57	10,180	1,830	2,480	640	1,700
Magnolia:											
Cucumbertree	Green	.44	7,400	1.56	10.0	30	3,140	330	990	440	520
	Dry	.48	12,300	1.82	12.2	35	6,310	570	1,340	660	700
Southern	Green	.46	6,800	1.11	15.4	54	2,700	460	1,040	610	740
	Dry	.50	11,200	1.40	12.8	29	5,460	860	1,530	740	1,020
Maple:											
Bigleaf	Green	.44	7,400	1.10	8.7	23	3,240	450	1,110	600	620
	Dry	.48	10,700	1.45	7.8	28	5,950	750	1,730	540	850
Black	Green	.52	7,900	1.33	12.8	48	3,270	600	1,130	720	840
	Dry	.57	13,300	1.62	12.5	40	6,680	1,020	1,820	670	1,180
Red	Green	.49	7,700	1.39	11.4	32	3,280	400	1,150	—	700
	Dry	.54	13,400	1.64	12.5	32	6,540	1,000	1,850	—	950
Silver	Green	.44	5,800	.94	11.0	29	2,490	370	1,050	560	590
	Dry	.47	8,900	1.14	8.3	25	5,220	740	1,480	500	700
Sugar	Green	.56	9,400	1.55	13.3	40	4,020	640	1,460	—	970
	Dry	.63	15,800	1.83	16.5	39	7,830	1,470	2,330	—	1,450

Table 4–2—*Mechanical properties[1] of some commercially important woods grown in the United States*—Continued

Common names of species	Moisture condition	Specific gravity[2]	Static bending: Modulus of rupture	Static bending: Modulus of elasticity[3]	Static bending: Work to maximum load	Impact bending—height of drop causing complete failure[4]	Compression parallel to grain—maximum crushing strength	Compression perpendicular to grain—fiber stress at proportional limit	Shear parallel to grain—maximum shearing strength	Tension perpendicular to grain—maximum tensile strength	Side hardness—load perpendicular to grain
			Psi	*Million psi*	*In–lb per in³*	*In*	*Psi*	*Psi*	*Psi*	*Psi*	*Lb*
HARDWOODS—continued											
Oak, red:											
Black	Green	.56	8,200	1.18	12.2	40	3,470	710	1,220	—	1,060
	Dry	.61	13,900	1.64	13.7	41	6,520	930	1,910	—	1,210
Cherrybark	Green	.61	10,800	1.79	14.7	54	4,620	760	1,320	800	1,240
	Dry	.68	18,100	2.28	18.3	49	8,740	1,250	2,000	840	1,480
Laurel	Green	.56	7,900	1.39	11.2	39	3,170	570	1,180	770	1,000
	Dry	.63	12,600	1.69	11.8	39	6,980	1,060	1,830	790	1,210
Northern red	Green	.56	8,300	1.35	13.2	44	3,440	610	1,210	750	1,000
	Dry	.63	14,300	1.82	14.5	43	6,760	1,010	1,780	800	1,290
Pin	Green	.58	8,300	1.32	14.0	48	3,680	720	1,290	800	1,070
	Dry	.63	14,000	1.73	14.8	45	6,820	1,020	2,080	1,050	1,510
Scarlet	Green	.60	10,400	1.48	15.0	54	4,090	830	1,410	700	1,200
	Dry	.67	17,400	1.91	20.5	53	8,330	1,120	1,890	870	1,400
Southern red	Green	.52	6,900	1.14	8.0	29	3,030	550	930	480	860
	Dry	.59	10,900	1.49	9.4	26	6,090	870	1,390	510	1,060
Water	Green	.56	8,900	1.55	11.1	39	3,740	620	1,240	820	1,010
	Dry	.63	15,400	2.02	21.5	44	6,770	1,020	2,020	920	1,190
Willow	Green	.56	7,400	1.29	8.8	35	3,000	610	1,180	760	980
	Dry	.69	14,500	1.90	14.6	42	7,040	1,130	1,650	—	1,460
Oak, white:											
Bur	Green	.58	7,200	.88	10.7	44	3,290	680	1,350	800	1,110
	Dry	.64	10,300	1.03	9.8	29	6,060	1,200	1,820	680	1,370
Chestnut	Green	.57	8,000	1.37	9.4	35	3,520	530	1,210	690	890
	Dry	.66	13,300	1.59	11.0	40	6,830	840	1,490	—	1,130
Live	Green	.80	11,900	1.58	12.3	—	5,430	2,040	2,210	—	—
	Dry	.88	18,400	1.98	18.9	—	8,900	2,840	2,660	—	—
Overcup	Green	.57	8,000	1.15	12.6	44	3,370	540	1,320	730	960
	Dry	.63	12,600	1.42	15.7	38	6,200	810	2,000	940	1,190
Post	Green	.60	8,100	1.09	11.0	44	3,480	860	1,280	790	1,130
	Dry	.67	13,200	1.51	13.2	46	6,600	1,430	1,840	780	1,360

Table 4 – 2—*Mechanical properties*[1] *of some commercially important woods grown in the United States*—Continued

Common names of species	Moisture condition	Specific gravity[2]	Static bending: Modulus of rupture	Static bending: Modulus of elasticity[3]	Static bending: Work to maximum load	Impact bending—height of drop causing complete failure[4]	Compression parallel to grain—maximum crushing strength	Compression perpendicular to grain—fiber stress at proportional limit	Shear parallel to grain—maximum shearing strength	Tension perpendicular to grain—maximum tensile strength	Side hardness—load perpendicular to grain
			Psi	*Million psi*	*In−lb per in*[3]	*In*	*Psi*	*Psi*	*Psi*	*Psi*	*Lb*
					HARDWOODS—continued						
Oak, white—con.											
Swamp chestnut	Green	.60	8,500	1.35	12.8	45	3,540	570	1,260	670	1,110
	Dry	.67	13,900	1.77	12.0	41	7,270	1,110	1,990	690	1,240
Swamp white	Green	.64	9,900	1.59	14.5	50	4,360	760	1,300	860	1,160
	Dry	.72	17,700	2.05	19.2	49	8,600	1,190	2,000	830	1,620
White	Green	.60	8,300	1.25	11.6	42	3,560	670	1,250	770	1,060
	Dry	.68	15,200	1.78	14.8	37	7,440	1,070	2,000	800	1,360
Sassafras	Green	.42	6,000	.91	7.1	—	2,730	370	950	—	—
	Dry	.46	9,000	1.12	8.7	—	4,760	850	1,240	—	—
Sweetgum	Green	.46	7,100	1.20	10.1	36	3,040	370	990	540	600
	Dry	.52	12,500	1.64	11.9	32	6,320	620	1,600	760	850
Sycamore, American	Green	.46	6,500	1.06	7.5	26	2,920	360	1,000	630	610
	Dry	.49	10,000	1.42	8.5	26	5,380	700	1,470	720	770
Tanoak	Green	.58	10,500	1.55	13.4	—	4,650	—	—	—	—
	—	—	—	—	—	—	—	—	—	—	—
Tupelo:											
Black	Green	.46	7,000	1.03	8.0	30	3,040	480	1,100	570	640
	Dry	.50	9,600	1.20	6.2	22	5,520	930	1,340	500	810
Water	Green	.46	7,300	1.05	8.3	30	3,370	480	1,190	600	710
	Dry	.50	9,600	1.26	6.9	23	5,920	870	1,590	700	880
Walnut, black	Green	.51	9,500	1.42	14.6	37	4,300	490	1,220	570	900
	Dry	.55	14,600	1.68	10.7	34	7,580	1,010	1,370	690	1,010
Willow, black	Green	.36	4,800	.79	11.0	—	2,040	180	680	—	—
	Dry	.39	7,800	1.01	8.8	—	4,100	430	1,250	—	—
Yellow-poplar	Green	.40	6,000	1.22	7.5	26	2,660	270	790	510	440
	Dry	.42	10,100	1.58	8.8	24	5,540	500	1,190	540	540

Table 4–2—*Mechanical properties[1] of some commercially important woods grown in the United States*—Continued

Common names of species	Moisture condition	Specific gravity[2]	Static bending: Modulus of rupture	Static bending: Modulus of elasticity[3]	Static bending: Work to maximum load	Impact bending—height of drop causing complete failure[4]	Compression parallel to grain—maximum crushing strength	Compression perpendicular to grain—fiber stress at proportional limit	Shear parallel to grain—maximum shearing strength	Tension perpendicular to grain—maximum tensile strength	Side hardness—load perpendicular to grain
			Psi	*Million psi*	*In–lb per in³*	*In*	*Psi*	*Psi*	*Psi*	*Psi*	*Lb*
					SOFTWOODS						
Baldcypress	Green	.42	6,600	1.18	6.6	25	3,580	400	810	300	390
	Dry	.46	10,600	1.44	8.2	24	6,360	730	1,000	270	510
Cedar:											
Alaska-	Green	.42	6,400	1.14	9.2	27	3,050	350	840	330	440
	Dry	.44	11,100	1.42	10.4	29	6,310	620	1,130	360	580
Atlantic white-	Green	.31	4,700	.75	5.9	18	2,390	240	690	180	290
	Dry	.32	6,800	.93	4.1	13	4,700	410	800	220	350
Eastern redcedar	Green	.44	7,000	.65	15.0	35	3,570	700	1,010	330	650
	Dry	.47	8,800	.88	8.3	22	6,020	920	—	—	900
Incense-	Green	.35	6,200	.84	6.4	17	3,150	370	830	280	390
	Dry	.37	8,000	1.04	5.4	17	5,200	590	880	270	470
Northern white-	Green	.29	4,200	.64	5.7	15	1,990	230	620	240	230
	Dry	.31	6,500	.80	4.8	12	3,960	310	850	240	320
Port-Orford-	Green	.39	6,600	1.30	7.4	21	3,140	300	840	180	380
	Dry	.43	12,700	1.70	9.1	28	6,250	720	1,370	400	630
Western redcedar	Green	.31	5,200	.94	5.0	17	2,770	240	770	230	260
	Dry	.32	7,500	1.11	5.8	17	4,560	460	990	220	350
Douglas-fir:[5]											
Coast	Green	.45	7,700	1.56	7.6	26	3,780	380	900	300	500
	Dry	.48	12,400	1.95	9.9	31	7,230	800	1,130	340	710
Interior West	Green	.46	7,700	1.51	7.2	26	3,870	420	940	290	510
	Dry	.50	12,600	1.83	10.6	32	7,430	760	1,290	350	660
Interior North	Green	.45	7,400	1.41	8.1	22	3,470	360	950	340	420
	Dry	.48	13,100	1.79	10.5	26	6,900	770	1,400	390	600
Interior South	Green	.43	6,800	1.16	8.0	15	3,110	340	950	250	360
	Dry	.46	11,900	1.49	9.0	20	6,230	740	1,510	330	510

Table 4-2—*Mechanical properties[1] of some commercially important woods grown in the United States*—Continued

Common names of species	Moisture condition	Specific gravity[2]	Static bending: Modulus of rupture	Static bending: Modulus of elasticity[3]	Static bending: Work to maximum load	Impact bending—height of drop causing complete failure[4]	Compression parallel to grain—maximum crushing strength	Compression perpendicular to grain—fiber stress at proportional limit	Shear parallel to grain—maximum shearing strength	Tension perpendicular to grain—maximum tensile strength	Side hardness—load perpendicular to grain
			Psi	*Million psi*	*In-lb per in³*	*In*	*Psi*	*Psi*	*Psi*	*Psi*	*Lb*
SOFTWOODS—continued											
Fir:											
Balsam	Green	.33	5,500	1.25	4.7	16	2,630	190	662	180	290
	Dry	.35	9,200	1.45	5.1	20	5,280	404	944	180	400
California red	Green	.36	5,800	1.17	6.4	21	2,760	330	770	380	360
	Dry	.38	10,500	1.50	8.9	24	5,460	610	1,040	390	500
Grand	Green	.35	5,800	1.25	5.6	22	2,940	270	740	240	360
	Dry	.37	8,900	1.57	7.5	28	5,290	500	900	240	490
Noble	Green	.37	6,200	1.38	6.0	19	3,010	270	800	230	290
	Dry	.39	10,700	1.72	8.8	23	6,100	520	1,050	220	410
Pacific silver	Green	.40	6,400	1.42	6.0	21	3,140	220	750	240	310
	Dry	.43	11,000	1.76	9.3	24	6,410	450	1,220	—	430
Subalpine	Green	.31	4,900	1.05	—	—	2,300	190	700	—	260
	Dry	.32	8,600	1.29	—	—	4,860	390	1,070	—	350
White	Green	.37	5,900	1.16	5.6	22	2,900	280	760	300	340
	Dry	.39	9,800	1.50	7.2	20	5,800	530	1,100	300	480
Hemlock:											
Eastern	Green	.38	6,400	1.07	6.7	21	3,080	360	850	230	400
	Dry	.40	8,900	1.20	6.8	21	5,410	650	1,060	—	500
Mountain	Green	.42	6,300	1.04	11.0	32	2,880	370	930	330	470
	Dry	.45	11,500	1.33	10.4	32	6,440	860	1,540	—	680
Western	Green	.42	6,600	1.31	6.9	22	3,360	280	860	290	410
	Dry	.45	11,300	1.63	8.3	23	7,200	550	1,290	340	540
Larch, western	Green	.48	7,700	1.46	10.3	29	3,760	400	870	330	510
	Dry	.52	13,000	1.87	12.6	35	7,620	930	1,360	430	830

Table 4–2—*Mechanical properties[1] of some commercially important woods grown in the United States*—**Continued**

Common names of species	Moisture condition	Specific gravity[2]	Static bending: Modulus of rupture	Static bending: Modulus of elasticity[3]	Static bending: Work to maximum load	Impact bending—height of drop causing complete failure[4]	Compression parallel to grain—maximum crushing strength	Compression perpendicular to grain—fiber stress at proportional limit	Shear parallel to grain—maximum shearing strength	Tension perpendicular to grain—maximum tensile strength	Side hardness—load perpendicular to grain
			Psi	*Million psi*	*In-lb per in³*	*In*	*Psi*	*Psi*	*Psi*	*Psi*	*Lb*
					SOFTWOODS—continued						
Pine:											
Eastern white	Green	.34	4,900	.99	5.2	17	2,440	220	680	250	290
	Dry	.35	8,600	1.24	6.8	18	4,800	440	900	310	380
Jack	Green	.40	6,000	1.07	7.2	26	2,950	300	750	360	400
	Dry	.43	9,900	1.35	8.3	27	5,660	580	1,170	420	570
Loblolly	Green	.47	7,300	1.40	8.2	30	3,510	390	860	260	450
	Dry	.51	12,800	1.79	10.4	30	7,130	790	1,390	470	690
Lodgepole	Green	.38	5,500	1.08	5.6	20	2,610	250	680	220	330
	Dry	.41	9,400	1.34	6.8	20	5,370	610	880	290	480
Longleaf	Green	.54	8,500	1.59	8.9	35	4,320	480	1,040	330	590
	Dry	.59	14,500	1.98	11.8	34	8,470	960	1,510	470	870
Pitch	Green	.47	6,800	1.20	9.2	—	2,950	360	860	—	—
	Dry	.52	10,800	1.43	9.2	—	5,940	820	1,360	—	—
Pond	Green	.51	7,400	1.28	7.5	—	3,660	440	940	—	—
	Dry	.56	11,600	1.75	8.6	—	7,540	910	1,380	—	—
Ponderosa	Green	.38	5,100	1.00	5.2	21	2,450	280	700	310	320
	Dry	.40	9,400	1.29	7.1	19	5,320	580	1,130	420	460
Red	Green	.41	5,800	1.28	6.1	26	2,730	260	690	300	340
	Dry	.46	11,000	1.63	9.9	26	6,070	600	1,210	460	560
Sand	Green	.46	7,500	1.02	9.6	—	3,440	450	1,140	—	—
	Dry	.48	11,600	1.41	9.6	—	6,920	836	—	—	—
Shortleaf	Green	.47	7,400	1.39	8.2	30	3,530	350	910	320	440
	Dry	.51	13,100	1.75	11.0	33	7,270	820	1,390	470	690
Slash	Green	.54	8,700	1.53	9.6	—	3,820	530	960	—	—
	Dry	.59	16,300	1.98	13.2	—	8,140	1,020	1,680	—	—
Spruce	Green	.41	6,000	1.00	—	—	2,840	280	900	—	450
	Dry	.44	10,400	1.23	—	—	5,650	730	1,490	—	660
Sugar	Green	.34	4,900	1.03	5.4	17	2,460	210	720	270	270
	Dry	.36	8,200	1.19	5.5	18	4,460	500	1,130	350	380
Virginia	Green	.45	7,300	1.22	10.9	34	3,420	390	890	400	540
	Dry	.48	13,000	1.52	13.7	32	6,710	910	1,350	380	740

Table 4–2—*Mechanical properties[1] of some commercially important woods grown in the United States*—Continued

Common names of species	Moisture condition	Specific gravity[2]	Static bending: Modulus of rupture	Static bending: Modulus of elasticity[3]	Static bending: Work to maximum load	Impact bending—height of drop causing complete failure[4]	Compression parallel to grain—maximum crushing strength	Compression perpendicular to grain—fiber stress at proportional limit	Shear parallel to grain—maximum shearing strength	Tension perpendicular to grain—maximum tensile strength	Side hardness—load perpendicular to grain
			Psi	*Million psi*	*In–lb per in³*	*In*	*Psi*	*Psi*	*Psi*	*Psi*	*Lb*
SOFTWOODS—continued											
Pine—con.											
Western white	Green	.35	4,700	1.19	5.0	19	2,430	190	680	260	260
	Dry	.38	9,700	1.46	8.8	23	5,040	470	1,040	—	420
Redwood:											
Old-growth	Green	.38	7,500	1.18	7.4	21	4,200	420	800	260	410
	Dry	.40	10,000	1.34	6.9	19	6,150	700	940	240	480
Young-growth	Green	.34	5,900	.96	5.7	16	3,110	270	890	300	350
	Dry	.35	7,900	1.10	5.2	15	5,220	520	1,110	250	420
Spruce:											
Black	Green	.38	6,100	1.38	7.4	24	2,840	240	739	100	370
	Dry	.42	10,800	1.61	10.5	23	5,960	550	1,230	—	520
Engelmann	Green	.33	4,700	1.03	5.1	16	2,180	200	640	240	260
	Dry	.35	9,300	1.30	6.4	18	4,480	410	1,200	350	390
Red	Green	.37	6,000	1.33	6.9	18	2,720	260	750	220	350
	Dry	.40	10,800	1.61	8.4	25	5,540	550	1,290	350	490
Sitka	Green	.37	5,700	1.23	6.3	24	2,670	280	760	250	350
	Dry	.40	10,200	1.57	9.4	25	5,610	580	1,150	370	510
White	Green	.33	5,000	1.14	6.0	22	2,350	210	640	220	320
	Dry	.36	9,400	1.43	7.7	20	5,180	430	970	360	480
Tamarack	Green	.49	7,200	1.24	7.2	28	3,480	390	860	260	380
	Dry	.53	11,600	1.64	7.1	23	7,160	800	1,280	400	590

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

[2] Specific gravity based on weight ovendry and volume at moisture content indicated.

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

[4] 50-pound hammer.

[5] Coast Douglas-fir is defined as Douglas-fir growing in the States of Oregon and Washington west of the summit of the Cascade Mountains. Interior West includes the State of California and all counties in Oregon and Washington east of but adjacent to the Cascade summit. Interior North includes the remainder of Oregon and Washington and the States of Idaho, Montana, and Wyoming. Interior South is made up of Utah, Colorado, Arizona, and New Mexico.

Table 4–3—*Mechanical properties of some commercially important woods grown in Canada and imported into the United States*[1,2]

Common names of species	Specific gravity	Static bending: Modulus of rupture	Static bending: Modulus of elasticity[3]	Compression parallel to grain—maximum crushing strength	Compression perpendicular to grain—fiber stress at proportional limit	Shear parallel to grain—maximum shearing strength
		Psi	*Million Psi*	*Psi*	*Psi*	*Psi*
			HARDWOODS			
Aspen:						
Quaking	0.37	5,500	1.31	2,350	200	720
		9,800	1.63	5,260	510	980
Big-toothed	.39	5,300	1.08	2,390	210	790
		9,500	1.26	4,760	470	1,100
Cottonwood:						
Balsam, poplar	.37	5,000	1.15	2,110	180	670
		10,100	1.67	5,020	420	890
Black	.30	4,100	.97	1,860	100	560
		7,100	1.28	4,020	260	860
Eastern	.35	4,700	.87	1,970	210	770
		7,500	1.13	3,840	470	1,160
			SOFTWOODS			
Cedar:						
Alaska-	.42	6,600	1.34	3,240	350	880
		11,600	1.59	6,640	690	1,340
Northern white-	.30	3,900	.52	1,890	200	660
		6,100	.63	3,590	390	1,000
Western redcedar	.31	5,300	1.05	2,780	280	700
		7,800	1.19	4,290	500	810
Douglas-fir	.45	7,500	1.61	3,610	460	920
		12,800	1.97	7,260	870	1,380
Fir:						
Subalpine	.33	5,200	1.26	2,500	260	680
		8,200	1.48	5,280	540	980
Pacific silver	.36	5,500	1.35	2,770	230	710
		10,000	1.64	5,930	520	1,190
Balsam	.34	5,300	1.13	2,440	240	680
		8,500	1.40	4,980	460	910
Hemlock:						
Eastern	.40	6,800	1.27	3,430	400	910
		9,700	1.41	5,970	630	1,260
Western	.41	7,000	1.48	3,580	370	750
		11,800	1.79	6,770	660	940

Table 4–3—*Mechanical properties of some commercially important woods grown in Canada and imported into the United States*[1,2]—Continued

Common names of species	Specific gravity	Static bending: Modulus of rupture	Static bending: Modulus of elasticity[3]	Compression parallel to grain—maximum crushing strength	Compression perpendicular to grain—fiber stress at proportional limit	Shear parallel to grain—maximum shearing strength
		Psi	*Million Psi*	*Psi*	*Psi*	*Psi*
			SOFTWOODS—continued			
Larch, western	.55	8,700	1.65	4,420	520	920
		15,500	2.08	8,840	1,060	1,340
Pine:						
Eastern white	.36	5,100	1.18	2,590	240	640
		9,500	1.36	5,230	490	880
Jack	.42	6,300	1.17	2,950	340	820
		11,300	1.48	5,870	830	1,190
Lodgepole	.40	5,600	1.27	2,860	280	720
		11,000	1.58	6,260	530	1,240
Ponderosa	.44	5,700	1.13	2,840	350	720
		10,600	1.38	6,130	760	1,020
Red	.39	5,000	1.07	2,370	280	710
		10,100	1.38	5,500	720	1,090
Western white	.36	4,800	1.19	2,520	240	650
		9,300	1.46	5,240	470	920
Spruce:						
Black	.41	5,900	1.32	2,760	300	800
		11,400	1.52	6,040	620	1,250
Engelmann	.38	5,700	1.25	2,810	270	700
		10,100	1.55	6,150	540	1,100
Red	.38	5,900	1.32	2,810	270	810
		10,300	1.60	5,590	550	1,330
Sitka	.35	5,400	1.37	2,560	290	630
		10,100	1.63	5,480	590	980
White	.35	5,100	1.15	2,470	240	670
		9,100	1.45	5,360	500	980
Tamarack	.48	6,800	1.24	3,130	410	920
		11,000	1.36	6,510	900	1,300

[1]Results of tests on small, clear, straight-grained specimens. Property values based on American Society for Testing and Materials Standard D 2555–70, "Standard methods for establishing clear wood values." Information on additional properties can be obtained from Department of Forestry, Canada, Publication No. 1104.

[2]The values in the first line for each species are from tests of green material; those in the second line are adjusted from the green condition to 12 percent moisture content using dry to green clear wood property ratios as reported in ASTM D 2555–70. Specific gravity is based on weight when ovendry and volume when green.

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

Table 4–4—*Mechanical properties*[1, 2] *of some woods imported into the United States*

Common and botanical names of species	Moisture content	Specific gravity[3]	Static bending: Modulus of rupture	Static bending: Modulus of elasticity[4]	Static bending: Work to maximum load	Compression parallel to grain—maximum crushing strength	Shear parallel to grain—maximum shearing strength	Side hardness—load perpendicular to grain	Sample origin[5]
	Pct		*Psi*	*Million Psi*	*In—lb per in*^{3}	*Psi*	*Psi*	*Lb*	
Afrormosia (*Pericopsis elata*)	Green	0.61	14,800	1.77	19.5	7,490	1,670	1,600	AF
	12		18,400	1.94	18.4	9,940	2,090	1,560	
Albarco (*Cariniana* spp.)	Green	.48	—	—	—	—	—	—	AM
	12		14,500	1.50	13.8	6,820	2,310	1,020	
Andiroba (*Carapa guianensis*)	Green	.54	10,300	1.69	9.8	4,780	1,220	880	AM
	12	—	15,500	2.00	14.0	8,120	1,510	1,130	
Angelin (*Andira* spp.)	Green	.65	—	—	—	—	—	—	AM
	12		18,000	2.49	—	9,200	1,840	1,750	
Angelique (*Dicorynia guianensis*)	Green	.60	11,400	1.84	12.0	5,590	1,340	1,100	AM
	12	—	17,400	2.19	15.2	8,770	1,660	1,290	
Avodire (*Turraeanthus africanus*)	Green	.48	—	—	—	—	—	—	AF
	12		12,700	1.49	9.4	7,150	2,030	1,080	
Azobe (*Lophira alata*)	Green	.87	16,900	2.16	12.0	9,520	2,040	2,890	AF
	12		24,500	2.47	—	12,600	2,960	3,350	
Balsa (*Ochroma pyramidale*)	Green	.16	—	—	—	—	—	—	AM
	12		3,140	.49	2.1	2,160	300	—	
Banak (*Virola* spp.)	Green	.42	5,600	1.64	4.1	2,390	720	320	AM
	12	—	10,900	2.04	10.0	5,140	980	510	
Benge (*Guibourtia arnoldiana*)	Green	.65	—	—	—	—	—	—	AF
	12		21,400	2.04	—	11,400	2,090	1,750	
Bubinga (*Guibourtia* spp.)	Green	.71	—	—	—	—	—	—	AF
	12		22,600	2.48	—	10,500	3,110	2,690	
Bulletwood (*Manilkara bidentata*)	Green	.85	17,300	2.70	13.6	8,690	1,900	2,230	AM
	12		27,300	3.45	28.5	11,640	2,500	3,190	

Table 4–4—*Mechanical properties*[1, 2] *of some woods imported into the United States*—Continued

Common and botanical names of species	Moisture content	Specific gravity[3]	Static bending: Modulus of rupture	Static bending: Modulus of elasticity[4]	Static bending: Work to maximum load	Compression parallel to grain—maximum crushing strength	Shear parallel to grain—maximum shearing strength	Side hardness—load perpendicular to grain	Sample origin[5]
	Pct		*Psi*	*Million Psi*	*In—lb per in³*	- - - - *Psi* - - - -		*Lb*	
Cativo (*Prioria copaifera*)	Green	.40	5,900	.94	5.4	2,460	860	440	AM
	12	—	8,600	1.11	7.2	4,290	1,060	630	
Ceiba (*Ceiba pentandra*)	Green	.25	2,200	.41	1.2	1,060	350	220	AM
	12		4,300	.54	2.8	2,380	550	240	
Courbaril (*Hymenaea courbaril*)	Green	.71	12,900	1.84	14.6	5,800	1,770	1,970	AM
	12	—	19,400	2.16	17.6	9,510	2,470	2,350	
Cuangare (*Dialyanthera* spp.)	Green	.31	4,000	1.01	—	2,080	590	230	AM
	12		7,300	1.52	—	4,760	830	380	
Cypress, Mexican (*Cupressus lusitanica*)	Green	.39	6,200	.92	—	2,880	950	340	AF[6]
	12		10,300	1.02	—	5,380	1,580	460	
Degame (*Calycophyllum candidissimum*)	Green	.67	14,300	1.93	18.6	6,200	1,660	1,630	AM
	12		22,300	2.27	27.0	9,670	2,120	1,940	
Determa (*Ocotea rubra*)	Green	.52	7,800	1.46	4.8	3,760	860	520	AM
	12		10,500	1.82	6.4	5,800	980	660	
Ekop (*Tetraberlinia tubmaniana*)	Green	.60	—	—	—	—	—	—	AF
	12		16,700	2.21	—	9,010	—	—	
Goncalo alves (*Astronium graveolens*)	Green	.84	12,100	1.94	6.7	6,580	1,760	1,910	AM
	12	—	16,600	2.23	10.4	10,320	1,960	2,160	
Greenheart (*Ocotea rodiaei*)	Green	.80	19,300	2.47	10.5	9,380	1,930	1,880	AM
	12		24,900	3.25	25.3	12,510	2,620	2,350	
Hura (*Hura crepitans*)	Green	.38	6,300	1.04	5.9	2,790	830	440	AM
	12		8,700	1.17	6.7	4,800	1,080	550	
Ilomba (*Pycnanthus angolensis*)	Green	.40	5,500	1.14	—	2,900	840	470	AF
	12		9,900	1.59	—	5,550	1,290	610	

Table 4–4—*Mechanical properties*[1, 2] *of some woods imported into the United States*—Continued

Common and botanical names of species	Moisture content	Specific gravity[3]	Static bending: Modulus of rupture	Static bending: Modulus of elasticity[4]	Static bending: Work to maximum load	Compression parallel to grain—maximum crushing strength	Shear parallel to grain—maximum shearing strength	Side hardness—load perpendicular to grain	Sample origin[5]
	Pct		*Psi*	*Million Psi*	*In—lb per in*^{3}	- - - - *Psi* - - - -		*Lb*	
Ipe (*Tabebuia spp.* —Lapacho group)	Green	.92	22,600	2.92	27.6	10,350	2,120	3,060	AM
	12		25,400	3.14	22.0	13,010	2,060	3,680	
Iroko (*Chlorophora* spp.)	Green	.54	10,200	1.29	10.5	4,910	1,310	1,080	AF
	12		12,400	1.46	9.0	7,590	1,800	1,260	
Jarrah (*Eucalyptus marginata*)	Green	.67	9,900	1.48	—	5,190	1,320	1,290	AS
	12	—	16,200	1.88	—	8,870	2,130	1,910	
Jelutong (*Dyera costulata*)	Green	.36	5,600	1.16	5.6	3,050	760	330	AS
	15		7,300	1.18	6.4	3,920	840	390	
Kaneelhart (*Licaria* spp.)	Green	.96	22,300	3.82	13.6	13,390	1,680	2,210	AM
	12		29,900	4.06	17.5	17,400	1,970	2,900	
Kapur (*Dryobalanops* spp.)	Green	.64	12,800	1.60	15.7	6,220	1,170	980	AS
	12		18,300	1.88	18.8	10,090	1,990	1,230	
Karri (*Eucalyptus diversicolor*)	Green	.82	11,200	1.94	11.6	5,450	1,510	1,360	AS
	12		20,160	2.60	25.4	10,800	2,420	2,040	
Kempas (*Koompassia malaccenis*)	Green	.71	14,500	2.41	12.2	7,930	1,460	1,480	AS
	12		17,700	2.69	15.3	9,520	1,790	1,710	
Keruing (*Dipterocarpus* spp.)	Green	.69	11,900	1.71	13.9	5,680	1,170	1,060	AS
	12		19,900	2.07	23.5	10,500	2,070	1,270	
Lignumvitae (*Guaiacum* spp.)	Green	1.05	—	—	—	—	—	—	AM
	12	—	—	—	—	11,400	—	4,500	
Limba (*Terminalia superba*)	Green	.38	6,000	.77	7.7	2,780	880	400	AF
	12		8,800	1.01	8.9	4,730	1,410	490	
Macawood (*Platymiscium* spp.)	Green	.94	22,300	3.02	—	10,540	1,840	3,320	AM
	12		27,600	3.20	—	16,100	2,540	3,150	

Table 4–4—*Mechanical properties*[1, 2] *of some woods imported into the United States*—Continued

Common and botanical names of species	Moisture content	Specific gravity[3]	Static bending: Modulus of rupture	Static bending: Modulus of elasticity[4]	Static bending: Work to maximum load	Compression parallel to grain—maximum crushing strength	Shear parallel to grain—maximum shearing strength	Side hardness—load perpendicular to grain	Sample origin[5]
	Pct		*Psi*	*Million Psi*	*In—lb per in³*	*Psi*	*Psi*	*Lb*	
Mahogany, African (*Khaya* spp.)	Green	.42	7,400	1.15	7.1	3,730	931	640	AF
	12		10,700	1.40	8.3	6,460	1,500	830	
Mahogany, Honduras (*Swietenia macrophylla*)	Green	.45	9,000	1.34	9.1	4,340	1,240	740	AM
	12	—	11,500	1.50	7.5	6,780	1,230	800	
Manbarklak (*Eschweilera* spp.)	Green	.87	17,100	2.70	17.4	7,340	1,630	2,280	AM
	12		26,500	3.14	33.3	11,210	2,070	3,480	
Manni (*Symphonia globulifera*)	Green	.58	11,200	1.96	11.2	5,160	1,140	940	AM
	12		16,900	2.46	16.5	8,820	1,420	1,120	
Marishballi (*Lincania* spp.)	Green	.88	17,100	2.93	13.4	7,580	1,620	2,250	AM
	12		27,700	3.34	14.2	13,390	1,750	3,570	
Merbau (*Intsia* spp.)	Green	.64	12,900	2.02	12.8	6,770	1,560	1,380	AS
	15	—	16,800	2.23	14.8	8,440	1,810	1,500	
Mersawa (*Anisoptera* spp.)	Green	.52	8,000	1.77	—	3,960	740	880	AS
	12		13,800	2.28	—	7,370	890	1,290	
Mora (*Mora* spp.)	Green	.78	12,600	2.33	13.5	6,400	1,400	1,450	AM
	12		22,100	2.96	18.5	11,840	1,900	2,300	
Oak (*Quercus* spp.)	Green	.76	—	—	—	—	—	—	AM
	12		23,000	3.02	16.5	—	—	2,500	
Obeche (*Triplochiton scleroxylon*)	Green	.30	5,100	.72	6.2	2,570	660	420	AF
	12		7,400	.86	6.9	3,930	990	430	
Okoume (*Aucoumea klaineana*)	Green	.33	—	—	—	—	—	—	AF
	12		7,400	1.14	—	3,970	970	380	
Opepe (*Nauclea diderrichii*)	Green	.63	13,600	1.73	12.2	7,480	1,900	1,520	AF
	12		17,400	1.94	14.4	10,400	2,480	1,630	

Table 4-4—*Mechanical properties*[1,2] *of some woods imported into the United States*—Continued

Common and botanical names of species	Moisture content	Specific gravity[3]	Static bending: Modulus of rupture	Static bending: Modulus of elasticity[4]	Static bending: Work to maximum load	Compression parallel to grain—maximum crushing strength	Shear parallel to grain—maximum shearing strength	Side hardness—load perpendicular to grain	Sample origin[5]
	Pct		*Psi*	*Million Psi*	*In—lb per in³*	*Psi*	*Psi*	*Lb*	
Ovangkol (*Guibourtia ehie*)	Green	.67	—	—	—	—	—	—	AF
	12		16,900	2.56	—	8,300	—	—	
Para-angelium (*Hymenolobium excelsum*)	Green	.63	14,600	1.95	12.8	7,460	1,600	1,720	AM
	12		17,600	2.05	15.9	8,990	2,010	1,720	
Parana-pine (*Araucaria augustifolia*)	Green	.46	7,200	1.35	9.7	4,010	970	560	AM
	12	—	13,500	1.61	12.2	7,660	1,730	780	
Pau marfim (*Balfourodendron riedelianum*)	Green	.73	14,400	1.66	—	6,070	—	—	AM
	15		18,900	—	—	8,190	—	—	
Peroba de campos (*Paratecoma peroba*)	Green	.62	—	—	—	—	—	—	AM
	12		15,400	1.77	10.1	8,880	2,130	1,600	
Peroba rosa (*Aspidosperma* spp.—Peroba group)	Green	.66	10,900	1.29	10.5	5,540	1,880	1,580	AM
	12		12,100	1.53	9.2	7,920	2,490	1,730	
Pilon (*Hyeronima* spp.)	Green	.65	10,700	1.88	8.3	4,960	1,200	1,220	AM
	12		18,200	2.27	12.1	9,620	1,720	1,700	
Pine, Caribbean (*Pinus caribaea*)	Green	.68	11,200	1.88	10.7	4,900	1,170	980	AM
	12	—	16,700	2.24	17.3	8,540	2,090	1,240	
Pine, ocote (*Pinus oocarpa*)	Green	.55	8,000	1.74	6.9	3,690	1,040	580	AM
	12	—	14,900	2.25	10.9	7,680	1,720	910	
Pine, radiata (*Pinus radiata*)	Green	.42	6,100	1.18	—	2,790	750	480	AS[6]
	12	—	11,700	1.48	—	6,080	1,600	750	
Piquia (*Caryocar* spp.)	Green	.72	12,400	1.82	8.4	6,290	1,640	1,720	AM
	12		17,000	2.16	15.8	8,410	1,990	1,720	
Primavera (*Cybistax donnell-smithii*)	Green	.40	7,200	.99	7.2	3,510	1,030	700	AM
	12		9,500	1.04	6.4	5,600	1,390	660	

Table 4–4—*Mechanical properties*[1, 2] *of some woods imported into the United States*—Continued

Common and botanical names of species	Moisture content	Specific gravity[3]	Static bending: Modulus of rupture	Static bending: Modulus of elasticity[4]	Static bending: Work to maximum load	Compression parallel to grain—maximum crushing strength	Shear parallel to grain—maximum shearing strength	Side hardness—load perpendicular to grain	Sample origin[5]
	Pct		*Psi*	*Million Psi*	*In—lb per in*^{3}	*Psi*	*Psi*	*Lb*	
Purpleheart (*Peltogyne* spp.)	Green	.67	13,700	2.00	14.8	7,020	1,640	1,810	AM
	12		19,200	2.27	17.6	10,320	2,220	1,860	
Ramin (*Gonystylus* spp.)	Green	.52	9,800	1.57	9.0	5,390	990	640	AS
	12	—	18,500	2.17	17.0	10,080	1,520	1,300	
Robe (*Tabebuia* spp.—Roble group)	Green	.52	10,800	1.45	11.7	4,910	1,250	910	AM
	12		13,800	1.60	12.5	7,340	1,450	960	
Rosewood, Brazilian (*Dalbergia nigra*)	Green	.80	14,100	1.84	13.2	5,510	2,360	2,440	AM
	12	—	19,000	1.88	—	9,600	2,110	2,720	
Rosewood, Indian (*Dalbergia latifolia*)	Green	.75	9,200	1.19	11.6	4,530	1,400	1,560	AS
	12		16,900	1.78	13.1	9,220	2,090	3,170	
Sande (*Brosimum* spp.—Utile group)	Green	.49	8,500	1.94	—	4,490	1,040	600	AM
	12		14,300	2.39	—	8,220	1,290	900	
Santa Maria (*Calophyllum brasiliense*)	Green	.52	10,500	1.59	12.7	4,560	1,260	890	AM
	12	—	14,600	1.83	16.1	6,910	2,080	1,150	
Sapele (*Entandrophragma cylindricum*)	Green	.55	10,200	1.49	10.5	5,010	1,250	1,020	AF
	12	—	15,300	1.82	15.7	8,160	2,280	1,510	
Sepetir (Pseudosindora palustris)	Green	.56	11,200	1.57	13.3	5,460	1,310	950	AS
	12		17,200	1.97	13.3	8,880	2,030	1,410	
Shorea (*Shorea* spp.—Baulau group)	Green	.68	11,700	2.10	—	5,380	1,440	1,350	AS
	12		18,800	2.61	—	10,180	2,190	1,780	
Shorea-Lauan-Meranti group, Dark red (*Shorea* spp.)	Green	.46	9,400	1.50	8.6	4,720	1,110	700	AS
	12		12,700	1.77	13.8	7,360	1,450	780	
Shorea-Lauan-Meranti group, Light red (*Shorea* spp.)	Green	.34	6,600	1.04	6.2	3,330	710	440	AS
	12		9,500	1.23	8.6	5,920	970	460	

Table 4-4—*Mechanical properties*[1, 2] *of some woods imported into the United States*—Continued

Common and botanical names of species	Moisture content	Specific gravity[3]	Static bending: Modulus of rupture	Static bending: Modulus of elasticity[4]	Static bending: Work to maximum load	Compression parallel to grain—maximum crushing strength	Shear parallel to grain—maximum shearing strength	Side hardness—load perpendicular to grain	Sample origin[5]
	Pct		*Psi*	*Million Psi*	*In—lb per in*[3]	*Psi*	*Psi*	*Lb*	
Shorea-White Meranti group (*Shorea spp.*)	Green	.55	9,800	1.30	8.3	5,490	1,320	1,000	AS
	15		12,400	1.49	11.4	6,350	1,540	1,140	
Shorea-Yellow Meranti group (*Shorea* spp.)	Green	.46	8,000	1.30	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	.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	.74	17,200	2.27	—	9,730	—	—	AM
	15		19,400	—	—	11,100	—	—	
Sucupira (*Diplotropis purpurea*)	Green	.78	17,400	2.68	13.0	8,020	1,800	1,980	AM
	12		20,600	2.87	14.8	12,140	1,960	2,140	
Teak (*Tectona grandis*)	Green	.55	11,600	1.37	13.4	5,960	1,290	930	AS
	12		14,600	1.55	12.0	8,410	1,890	1,000	
Tornillo (*Cedrelinga catenaeformis*)	Green	.45	8,400	—	—	4,100	1,170	870	AM
	12	—	—	—	—	—	—	—	
Wallaba (*Eperua* spp.)	Green	.78	14,300	2.33	—	8,040	—	1,540	AM
	12	—	19,100	2.28	—	10,760	—	2,040	

[1] 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.

[2] Some property values have been adjusted to 12 percent moisture content; others are based on moisture content at time of test.

[3] Specific gravity based on weight ovendry and volume green.

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

[5] Key to code letters: AF, Africa; AM, Tropical America; AS, Asia.

[6] Plantation grown.

Table 4–5—*Average coefficient of variation for some mechanical properties of clear wood*

Property	Coefficient of variation[1]
	Pct
Static bending:	
Fiber stress at proportional limit	22
Modulus of rupture	16
Modulus of elasticity	22
Work to maximum load	34
Impact bending, height of drop causing complete failure	25
Compression parallel to grain:	
Fiber stress at proportional limit	24
Maximum crushing strength	18
Compression perpendicular to grian, fiber stress at proportional limit	28
Shear parallel to grain, maximum shearing strength	14
Tension perpendicular to grain, maximum tensile strength	25
Hardness:	
Perpendicular to grain	20
Toughness	34
Specific gravity	10

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

Table 4–6—*Average parallel-to-grain tensile strength of some species of wood*[1]

Species	Tensile strength
	Psi
HARDWOODS	
Beech, American	12,500
Elm:	
Cedar	17,500
Maple, sugar	15,700
Oak:	
Overcup	11,300
Pin	16,300
Poplar, balsam	7,400
Sweetgum	13,600
Willow, black	10,600
Yellow-poplar	15,900
SOFTWOODS	
Baldcypress	8,500
Cedar:	
Port-Orford	11,400
Western redcedar	6,600
Douglas-fir, Interior North	15,600
Fir:	
California red	11,300
Pacific silver	13,800
Hemlock, western	13,000
Larch, western	16,200
Pine:	
Eastern white	10,600
Loblolly	11,600
Ponderosa	8,400
Virginia	13,700
Redwood:	
Virgin	9,400
Young-growth	9,100
Spruce:	
Engelmann	12,300
Sitka	8,600

[1]Results of tests on small, clear, straight-grained specimens tested in the green moisture condition. For the hardwood species, specimens tested at 12 percent moisture content averaged about 32 percent higher; softwoods, about 13 percent.

Table 4–7—*Average toughness values*[1] *for samples of a few species of wood*

Species	Moisture content	Specific gravity[2]	Toughness[3] Radial	Toughness[3] Tangential
	Pct		In–lb	In–lb
HARDWOODS				
Birch, yellow	12	0.65	500	620
Hickory:				
(Mockernut, pignut, sand)	Green	.64	700	720
	12	.71	620	660
Maple, sugar	14	.64	370	360
Oak, red:				
Pin	12	.64	430	430
Scarlet	11	.66	510	440
Oak, white:				
Overcup	Green	.56	730	680
	13	.62	340	310
Sweetgum	Green	.48	340	330
	13	.51	260	260
Willow, black	Green	.38	310	360
	11	.40	210	230
Yellow-poplar	Green	.43	320	300
	12	.45	220	210
SOFTWOODS				
Cedar:				
Alaska-	10	.48	210	230
Western redcedar	9	.33	90	130
Douglas-fir:				
Coast	Green	.44	210	360
	12	.47	200	360
Interior West	Green	.48	200	300
	13	.51	210	340
Interior North	Green	.43	170	240
	14	.46	160	250
Interior South	Green	.38	130	180
	14	.40	120	180
Fir:				
California red	Green	.36	130	180
	12	.39	120	170
Noble	Green	.36	—	240
	12	.39	—	220
Pacific silver	Green	.37	150	230
	13	.40	170	260
White	Green	.36	140	220
	13	.38	130	200
SOFTWOODS—continued				
Hemlock:				
Mountain	Green	.41	250	280
	14	.44	140	170
Western	Green	.38	150	170
	12	.41	140	210
Larch, western	Green	.51	270	400
	12	.55	210	340
Pine:				
Eastern white	Green	.33	120	160
	12	.34	110	120
Jack	Green	.41	200	380
	12	.42	140	240
Loblolly	Green	.48	310	380
	12	.51	160	260
Lodgepole	Green	.38	160	210
Ponderosa	Green	.38	190	270
	11	.43	150	190
Red	Green	.40	210	350
	12	.43	160	290
Shortleaf	Green	.47	290	400
	13	.50	150	230
Slash	Green	.55	350	450
	12	.59	210	320
Virginia	Green	.45	340	470
	12	.49	170	250
Redwood:				
Old-growth	Green	.39	110	200
	11	.39	90	140
Young-growth	Green	.33	110	140
	12	.34	90	110
Spruce, Engelmann	Green	.34	150	190
	12	.35	110	180

[1] Results of tests on small, clear, straight-grained specimens.
[2] Based on ovendry weight and volume at moisture content of test.
[3] Properties based on specimen size of 2 centimeters square by 28 centimeters long; radial indicates load applied to radial face and tangential indicates load applied to tangential face of specimens.

(This discussion began on page 4-5.)

Approximate relationships between various mechanical properties and specific gravity for clear straight-grained wood of hardwoods and softwoods are given in table 4−8 as power functions. Those relationships are based on average values for the 43 softwood and 66 hardwood species presented in table 4−2. It is recognized that the average data vary around the relationships, so that individual average species values or an individual specimen value are not accurately predicted by the relationships. In fact, mechanical properties within a species tend to be linearly related with specific gravity rather than curvilinearly, and 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 mechanical properties of a wood member is due to the interruption of continuity and change in direction of wood fibers associated with the knot. The influence of knots depends on their size, location, shape, soundness, attendant local slope of grain, and the type of stress to which a member is subjected.

The shape (form) of a knot appearing on a sawed surface depends upon the direction of the exposing cut. If, when sawing lumber from a log, a branch is sawed through at right angles to its length as in flat-sawn boards, a nearly round knot results; when cut diagonally (as in a bastard-sawn board), an oval knot; and when sawed lengthwise (as in a quarter-sawn board), a spike knot.

Knots are further classified as intergrown or encased (fig. 4−2). 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, and an encased knot results; fibers of the bole are not continuous with fibers of encased knots. Encased knots and knotholes tend to be accompanied by less cross grain than are intergrown knots and are, therefore, generally less serious with regard to most mechanical properties.

Most mechanical properties are lower at sections containing knots than in clear straight-grained wood because (1) the clear wood is displaced by the knot, (2) the fibers around the knot are distorted, causing cross grain, (3) the discontinuity of wood fiber leads to stress concentrations, and (4) checking often occurs around knots in drying. Hardness and strength in compression perpendicular to the grain are exceptions, where the 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

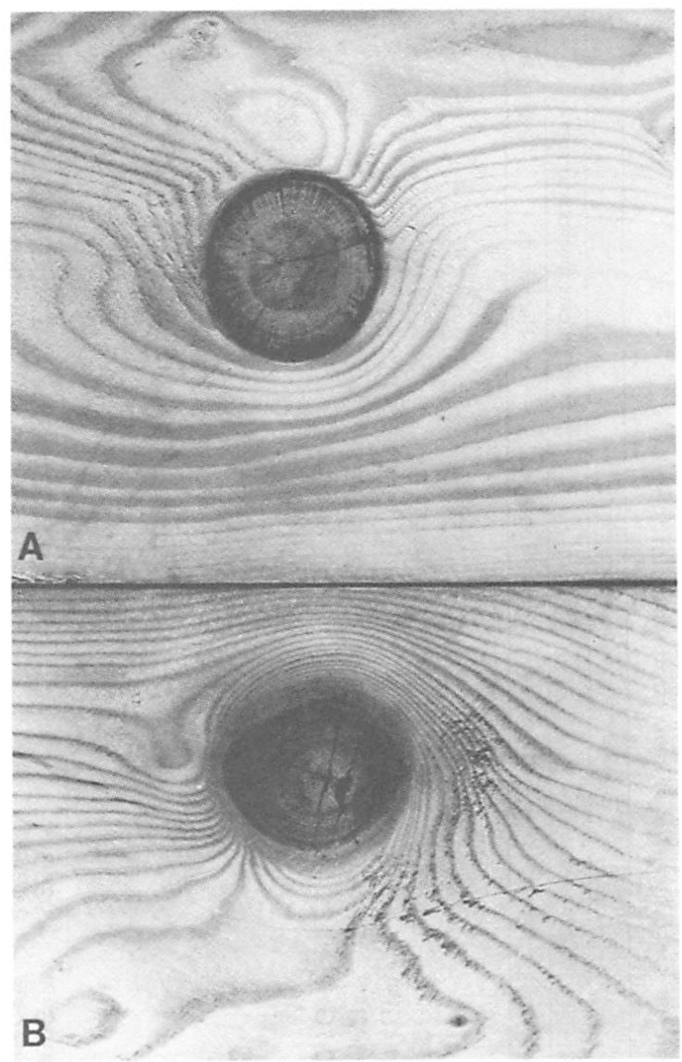

Figure 4−2—*A*, Encased knot. *B*, Intergrown knot. (M84 0261)

on bending are somewhat less than those in axial tension. 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 when the knot is on the upper side (subjected to compression stresses).

In long columns, knots are important in that they affect stiffness. In short or intermediate columns, the reduction in strength caused by knots is approximately proportional to the size of the knot; 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 knots in sawed timbers. Although the grain is irregular around knots in both forms of timber, its angle with the surface is less in naturally round than in sawed timber. Further, in round timbers there is no discontinuity in

Table 4—8—*Functions relating mechanical properties to specific gravity of clear, straight-grained wood*

Property		Specific gravity-strength relation[1]					
		Green wood			Wood at 12 percent moisture content		
		Softwoods	Hardwoods	All species[2]	Softwoods	Hardwoods	All species[2]
Static bending:							
Fiber stress at proportional limit	psi	$8,420G^{0.92}$	$8,480G^{1.04}$		$14,200G^{0.91}$	$12,200G^{0.80}$	
Modulus of elasticity	million psi	$2.44G^{0.81}$	$1.91G^{0.64}$		$3.13G^{0.90}$	$2.33G^{0.65}$	
Modulus of rupture	psi	$16,230G^{1.04}$	$16,700G^{1.12}$		$25,600G^{1.05}$	$24,400G^{1.10}$	
Work to maximum load	in-lb per in^3	$20.7G^{1.16}$	$31.4G^{1.48}$		$24.2G^{1.24}$	$29.7G^{1.47}$	
Total work	in-lb per in^3			$103G^{2.00}$			$72.7G^{1.75}$
Impact bending, height of drop causing complete failure	in.			$114G^{1.75}$			$94.6G^{1.75}$
Compression parallel to grain:							
Fiber stress at proportional limit	psi	$5,400G^{0.90}$	$4,930G^{0.96}$		$10,100G^{1.02}$	$6,210G^{0.57}$	
Modulus of elasticity	million psi	$3.24G^{0.92}$	$2.03G^{0.55}$		$3.72G^{0.91}$	$2.70G^{0.63}$	
Maximum crushing strength	psi	$7,740G^{1.02}$	$6,630G^{1.02}$		$14,600G^{1.04}$	$10,600G^{0.83}$	
Shear parallel to grain	psi	$1,560G^{0.72}$	$2,510G^{1.20}$		$2,430G^{0.86}$	$3,200G^{1.15}$	
Compression perpendicular to grain:							
Fiber stress at porportional limit	psi	$1,360G^{1.60}$	$2,380G^{2.32}$		$2,540G^{1.65}$	$2,920G^{2.03}$	
Hardness:							
End				$3,740G^{2.25}$			$4,800G^{2.25}$
Side				$3,420G^{2.25}$			$3,770G^{2.25}$

[1] The properties and values should be read as equations; for example: modulus of rupture for green wood of softwoods = $16,230G^{1.04}$, where *G* represents the specific gravity of ovendry wood, based on the volume at the moisture condition indicated.

[2] As reported in USDA Bulletin No. 676, "The relation of the shrinkage and strength properties of wood to its specific gravity" by J. A. Newlin and T.R.C. Wilson, 1919.

wood fibers caused by 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, by the way the wood was removed from the log, or because of grain irregularities that occurred during growth.

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:

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

in which N represents the strength property at an angle θ from the fiber direction, Q is the strength perpendicular to the grain, P is the strength parallel to the grain, and n is an empirically determined constant. The formula has been used for modulus of elasticity as well as strength properties. Values of n and associated ratios of Q/P have been tabulated below from available literature:

Property	*n*	*Q/P*
Tensile strength	1.5–2	0.04–0.07
Compressive strength	2–2.5	0.03–0.4
Bending strength	1.5–2	0.04–0.1
Modulus of elasticity	2	0.04–0.12
Toughness	1.5–2	0.06–0.1

The Hankinson-type formula can be graphically depicted as a function of Q/P and n. Figure 4–3 shows the strength in any direction expressed as a fraction of the strength parallel to the 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 a 1-inch deviation of the grain from the edge or long axis of the piece and the distance in inches within which this deviation occurs (tan θ). Table 4–9 gives the effect of grain slope on some properties of wood, as determined from tests. The values in table 4–9 for modulus of rupture fall very close to the curve in figure 4–3 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 for compression, $Q/P = 0.1$, $n = 2.5$.

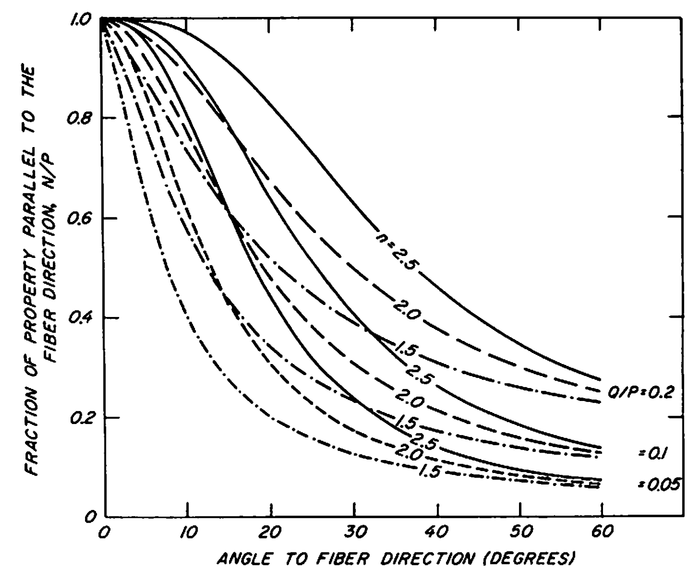

Figure 4–3—Effect of grain angle on mechanical property of clear wood according to a Hankinson-type formula. *Q/P* is the ratio of the mechanical property across the grain (*Q*) to that parallel to the grain (*P*); *n* is an empirically determined constant. (M140 730)

The term "cross grain" indicates the condition measured by slope of grain. Two important forms of cross grain are spiral grain and diagonal grain (fig. 4–4). Other types are wavy, dipped, interlocked, and curly grain. Some of the mechanical property values in table 4–4 are based on specimens with interlocked grain, because that is characteristic for some of the species.

Spiral grain in a tree is caused by fibers growing in a winding or spiral course about the bole of the tree instead of in a vertical course. In sawn products, spiral grain can be defined as fibers lying in the tangential plane of the growth rings, not parallel to the longitudinal axis of the product (see fig. 4–4*B* for a simple case). Spiral grain often goes undetected by ordinary visual inspection in sawn products. The best test for spiral grain is to split a sample section from the piece in the radial direction. A nondestructive method of determining the presence of spiral grain is to note the alignment of pores, rays, and resin ducts on a flat-sawn face. Drying checks on a flat-sawn surface follow the fibers and indicate the fiber slope.

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

Cross grain can be quite localized as a result of the distur-

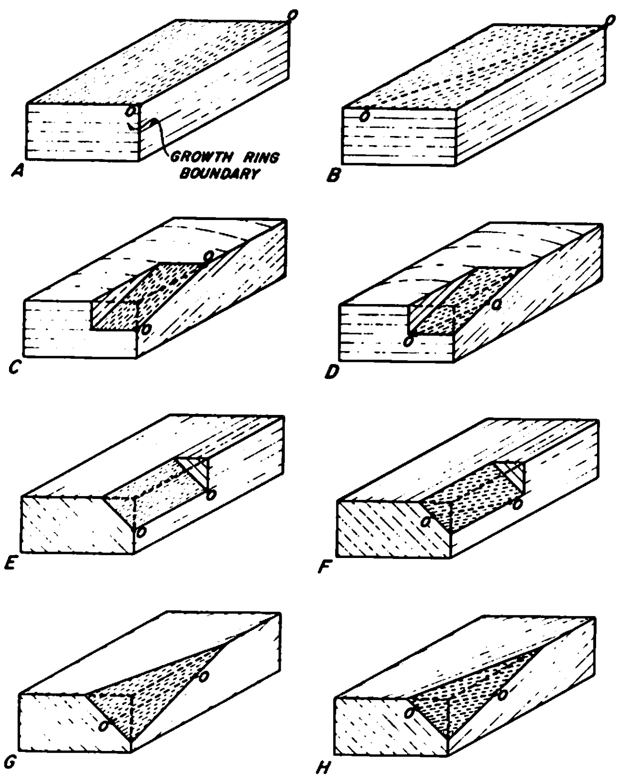

Figure 4–4—Schematic views of wood specimens containing straight grain and cross grain to illustrate the relationship of fiber orientation (0–0) to the axes of the piece. Specimens *A* through *D* have radial and tangential surfaces; *E* through *H* do not. *A* and *E* contain no cross grain. *B*, *D*, *F*, and *H* have spiral grain. *C*, *D*, *G*, and *H* have diagonal grain. (M139 385)

bance of growth patterns by a branch. This condition, termed "local slope of grain," may be present even though the branch (knot) may have been removed in a sawing operation. Often the degree of local cross grain may be difficult to determine.

Any form of cross grain can have a serious 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 contiguous surfaces 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 the spiral grain slope on the flat-grain surface of figure 4–4*D* is 1 in 12 and the diagonal-grain slope is 1 in 18. The combined slope is

$$\sqrt{\left(\frac{1}{18}\right)^2 + \left(\frac{1}{12}\right)^2} = \frac{1}{10} \text{ or slope of 1 in 10}$$

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. 4–5). Perpendicular-to-grain properties depend somewhat upon orientation of annual rings with respect to the direction of stress. Compression perpendicular-to-grain values in table 4–2 are derived from tests in which the load is 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

Table 4–9—*Strength of wood members with various grain slopes compared to strength of a straight-grained member, expressed as percentages*

Maximum slope of grain in member	Modulus of rupture	Impact bending—height of drop causing complete failure (50-lb hammer)	Compression parallel to grain—maximum crushing strength
	Percent		
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

orientations. In some species, there is no difference in 0° and 90° orientation properties. Other species exhibit slightly higher shear parallel or tension perpendicular properties for the 0° orientation than for the 90° orientation; the converse is true for about an equal number of species.

The effects at intermediate annual ring orientations have been studied in a limited way. Modulus of elasticity, compression 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 the 45° orientation is 40 to 60 percent lower. 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 90° orientation.

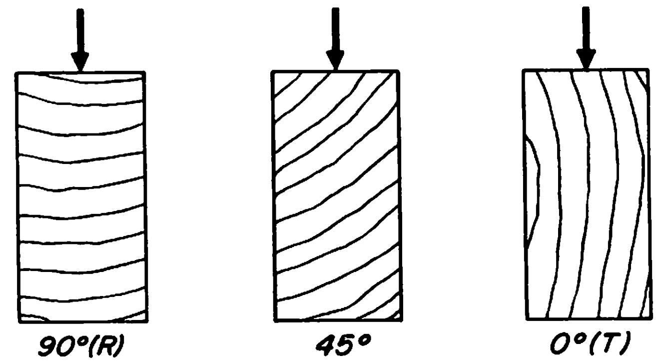

Figure 4–5—The direction of load in relation to the direction of the annual growth rings: 90° or perpendicular (R): 45°; 0° or parallel (T). (M140 729)

Reaction Wood

Abnormal woody tissue is frequently associated with leaning boles and crooked limbs of both conifers and hardwoods. It is generally believed that it 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 the density over that of normal wood. The specific gravity of compression wood is commonly 30 to 40 percent greater than normal wood, while tension wood commonly ranges between 5 and 10 percent greater but may be as much as 30 percent greater than normal wood.

Compression and tension wood undergo extensive longitudinal shrinkage when subjected to moisture loss reaching below the fiber saturation point. Longitudinal shrinkage in compression wood ranges to 10 times that for normal wood and in tension wood perhaps 5 times that for normal wood. When reaction wood is present in the same board with normal wood, unequal longitudinal shrinkage causes internal stresses that result in warping. This warp sometimes occurs in rough lumber but more often in planed, ripped, or resawed lumber (fig. 4–6*C*). In extreme cases, the unequal longitudinal shrinkage results in axial tension failure over a portion of the cross section of the lumber (fig. 4–6*B*).

Reaction wood, particularly compression wood in the green condition, may be somewhat stronger than normal wood. However, when compared to normal wood of comparable specific gravity, the 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.

Because of its abnormal properties, it may be desirable to eliminate reaction wood from raw material. In logs, compression wood is characterized by eccentric growth about the pith and by the large proportion of summerwood at the point of greatest eccentricity (fig. 4–6*A*). Fortunately, pronounced compression wood in lumber can be detected by ordinary visual examination. It is usually somewhat darker than normal wood because of the greater proportion of summerwood and it frequently has a relatively lifeless appearance, especially in woods which normally have an abrupt transition from earlywood to latewood (fig. 4–6). Because it is more opaque than normal wood, intermediate stages of compression wood can be detected by transmitting light through thin cross sections, but borderline forms of compression wood that merge with normal wood are commonly detected only by microscopic examination.

Tension wood is more difficult to detect than compression wood. However, eccentric growth as seen on the transverse section suggests its presence. Also, the tough tension wood fibers resist being cut cleanly and this results in a woolly condition on the surfaces of sawn boards, especially when surfaced in the green condition (fig. 4–7). In some species, tension wood may show up 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.

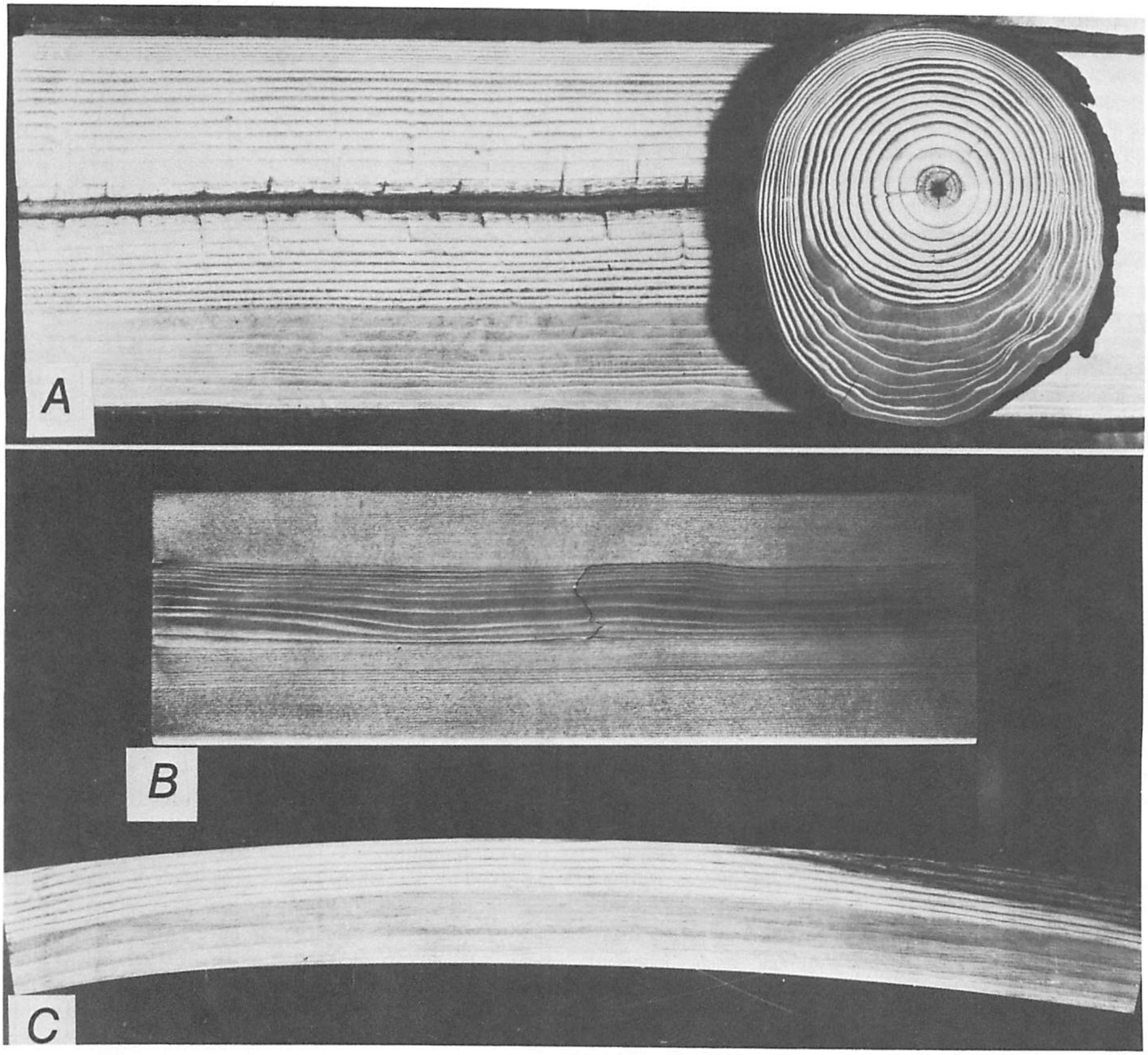

Figure 4–6—*A*, Eccentric growth about the pith in a cross section containing compression wood. The dark area in the lower third of the cross section is compression wood. *B*, Axial tension break caused by excessive longitudinal shrinkage of compression wood. *C*, Warp caused by excessive longitudinal shrinkage of compression wood. (M41 434)

Compression Failures

Excessive bending of standing trees from wind or snow, felling trees across boulders, logs, or irregularities in the ground, or the rough handling of logs or lumber may produce excessive compression stresses along the grain which cause minute compression failures. In some instances, such failures are visible on the surface of a board as minute lines or zones formed by the crumpling or buckling of the cells (fig 4–8*A*), although usually they appear only as white lines or may even be invisible to the naked eye. Their presence may be indicated by fiber breakage on end grain (fig. 4–8*B*). Compression failures should not be confused with compression wood.

Products containing visible compression failures may have

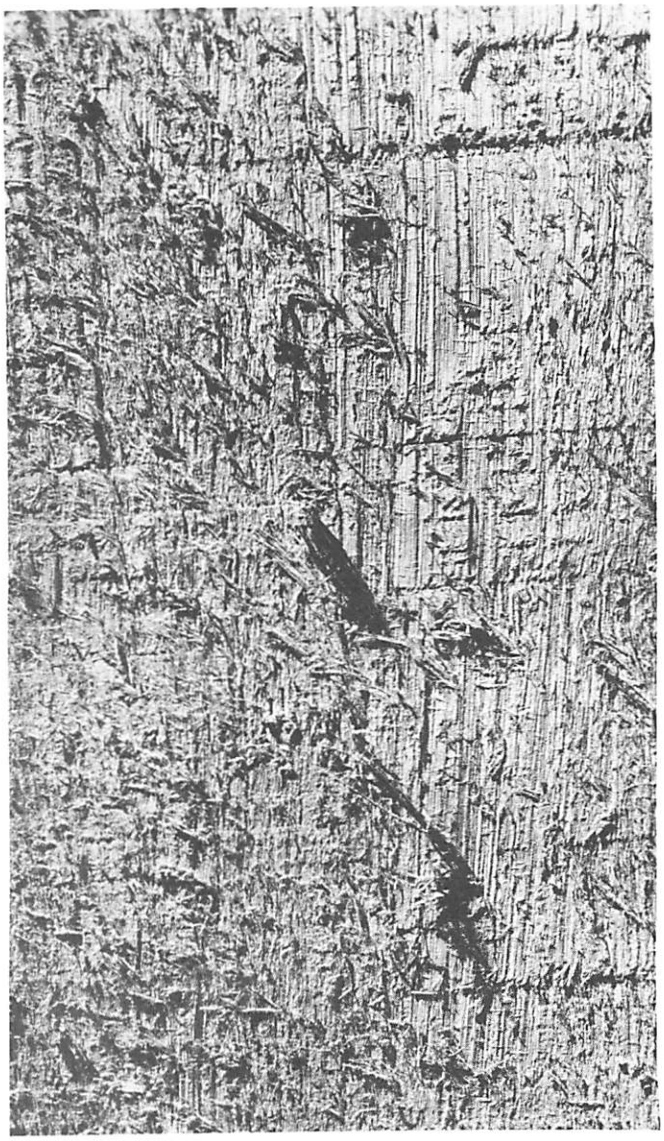

Figure 4–7—Projecting tension wood fibers on the sawn surface of a mahogany board. (M81 915)

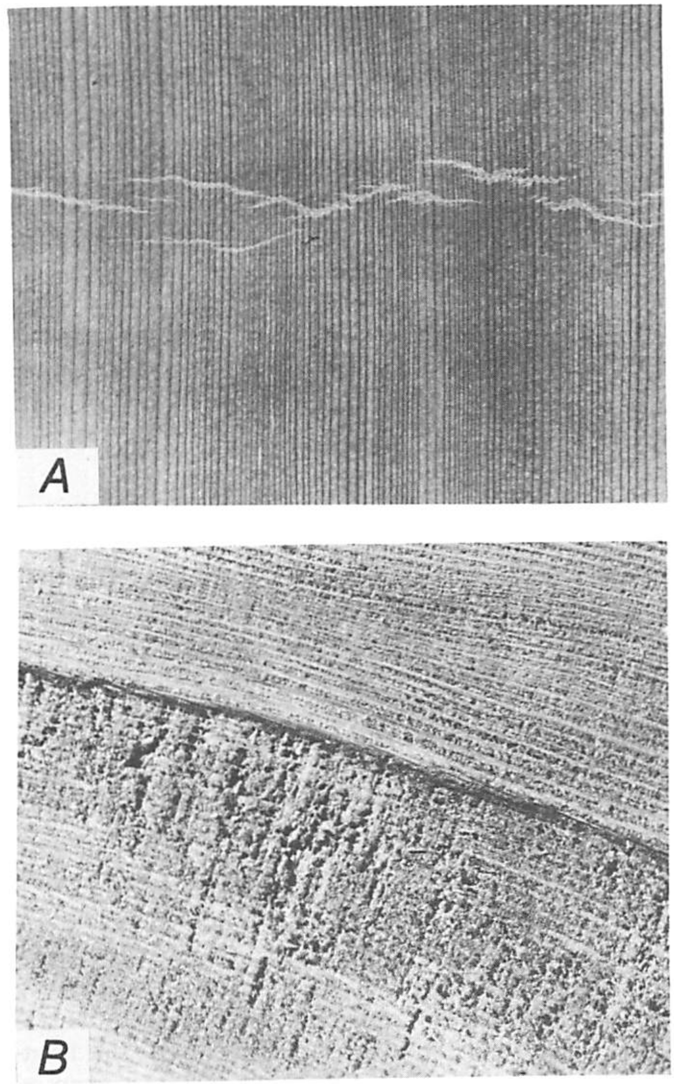

Figure 4–8—*A*, Compression failure is shown by the irregular lines across the grain. *B*, End-grain surfaces of spruce lumber show fiber breakage caused by compression failures below the dark line. (M45 594, M81 195)

low strength properties, especially in tensile strength and shock resistance. Tensile strength of wood containing compression failures may be as low as one-third of the strength of matched clear wood. Even slight compression failures, visible only under the 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 them.

Compression failures are often difficult to detect with the unaided eye, and special efforts including optimum lighting are required to aid detection.

Pitch Pockets

A pitch pocket is a well-defined opening that contains free resin. It extends parallel to the annual rings and 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 containing them should be inspected for shake or separations 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 are often 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, although they do impair the appearance of the wood.

Extractives

Many species of wood contain extraneous materials or extractives that can be removed by solvents that do not degrade the cellulosic/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 removal of extractives. The extent to which the extractives influence the strength is apparently a function of the amount of extractives, the moisture content of the piece, and the mechanical property under consideration.

Timber From Live Versus 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 seasoning degrade has not occurred. In a living tree, the heartwood is entirely dead, and in the sapwood only a comparatively few cells are living. 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 in time the heartwood will be similarly affected. Such deterioration occurs also in logs that have been cut from live trees and improperly cared for afterwards. Because of variations in climatic and local weather conditions and in other factors that affect deterioration, the time during which 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 as strong as wood from live trees. Also, logs of some of the more durable species have had thoroughly sound heartwood after lying on the ground in the forest for many years.

On the other hand, 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 timber 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.

Effect of Manufacturing and Service Environment on Mechanical Properties

Moisture Content—Drying

Many mechanical properties are affected by changes in moisture content below the fiber saturation point. Most properties reported in tables 4–2, 4–3, and 4–4 increase with decrease in moisture content. The relation that describes these clear wood property changes at about 70 °F 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 and M the moisture content in percent. M_p is the moisture content at the intersection of a horizontal line representing the strength of green wood and an inclined line representing the logarithm of strength-moisture content relationship for dry wood. This moisture content is slightly less than the fiber saturation point. Table 4–10 gives values of M_p for a few species; for other species, $M_p = 25$ may be assumed.

P_{12} is the property value at 12 percent moisture content, and P_g (green condition) is the property value for all moisture contents greater than M_p. Average property values of P_{12} and P_g are given for many species in tables 4–2, 4–3, and 4–4. The formula for moisture content adjustment is not recommended for work to maximum load, impact bending, and tension perpendicular. 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 the modulus of rupture of white ash at 8 percent moisture content is wanted. Using information from tables 4–2 and 4–10:

$$P_8 = (15{,}400)\left(\frac{15{,}400}{9{,}600}\right)^{\left(\frac{4}{12}\right)}$$

$$P_8 = 18{,}030 \text{ psi}$$

Table 4–10—*Intersection moisture content values for selected species*[1]

Species	M_p
	Pct
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

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

Table 4–11 tabulates approximate increases in property values at 6 percent moisture content and approximate decreases at 20 percent moisture content relative to those at 12 percent moisture content. The middle trend values are based on results of many reported studies. The values should be used with caution (i.e., treated only as trends) because of the variation in results from different studies.

The increase in mechanical properties discussed above assumes small, clear specimens in a drying process in which no deterioration of the product (degrade) occurs. The property changes applied to large wood specimens such as lumber are discussed in chapter 6.

Drying degrade can take several forms. Perhaps the most common degrade is surface and end checking. Checks most often limit mechanical properties.

Although visual signs of degrade may not be present, some loss of strength may occur in some species dried at high temperatures (110 °C and higher). Losses in excess of 10 percent have been observed in modulus of rupture and in shear of small clear wood specimens and in modulus of rupture and axial tensile strength of lumber.

Further information on moisture content is included in chapter 14.

Table 4–11—*Approximate middle trend effects of moisture content on mechanical properties of clear wood at about 20 °C*

Property	Relative change in property from 12 percent moisture content: At 6 percent moisture content	Relative change in property from 12 percent moisture content: At 20 percent moisture content
	Percent	Percent
Modulus of elasticity parallel to the grain	+9	−13
Modulus of elasticity perpendicular to the grain	+20	−23
Shear modulus	+20	−20
Bending strength	+30	−25
Tensile strength parallel to the grain	+8	−15
Compressive strength parallel to the grain	+35	−35
Shear strength parallel to the grain	+18	−18
Tensile strength perpendicular to the grain	+12	−20
Compressive strength perpendicular to the grain at the proportional limit	+30	−30

Temperature

Reversible Effects

In general, the mechanical properties of wood decrease when heated and increase when cooled. At a constant moisture content and below about 150 °C, 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 100 °C, 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 4−9 illustrates the immediate effect of temperature on modulus of elasticity parallel to the grain, relative to values at 20 °C, based on a composite of results. Figure 4−10 gives similar information for modulus of rupture and figure 4−11 for compression parallel to grain. Figures 4−9 through 4−11 represent an interpretation of data from several investigators. The width of the band illustrates variability between and within reported trends.

Table 4−12 lists percentage changes in properties at −50 °C and +50 °C relative to those at 20 °C for a number of moisture conditions. The large changes at −50 °C for wet wood (at the fiber saturation point or wetter) reflect the presence of ice in the wood cell cavities.

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 which 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 due to heating in steam and in water is shown as a function of temperature and heating time in figure 4−12, based on tests of Douglas-fir and Sitka spruce. From the same studies, work to maximum load was affected more than modulus of rupture by heating in water (fig. 4−13). The effect of oven heating (wood at 0 pct moisture content) on the modulus of rupture and modulus of elasticity is shown in figures 4−14 and 4−15, respectively, as derived from tests on four softwoods and two hardwoods. Note that the permanent property losses discussed above are based on tests conducted after the specimens have been cooled to room temperature and conditioned to the range of 7 to 12 percent moisture content. If specimens are tested hot, the percentage reductions due to permanent effects are 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 exposure periods of 1 month each as it would after a single 6-month exposure period.

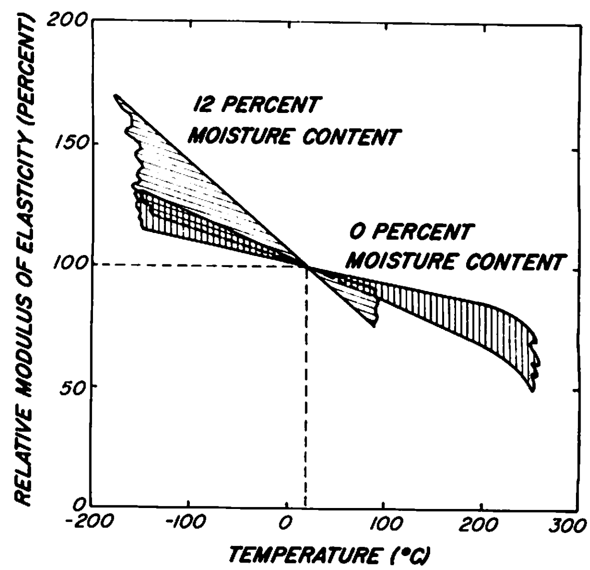

Figure 4−9—The immediate effect of temperature on modulus of elasticity parallel to the grain at two moisture contents relative to value at 20 °C. The plot is a composite of results from several studies. Variability in reported trends is illustrated by the width of bands. (ML84 5719)

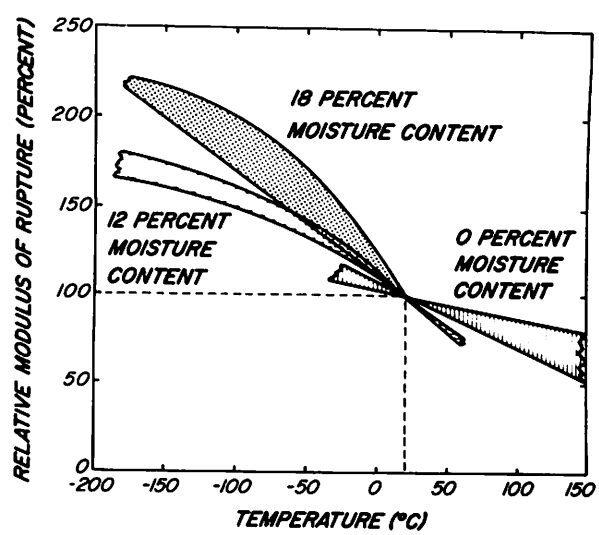

Figure 4−10—The immediate effect of temperature on modulus of rupture in bending at three moisture contents relative to value at 20 °C. The plot is a composite of results from several studies. Variability in reported trends is illustrated by the width. (ML84 5720)

The shape and size of wood pieces are important in analyz-

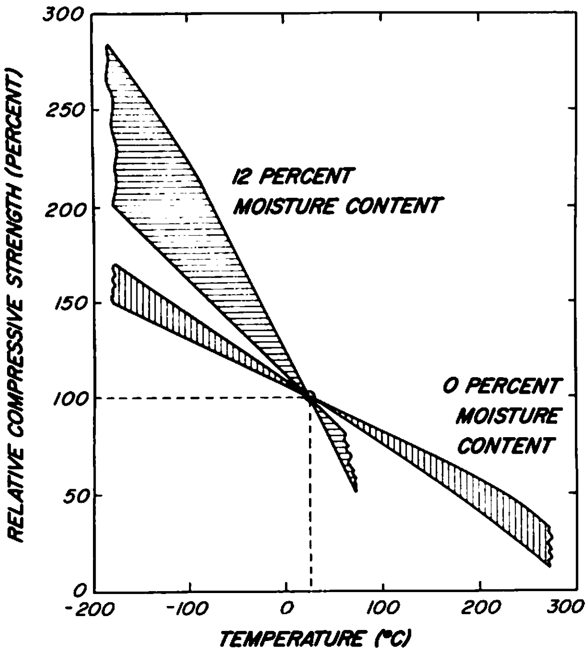

Figure 4–11—The immediate effect of temperature on compressive strength parallel to the grain at two moisture contents relative to value at 20 °C. The plot is a composite of results from several studies. Variability of reported trends is illustrated by the width of bands. (ML84 5721)

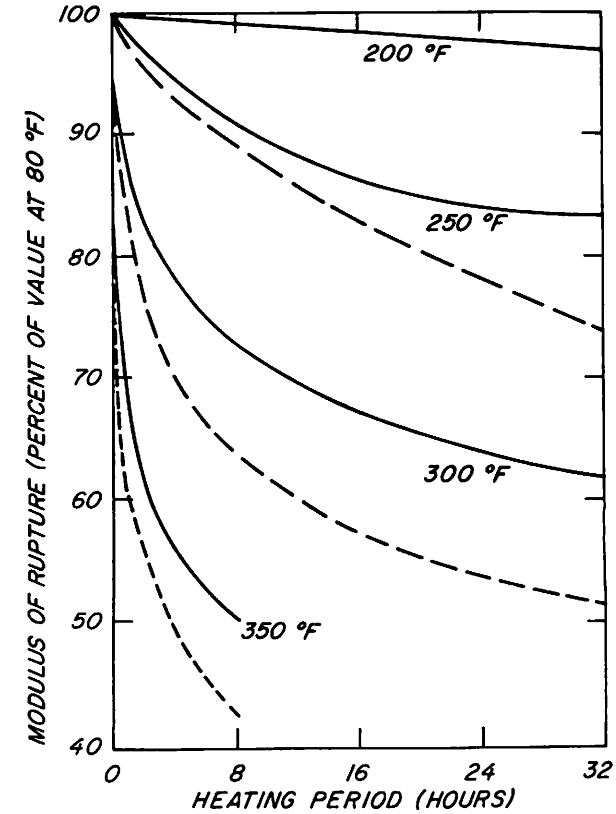

Figure 4–12—Permanent effect of heating in water (solid line) and in steam (dashed line) on the modulus of rupture. All data based on tests of Douglas-fir and Sitka spruce tested at room temperature. (M140 731)

ing the influence of temperature. If the 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 inner parts will be less than for outer parts. The type of loading must be considered however. If the member is to be stressed in bending, the outer fibers of a piece are 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, wood often will not reach the daily extremes in temperature of the air around it in ordinary construction; 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 given in tables 4–2, 4–3, and 4–4 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 minutes. Higher values of strength are obtained for wood loaded at more rapid rates and lower values are obtained at slower rates. For example, the load required to produce failure in a wood member in one second is approximately 10 percent higher than that obtained in a standard strength test. Over several orders of magnitude of rate of loading, strength is approximately an exponential function of rate.

Figure 4–16 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/Relaxation

When first loaded, a wood member deforms elastically. If the load is maintained, additional time-dependent deformation occurs. This is called creep. Even at very low stresses, creep takes place and can continue over a period of years. For sufficiently high loads, failure will eventually occur. This failure phenomenon, termed "duration of load," is discussed in the next section.

Table 4–12—***Approximate middle trend effects of temperature on mechanical properties of clear wood at various moisture conditions***

Property	Moisture condition	Relative change in mechanical property from 20 °C: At -50 °C	At +50 °C
		------ *Percent* ------	
Modulus of elasticity parallel to the grain	0	+11	−6
	12	+17	−7
	>FSP[1]	+50	—
Modulus of elasticity perpendicular to the grain	6	—	−20
	12	—	−35
	≧20	—	−38
Shear modulus	>FSP[1]	—	−25
Bending strength	≦4	+18	−10
	11–15	+35	−20
	18–20	+60	−25
	>FSP[1]	+110	−25
Tensile strength parallel to the grain	0–12	—	−4
Compressive strength parallel to the grain	0	+20	−10
	12–45	+50	−25
Shear strength parallel to the grain	>FSP[1]	—	−25
Tensile strength perpendicular to the grain	4–6	—	−10
	11–16	—	−20
	≧18	—	−30
Compressive strength perpendicular to the grain at the proportional limit	0–6	—	−20
	≧10	—	−35

[1] Moisture content higher than the fiber saturation point.

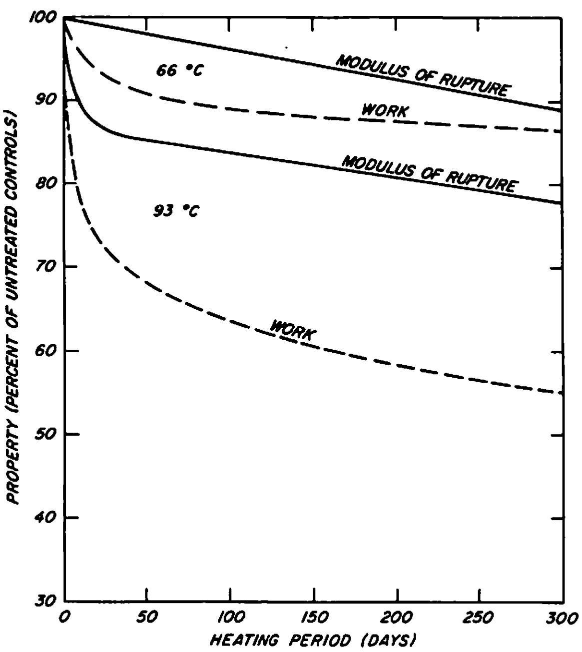

Figure 4–13—Permanent effect of heating in water on work to maximum load and on modulus of rupture. All data based on tests of Douglas-fir and Sitka spruce tested at room temperature. (M140 732)

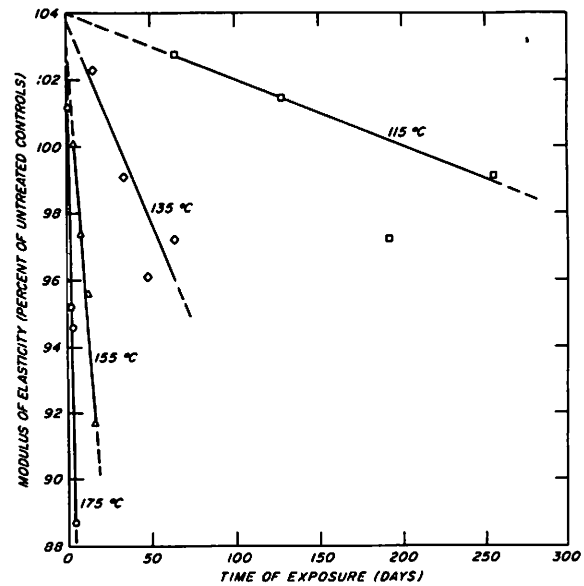

Figure 4–15—Permanent effect of oven heating at four temperatures on modulus of elasticity, based on four softwood and two hardwood species. All tests conducted at room temperature. (M140 727)

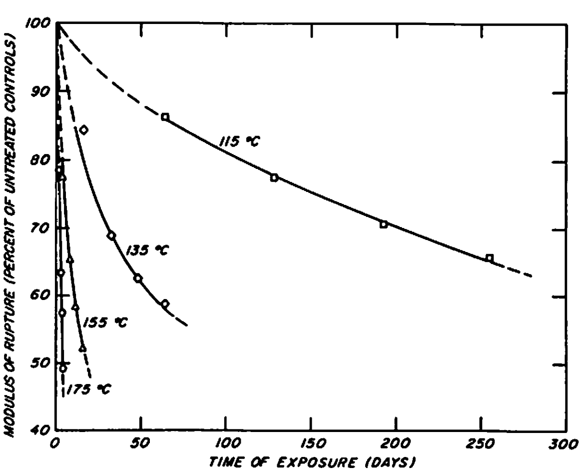

Figure 4–14—Permanent effect of oven heating at four temperatures on the modulus of rupture, based on four softwood and two hardwood species. All tests conducted at room temperature. (M140 726)

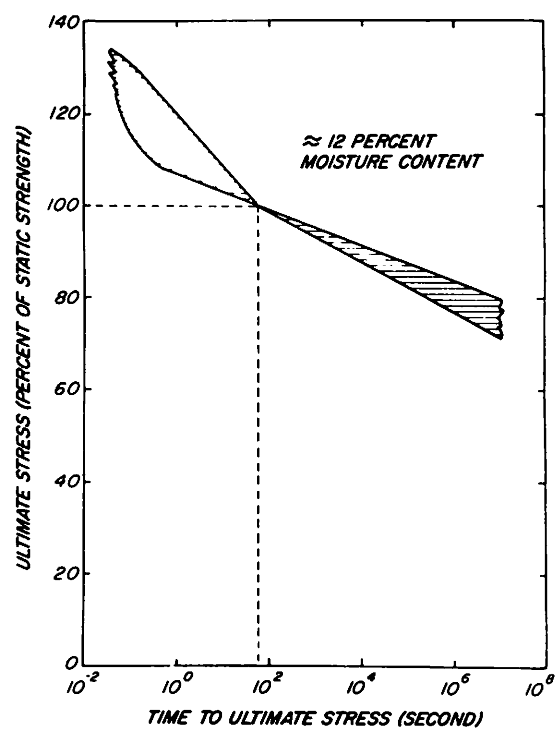

Figure 4–16—Relationship of ultimate stress at short time loading to that at 5-minute loading, based on a composite of results from rate of loading studies on bending, compression, and shear parallel to the grain. Variability in reported trends is indicated by width of band. (ML84 5722)

At typical design levels and use environments the additional deformation due to creep after several years 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 4−17; creep is greater under higher stresses than lower ones.

Ordinary climatic variations in temperature and humidity will cause creep to increase. An increase of about 50 °F in temperature can cause a twofold 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 an immediate and complete recovery of the original elastic deformation and, after time, a recovery of approximately one-half of the creep 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 percent of its original value within a few months. This reduction of stress with time is commonly termed "relaxation."

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

Duration of Stress

The duration of stress, 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 a member can safely carry. The duration of stress may be affected by changes in temperature and relative humidity.

The constant stress a wood member can sustain is approximately an exponential function of time to failure as illustrated in figure 4-18. The 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 of time, the load required to produce failure is much less than that determined from the strength properties in tables 4−2, 4−3, and 4−4. Based on figure 4−18, a wood mem-

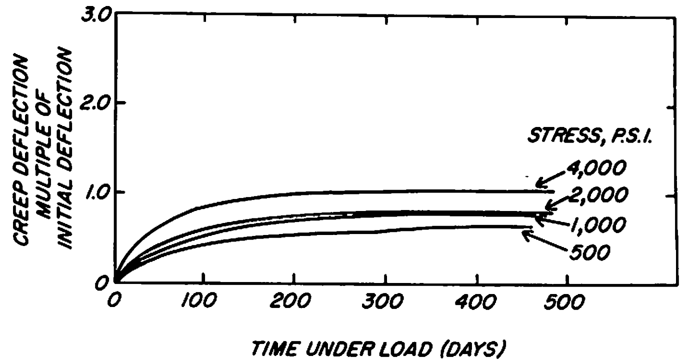

Figure 4−17—An illustration of creep as influenced by four levels of stress. (Adapted from Kingston.) (M140 725)

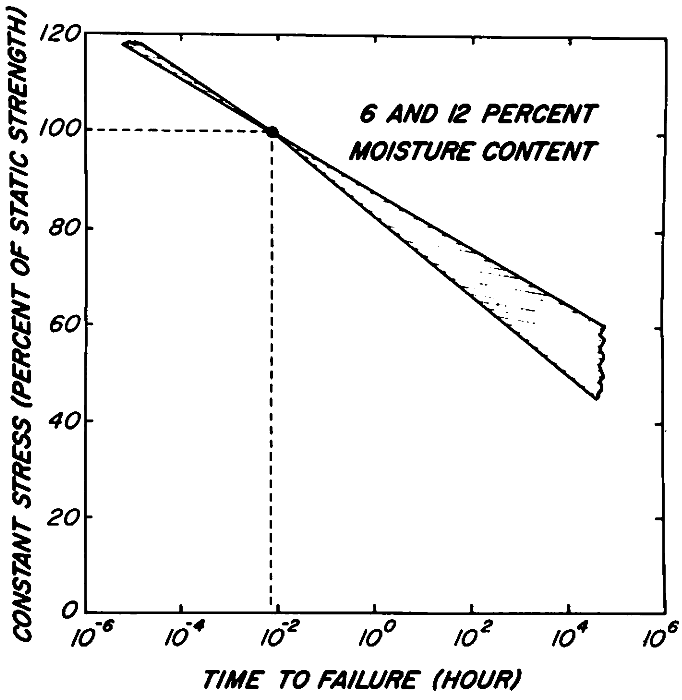

Figure 4−18—Relationship between stress due to constant load and time to failure for small clear wood specimens, based on 28 seconds' duration at 100 percent stress level. The figure is a composite of trends from several studies, mostly dealing with bending but with some on compression parallel to the grain and bending perpendicular to the grain. Variability in reported trends is indicated by the width of band. (ML84 5723) ber under the continuous action of bending stress for 10 years may carry only 60 percent (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 stress 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 continuously applied.

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 specimens of wood under large cyclic changes in temperature and relative humidity. Fortunately, changes in temperature and relative humidity in the typical service environment for wood are moderate.

Fatigue

The term "fatigue" in engineering 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, i.e. always compression or always tension) or reversed (stresses of alternating sign). When sufficiently high and repetitious enough, 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; whether the loading is repeated or reversed; range factor (ratio of minimum to maximum stress per cycle); and other factors such as temperature, moisture content and specimen size. Positive range ratios imply repeated loading while negative ratios imply reversed loading.

A summary of results from several fatigue studies on wood is given in table 4−13. Most of the results are for repeated loading with a range ratio of 0.1, meaning that the minimum stress per cycle is 10 percent of the maximum stress. The maximum stress per cycle, expressed as a percent 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, 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 8-1/3 hertz. 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 when wood contains a combination of both 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 is 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 to other properties. Little is known about other factors that may affect fatigue strength in wood.

Creep, temperature rise, and loss of moisture content occur in testing wood for fatigue strength. At stresses that cause failure in about 10^6 cycles at 40 hertz, temperature rises of 15 °C have been reported for compression parallel fatigue (range ratio slightly greater than zero), for tension parallel fatigue (range ratio = 0), and for reversed bending fatigue (range ratio = −1). The rate of temperature rise is high initially, but it then diminishes to a moderate rate which is maintained 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.

Age

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 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.

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 amount of swelling, and this loss is regained upon removal of the swelling liquid. Liquid ammonia markedly reduces the strength and stiffness of wood, but most of the reduction is regained upon removal of the ammonia.

Chemical solutions that decompose wood substance have a permanent effect on strength. The following generalizations summarize the effect of chemicals: (1) Some species are quite resistant to attack by dilute mineral and organic acids, (2) *oxidizing* acids such as nitric acid degrade wood more than nonoxidizing acids, (3) alkaline solutions are more destructive than acidic solutions, and (4) hardwoods are more susceptible to attack by both acids and alkalies than are softwoods. 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.

A general discussion of the resistance of wood to chemical degradation is given in chapter 3.

Wood Treatment With Chemicals

Wood products sometimes are treated with preservative or fire-retarding salts, usually in water solution, to impart resistance to decay or fire. Such products generally are kiln dried after treatment. At levels of preservative treatments required for underground or ground-contact service, mechanical properties are essentially unchanged except that work to maximum load, height of drop in impact bending, and toughness are reduced somewhat. Heavy salt treatments required for protection in marine environments may reduce bending

Table 4–13—*A summary of reported results on cyclic fatigue*[1]

Property	Range ratio	Cyclic frequency	Maximum stress per cycle, percentage of estimated static strength	Approximate fatigue life, 10^6 cycles
		Hz		
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	.1	8-1/3	60	2
Bending, third-point				
Small knots	.1	8-1/3	50	2
Clear, 1:12 slope of grain	.1	8-1/3	50	2
Small knots, 1:12 slope of grain	.1	8-1/3	40	2
Tension parallel to grain				
Clear, straight grain	.1	15	50	30
Clear, straight grain	0	40	60	3.5
Scarf joint	.1	15	50	30
Finger joint	.1	15	40	30
Compression parallel to grain				
Clear, straight grain	.1	40	75	3.5
Shear parallel to grain				
Glue laminated	.1	15	45	30

[1] Starting moisture contents about 12 to 15 percent.

strength by 10 percent or more and work properties by up to 50 percent. Further strength reduction may be observed if temperatures and pressures involved in treating and subsequent drying are not controlled within acceptable limits. See chapter 18 for details on treating conditions.

Strength properties are also affected to some extent by the combined effects of fire-retardant chemicals, treatment methods, and kiln drying. A variety of fire-retardant treatments have been studied. Collectively the studies indicate that modulus of rupture, work to maximum load, and toughness are reduced by varying amounts depending on species and type of fire retardant. Work to maximum load and toughness are most affected, with reductions of as much as 45 percent. A reduction in modulus of rupture of 20 percent has been observed; a design reduction of 10 percent is frequently used. Stiffness is not appreciably affected.

Wood is also sometimes impregnated with monomers, such as methyl methacrylate, which are subsequently polymerized. Many of the mechanical properties of the resulting 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 are variables that influence composite properties.

Nuclear Radiation

There are occasions when wood is subjected to nuclear radiation. Examples are wooden structures closely associated with nuclear reactors, or when nuclear radiation is used for polymerizing plastic impregnants in wood, or for 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 increases above 1 megarad, tensile strength parallel to grain and toughness decrease. At a dosage of 300 megarads, tensile strength is reduced about 90 percent. Gamma rays also affect compressive strength parallel to grain above 1 megarad, but strength losses with further dosage are less than for tensile strength. Only about one-third of the 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.

Molding and Staining Fungi

Molding and staining fungi do not seriously affect most mechanical properties of wood because they feed upon 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 weakening.

Though little loss in strength is encountered at the lower levels of biological staining, intense staining may reduce specific gravity by 1 to 2 percent, surface hardness by 2 to 10 percent, bending and crushing strength by 1 to 5 percent, and toughness or shock resistance properties by 15 to 30 percent.

Although molds and stains usually do not have major effects on strength, conditions that favor these organisms are also ideal for the development of wood-destroying or decay fungi and the soft-rot fungi (see ch. 17). Pieces containing mold and stain should be examined closely for decay if they are used for structural purposes.

Decay

Unlike molding and staining fungi, the wood-destroying (decay) fungi seriously reduce strength. These decay fungi metabolize the cellulose fraction of wood which 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 percent before a measurable weight loss is observed and before there are visible signs of decay. When weight loss reaches 5–10 percent, mechanical properties are reduced from 20–80 percent. Toughness, impact bending, and work to maximum load in bending are reduced most, shear and hardness the least, while other properties show an intermediate effect. Thus, when strength is important, adequate measures should be taken to (1) prevent decay before it occurs, (2) control incipient decay by remedial measures (see ch. 17), or (3) 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 percent 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 unseasoned or seasoned lumber. Damage in the standing tree is difficult to control, but otherwise insect damage can be largely eliminated by proper control methods.

Insect holes are generally classified as pinholes, grub holes, and powderpost holes. The powderpost larvae, by their irregular burrows, may destroy most of the interior of a piece, while the surface shows only small holes, 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, and, when strength is an important consideration, the safe procedure is to eliminate pieces containing insect holes.

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