6.7 WOOD

by Staff, Forest Products Laboratory, USDA Forest Service. Prepared under the direction of David W. Green

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COMPOSITION, STRUCTURE, AND NOMENCLATURE

by David W. Green

Wood is a naturally formed organic material consisting essentially of elongated tubular elements called cells arranged in a parallel manner for the most part. These cells vary in dimensions and wall thickness with position in the tree, age, conditions of growth, and kind of tree. The walls of the cells are formed principally of chain molecules of cellulose, polymerized from glucose residues and oriented as a partly crystalline material. These chains are aggregated in the cell wall at a variable angle, roughly parallel to the axis of the cell. The cells are cemented by an amorphous material called lignin. The complex structure of the gross wood approximates a rhombic system. The direction parallel to the grain and the axis of the stem is longitudinal (L), the two axes across the grain are radial (R) and tangential (T) with respect to the cylinder of the tree stem. This anisotropy and the molecular orientation account for the major differences in physical and mechanical properties with respect to direction which are present in wood.

Natural variability of any given physical measurement in wood approximates the normal probability curve. It is traceable to the difference in the growth of individual samples and at present cannot be controlled. For engineering purposes, statistical evaluation is employed for determination of safe working limits.

Lumber is classified as hardwood, which is produced by the broad-leafed trees (angiosperms), such as oak, maple, and ash; and softwood, the product of coniferous trees (gymnosperms), such as pines. larch, spruce, and hemlock. The terms *hard* and *soft* have no relation to the actual hardness of the wood. **Sapwood** is the living wood of pale color on the outside of the stem. **Heartwood** is the inner core of physiologically inactive wood in a tree and is usually darker, somewhat heavier, due to infiltrated material, and more decay-resistant than the sapwood. Other terms relating to wood, veneer, and plywood are defined in ASTM D 9, D 1038, and the "Wood Handbook."

Standard nomenclature of lumber is based on commercial practice which groups woods of similar technical qualities but separate botanical identities under a single name. For listings of domestic hardwoods and softwoods, see ASTM D 1165 and the "Wood Handbook.''

The chemical composition of woody cell walls is generally about 40 to 50 percent cellulose, 15 to 35 percent lignin, less than 1 percent mineral, 20 to 35 percent hemicellulose, and the remainder extractable matter of a variety of sorts. Softwoods and hardwoods have about the same cellulose content.

PHYSICAL AND MECHANICAL PROPERTIES OF CLEAR WOOD

by David W. Green, Robert White, Anton TenWolde, William Simpson, Joseph Murphy, and Robert Ross

Moisture Relations

Wood is a hygroscopic material which contains water in varying amounts, depending upon the relative humidity and temperature of the surrounding atmosphere. **Equilibrium conditions** are established as shown in Table 6.7.1. The standard reference condition for wood is oven-dry weight, which is determined by drying at 100 to 105°C until there is no significant change in weight.

Moisture content is the amount of water contained in the wood, usually expressed as a percentage of the mass of the oven-dry wood. Moisture can exist in wood as **free water** in the cell cavities as well as water **bound** chemically within the intermolecular regions of the cell wall. The moisture content at which cell walls are completely saturated but at which no water exists in the cell cavities is called the **fiber saturation point.** Below the fiber saturation point, the cell wall shrinks as moisture is removed, and the physical and mechanical properties begin to change as a function of moisture content. **Air-dry wood** has a moisture content of 12 to 15 percent. **Green wood** is wood with moisture content above the fiber saturation point. The moisture content of green wood typically ranges from 40 to 250 percent.

Dimensional Changes

Shrinkage or **swelling** is a result of change in water content within the cell wall. Wood is dimensionally stable when the moisture content is above the fiber saturation point (about 28 percent for shrinkage estimates). Shrinkage is expressed as a percentage of the dimensional change based on the green wood size. Wood is an anisotropic material with respect to shrinkage. **Longitudinal shrinkage** (along the grain) ranges from 0.1 to 0.3 percent as the wood dries from green to oven-dry and is usually neglected. Wood shrinks most in the direction of the annual growth rings **(tangential shrinkage)** and about one-half as much across the rings (radial shrinkage). Average shrinkage values for a number of commercially important species are shown in Table 6.7.2. Shrinkage to any moisture condition can be estimated by assuming that the change is linear from green to oven-dry and that about one-half occurs in drying to 12 percent.

Swelling in polar liquids other than water is inversely related to the size of the molecule of the liquid. It has been shown that the tendency to hydrogen bonding on the dielectric constant is a close, direct indicator of the swelling power of water-free organic liquids. In general, the strength values for wood swollen in any polar liquid are similar when there is equal swelling in the wood.

Swelling in aqueous solutions of sulfuric and phosphoric acids. zinc chloride, and sodium hydroxide above pH 8 may be as much as 25 percent greater in the transverse direction than in water. The transverse swelling may be accompanied by longitudinal shrinkage up to 5 percent. The swelling reflects a chemical change in the cell walls, and the accompanying strength changes are related to the degradation of the cellulose.

Dimensional stabilization of wood cannot be completely attained. Two or three coats of varnish, enamel, or synthetic lacquer may be 50 to 85 percent efficient in preventing short-term dimensional changes. Metal foil embedded in multiple coats of varnish may be 90 to 95 percent efficient in short-term cycling. The best long-term stabilization results from internal bulking of the cell wall by the use of materials such as phenolic resins polymerized in situ or water solutions of polyethylene glycol (PEG) on green wood. The presence of the bulking agents alters the properties of the treated wood. Phenol increases electrical resistance, hardness, compression strength, weight, and decay resistance but lowers the impact strength. Polyethylene glycol maintains strength values at the green wood level, reduces electric resistance, and can be finished only with polyurethane resins.

Mechanical Properties

Average **mechanical properties** determined from tests on clear, straight-grained wood at 12 percent moisture content are given in Table 6.7.2. Approximate standard deviation(s) can be estimated from

$$s = CX$$

where X is average value for species and

$$C = \begin{cases} 0.10 & \text{for specific gravity} \\ 0.22 & \text{for modulus of elasticity} \\ 0.16 & \text{for modulus of rupture} \\ 0.18 & \text{for maximum crushing strength parallel to grain} \\ 0.14 & \text{for compression strength perpendicular to grain} \\ 0.25 & \text{for tensile strength perpendicular to grain} \\ 0.25 & \text{for impact bending strength} \\ 0.10 & \text{for shear strength parallel to grain} \end{cases}$$

Relatively few data are available on tensile strength parallel to the grain. The modulus of rupture is considered to be a conservative estimate for the tensile strength of clear wood.

Mechanical properties remain constant as long as the moisture content is above the fiber saturation point. Below the fiber saturation point, properties generally increase with decreasing moisture content down to about 8 percent. Below about 8 percent moisture content, some properties, principally tensile strength parallel to the grain and shear strength, may decrease with further drying. An approximate adjustment for clear wood properties between about 8 percent moisture and green can be obtained by using an annual compound-interest type of formula

$$P_2 = P_1 \left(1 + \frac{C}{100}\right)^{-(M_2 - M_1)}$$

where P_1 is the known property at moisture content M_1, P_2 is the property to be calculated at moisture content M_2, and Cis the assumed percentage change in property per percentage change in moisture content. Values of P_1, at 12 percent moisture content are given in Table 6.7.2, and values of C are given in Table 6.7.3. For the purposes of property adjustment. green is assumed to be 23 percent moisture content. The formula should not be used with redwood and cedars. A more accurate adjustment formula is given in "Wood Handbook." Additional data and tests on green wood can be found in "Wood Handbook" and on the Web at www.fpl.fs.fed.us. Data on foreign species are given in "Tropical Timbers of the World."

Table 6.7.1 Moisture Content of Wood in Equilibrium with Stated Dry-Bulb Temperature and Relative Humidity

Temperature (dry-bulb)		Moisture content, % at various relative-humidity levels																			
°F	(°C)	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	98
30	−1.3	1.4	2.6	3.7	4.6	5.5	6.3	7.1	7.9	8.7	9.5	10.4	11.3	12.4	13.5	14.9	16.5	18.5	21.0	24.3	26.9
40	4.2	1.4	2.6	3.7	4.6	5.5	6.3	7.1	7.9	8.7	9.5	10.4	11.3	12.3	13.5	14.9	16.5	18.5	21.0	24.3	26.9
50	9.8	1.4	2.6	3.6	4.6	5.5	6.3	7.1	7.9	8.7	9.5	10.3	11.2	12.3	13.4	14.8	16.4	18.4	20.9	24.3	26.9
60	15	1.3	2.5	3.6	4.6	5.4	6.2	7.0	7.8	8.6	9.4	10.2	11.1	12.1	13.3	14.6	16.2	18.2	20.7	24.1	26.8
70	21	1.3	2.5	3.5	4.5	5.4	6.2	6.9	7.7	8.5	9.2	10.1	11.0	12.0	13.1	14.4	16.0	17.9	20.5	23.9	26.6
80	26	1.3	2.4	3.5	4.4	5.3	6.1	6.8	7.6	8.3	9.1	9.9	10.8	11.7	12.9	14.2	15.7	17.7	20.2	23.6	26.3
90	32	1.2	2.3	3.4	4.3	5.1	5.9	6.7	7.4	8.1	8.9	9.7	10.5	11.5	12.6	13.9	15.4	17.3	19.8	23.3	26.0
100	38	1.2	2.3	3.3	4.2	5.0	5.8	6.5	7.2	7.9	8.7	9.5	10.3	11.2	12.3	13.6	1.51	17.0	19.5	22.9	25.6
110	43	1.1	2.2	3.2	4.0	4.9	5.6	6.3	7.0	7.7	8.4	9.2	10.0	11.0	12.0	13.2	14.7	16.6	19.1	22.4	25.2
120	49	1.1	2.1	3.0	3.9	4.7	5.4	6.1	6.8	7.5	8.2	8.9	9.7	10.6	11.7	12.9	14.4	16.2	18.6	22.0	24.7
130	54	1.0	2.0	2.9	3.7	4.5	5.2	5.9	6.6	7.2	7.9	8.7	9.4	10.3	11.3	12.5	14.0	15.8	18.2	21.5	24.2
140	60	0.9	1.9	2.8	3.6	4.3	5.0	5.7	6.3	7.0	7.7	8.4	9.1	10.0	11.0	12.1	13.6	15.3	17.7	21.0	23.7
150	65	0.9	1.8	2.6	3.4	4.1	4.8	5.5	6.1	6.7	7.4	8.1	8.8	9.7	10.6	11.8	13.1	14.9	17.2	20.4	23.1
160	71	0.8	1.6	2.4	3.2	3.9	4.6	5.2	5.8	6.4	7.1	7.8	8.5	9.3	10.3	11.4	12.7	14.4	16.7	19.9	22.5
170	76	0.7	1.5	2.3	3.0	3.7	4.3	4.9	5.6	6.2	6.8	7.4	8.2	9.0	9.9	11.0	12.3	14.0	16.2	19.3	21.9
180	81	0.7	1.4	2.1	2.8	3.5	4.1	4.7	5.3	5.9	6.5	7.1	7.8	8.6	9.5	10.5	11.8	13.5	15.7	18.7	21.3
190	88	0.6	1.3	1.9	2.6	3.2	3.8	4.4	5.0	5.5	6.1	6.8	7.5	8.2	9.1	10.1	11.4	13.0	15.1	18.1	20.7
200	93	0.5	1.1	1.7	2.4	3.0	3.5	4.1	4.6	5.2	5.8	6.4	7.1	7.8	8.7	9.7	10.9	12.5	14.6	17.5	20.0
210	99	0.5	1.0	1.6	2.1	2.7	3.2	3.8	4.3	4.9	5.4	6.0	6.7	7.4	8.3	9.2	10.4	12.0	14.0	16.9	19.3
220	104	0.4	0.9	1.4	1.9	2.4	2.9	3.4	3.9	4.5	5.0	5.6	6.3	7.0	7.8	8.8	9.9		*	*	*
230	110	0.3	0.8	1.2	1.6	2.1	2.6	3.1	3.6	4.2	4.7	5.3	6.0	6.7	*	*	*	*	*	*	*
240	115	0.3	0.6	0.9	1.3	1.7	2.1	2.6	3.1	3.5	4.1	4.6	*	*	*	*	*	*	*	*	*
250	121	0.2	0.4	0.7	1.0	1.3	1.7	2.1	2.5	2.9	*	*	*	*	*	*	*	*	*	*	*
260	126	0.2	0.3	0.5	0.7	0.9	1.1	1.4	*	*	*	*	*	*	*	*	*	*	*	*	*
270	132	0.1	0.1	0.2	0.3	0.4	0.4	*	*	*	*	*	*	*	*	*	*	*	*	*	*

* Conditions not possible at atmospheric pressure.
SOURCE "Wood Handbook," Forest Products Laboratory, 1999.

Table 6.7.2 Strength and Related Properties of Wood at 12% Moisture Content (Average Values from Tests on Clear Pieces of 2 in x 2 in Cross Section per ASTM D 143)

Kind of wood	Specific gravity, oven-dry volume	Density at 12% m.c. lb/ft³	Shrinkage, % from green to oven-dry condition based on dimension when green: Rad.	Shrinkage: Tan.	Static bending: Modulus of rupture, lb/in²	Static bending: Modulus of elasticity, ×10³ lb/in²	Max crushing strength parallel to grain, lb/in²	Compression perpendicular to grain at proportional limit, lb/in²	Tensile strength perpendicular to grain, lb/in²	Impact bending, height of drop in inches for failure with 50-lb hammer	Shear strength parallel to grain, lb/in², avg of *R* and *T*	Hardness perpendicular to grain, lb, avg of *R* and *T*
Hardwoods												
Ash, white	0.60	42	4.9	7.8	15,400	1,740	7,410	1,160	940	43	1,910	1,320
Basswood	0.37	26	6.6	9.3	8,700	1,460	4,730	370	350	16	990	410
Beech	0.64	45	5.5	11.9	14,900	1,720	7,300	1,010	1,010	41	2,010	1,300
Birch, yellow	0.62	43	7.3	9.5	16,600	2,010	8,170	970	920	55	1,880	1,260
Cherry, black	0.50	35	3.7	7.1	12,300	1,490	7,110	690	560	29	1,700	950
Cottonwood, eastern	0.40	28	3.9	9.2	8,500	1,370	4,910	380	580	20	930	430
Elm, American	0.50	35	4.2	9.5	11,800	1,340	5,520	690	660	39	1,510	830
Elm, rock	0.63	44	4.8	8.1	14,800	1,540	7,050	1,230		56	1,920	1,320
Sweetgum	0.52	36	5.4	10.2	12,500	1,640	6,320	620	760	32	1,600	850
Hickory, shagbark	0.72	50	7.0	10.5	20,200	2,160	9,210	1,760		67	2,430	
Maple, sugar	0.63	44	4.8	9.9	15,800	1,830	7,830	1,470		39	2,330	1,450
Oak, red, northern	0.63	44	4.0	8.6	14,300	1,820	6,760	1,010	800	43	1,780	1,290
Oak, white	0.64	48	5.6	10.5	15,200	1,780	7,440	1.070	800	37	2,000	1,360
Poplar, yellow	0.42	29	4.6	8.2	10,100	1,580	5,540	500	540	24	1,190	540
Tupelo, black	0.50	35	4.2	7.6	9,600	1,200	5,520	930	500	22	1,340	810
Walnut, black	0.35	38	5.5	7.8	14,600	1,680	7,580	1,010	690	34	1,370	1,010
Softwoods												
Cedar, western red	0.32	23	2.4	5.0	7,500	1,110	4,560	460	220	17	990	350
Cypress, bald	0.46	32	3.8	6.2	10,600	1,440	6,360	730	300	24	1,900	510
Douglas, coast	0.48	34	4.8	7.6	12,400	1,950	7,230	800	340	31	1,130	710
Hemlock, eastern	0.40	28	3.0	6.8	8,900	1,20	5,410	650		21	1,060	500
Hemlock, western	0.45	29	4.2	7.8	11,300	1,630	7,200	550	340	26	1,290	540
Larch, western	0.52	38	4.5	9.1	13,000	1,870	7,620	930	430	35	1,360	830
Pine, red	0.46	31	3.8	7.2	11,000	1,630	6,070	600	460	26	1,210	560
Pine, ponderosa	0.40	28	3.9	6.2	9,400	1,290	5,320	580	420	19	1,130	460
Pine, eastern white	0.35	24	2.1	6.1	8,600	1,240	4,800	440	310	18	900	380
Pine, western white	0.38	27	4.1	7.4	9,700	1.460	5,040	470		23	1,040	420
Pine, shortleaf	0.51	36	4.6	1.7	13,100	1,750	7,270	820	470	33	1,390	690
Redwood	0.40	28	2.6	4.4	10,000	1,340	6,150	700	240	19	940	480
Spruce, sitka	0.40	28	4.3	7.5	10,200	1,570	5,610	580	370	25	1,150	510
Spruce, black	0.42	29	4.1	6.8	10,800	1,610	5,960	550		20	1,230	520

SOURCE: Tabulated from "Wood Handbook," Tropical Woods no. 95, and unpublished data from the USDA Forest Service, Forest Products Laboratroy.

Table 6.7.3 Functions Relating Mechanical Properties to Specific Gravity and Moisture Content of Clear, Straight-Grained Wood

	Specific gravity–strength relation*				Change for 1% change in moisture content, %
	Green wood		Wood at 12% moisture content		
	Softwood	Hardwood	Softwood	Hardwood	
Static bending					
Modulus of elasticity (10^6 lb/in^2)	$2.331G^{0.76}$	$2.02G^{0.72}$	$2.966G^{0.84}$	$2.398.G^{0.70}$	2.0
Modulus of rupture (lb/in^2)	$15{,}889G^{1.01}$	$17{,}209G^{1.16}$	$24{,}763G^{1.01}$	$24{,}850G^{1.13}$	4.0
Maximum crushing strength parallel to grain (lb/in^2)	$7{,}207G^{0.94}$	$7{,}111G^{1.11}$	$13{,}592G^{0.97}$	$11{,}033G^{0.89}$	6.0
Shear parallel to grain (lb/in^2)	$1{,}585G^{0.73}$	$2{,}5766^{1.24}$	$2{,}314G^{0.85}$	$3{,}174G^{1.13}$	3.0
Compression perpendicular to grain at proportional limit (lb/in^2)	$1{,}360G^{1.60}$	$2{,}678G^{2.48}$	$2{,}393G^{1.57}$	$3{,}128G^{2.09}$	5.5
Hardness perpendicular to grain (lb)	$1{,}399G^{1.41}$	$3{,}721G^{2.31}$	$1{,}931G^{1.50}$	$3{,}438G^{2.10}$	2.5

*The properties and values should be read as equations; e.g., modulus of rupture for green wood of softwoods = $15{,}889G^{1.01}$, where G represents the specific gravity of wood based on the oven-dry weight and the volume ai the moisture condition indicated.

Specific Gravity and Density

Specific gravity G_m of wood at a given moisture condition m is the ratio of the weight of the oven-dry wood W_o to the weight of water displaced by the sample at the given moisture condition w_m:

$$G_m = \frac{W_o}{w_m}$$

This definition is required because volume and weight are constant only under special conditions. The weight density of wood D (unit weight) at any given moisture content is the oven-dry weight plus the contained water divided by the volume of the piece at that same moisture content. Average values for specific gravity oven-dry and weight density at 12 percent moisture content are given in Table 6.7.2. Specific gravity of solid. dry wood substance based on helium displacement is 1.46, or about 91 lb/ft^3.

Convenion of weight density from one moisture condition to another can be accomplished by the following equation ("Standard Handbook for Mechanical Engineers," 9th ed., McGraw-Hill):

$$D_2 = D_1 \frac{100 + M_2}{100 + M_1 + 0.0135D_1(M_2 - M_1)}$$

where D_1 is the weight density, lb/ft^3, which is known for some moisture condition M_1; D_2 is desired weight density at moisture content M_2. Moisture contents M_1 and M_2 are expressed in percentage.

Specific gravity and strength properties vary directly in an exponential relationship $S = KG^N$. Table 6.7.3 gives values for K and the exponent N for various strength properties. The equation is based on more than 160 kinds of wood and yields estimated average values for wood in general. This relationship is the best general index to the quality of defect-free wood.

Load Direction and Relation to Grain of Wood

All strength properties vary with the orthotropic axes of the wood in a manner approximated by Hankinson's formula ("Wood Handbook")

$$N = \frac{PQ}{P\sin^2\theta + Q\cos^2\theta}$$

where N is allowable stress induced by a load acting at M angle to the grain direction, lb/in^2; P is allowable stress parallel to the grain, lb/in^2; Q is allowable stress perpendicular to the grain, lb/in^2; and q is angle between the direction of load and the direction of grain.

The deviation of the grain from the long axis of the member to which the load is applied is known as the slope of grain and is determined by measuring the length of run in inches along the axis for a 1-in deviation of the grain from the axis. The effect of grain slope on the important strength properties is shown in Table 6.7.4.

Rheological Properties

Wood exhibits viscoelastic characteristics. When first loaded, a wood member deforms elastically. If the load is maintained, additional time-dependent deformation occurs. Because of this time-dependent relation, the rate of loading is an important factor to consider in the testing and use of wood. For example, the load required to produce failure in 1 s is approximately 10 percent higher than that obtained in a standard 5-min strength test. Impact and dynamic measures of elasticity of small specimens are about 10 percent higher than those for static measures. Impact strengths are also affected by this relationship. In the impact bending test, a 50-lb (23-kg) hammer is dropped upon a beam from increasing heights until complete rupture occurs. The maximum height, as shown in Table 6.7.2, is for comparative purposes only.

Table 6.7.4 Strength of Wood Members with Various Grain Slopes as Percentages of Straight-Grained Members

Maximum slope of grain in member	Static bending: Modulus of rupture, %	Static bending: Modulus of elasticity, %	Impact bending: drop height to failure (50-lb hammer), %	Maximum crushing strength parallel to grain, %
Straight-grained	100	100	100	100
1 in 25	96	97	95	100
1 in 20	93	96	90	100
1 in 15	89	94	81	100
1 in 10	81	89	62	99
1 in 5	55	67	36	93

SOURCE: "Wood Handbook."

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** of wood is a complex function of temperature and moisture content. The value of internal friction, expressed by logarithmic decrement, ranges from 0.1 for hot, moist wood to less than 0.02 for hot, dry wood. Cool wood, regardless of moisture content, has an intermediate value.

The term ***fatigue*** in engineering is defined as progressive damage that occurs in a material subjected to cyclic loading. ***Fatigue life*** is a term used to define the number of cycles sustained before failure. Researchers at the USDA Forest Service Forest Products Laboratory have found that small cantilever bending specimens subjected to fully reversed stresses, at 30 Hz with maximum stress equal to 30 percent of estimated static strength and at 12 percent moisture content and 75°F(24°C), have a fatigue life of approximately 30 million cycles.

Thermal Properties

The coefficients of thermal expansion in wood vary with the structural axes. According to Weatherwax and Stamm *(Trans. ASTM* E 69, 1947, p. 421), the longitudinal coefficient for the temperature range + 150 to −50°Caverages 3.39×10^{6}/°C and is independent of specific gravity. Across the grain, for an average specific gravity oven-dry of 0.46, the radial coefficient α_r is 25.7×10^{6}/°C and the tangential α_t is 34.8×10^{6}/°C. Both α_r and α_t vary with specific gravity approximately to the first power. Thermal expansions are usually overshadowed by the larger dimensional changes due to moisture.

Thermal conductivity of wood varies principally with the direction of heat with respect to the grain. Approximate transverse conductivity can be calculated with a linear equation of the form

$$k + G(B + CM) + A$$

where G is specific gravity, based on oven-dry weight and volume at a given moisture content M percent; for specific gravities above 0.3, temperatures around 75°F (24°C), and moisture contents below 25 percent, the values of constants A, B, and C are $A = 0.129$, $B = 1.34$, and $C = 0.028$ in English units, with k in Btu · in/(h · ft^2 · F) (TenWolde et al., 1988). Conductivity in watts per meter per kelvin is obtained by multiplying the result by 0.154. The effect of temperature on thermal conductivity is relatively minor and increases about 1 to 2 percent per 10°F (2, to 3 percent per 10°C). Longitudinal conductivity is considerably greater than transverse conductivity, but reported values vary widely. It has been reported as 1.5 to 2.8 times larger than transverse conductivity, with an average of about 1.8.

Specific heat of wood is virtually independent of specific gravity and varies principally with temperature and moisture content. Wilkes found that the approximate specific heat of dry wood can be calculated with

$$c_{p0} = a_0 + a_1 T$$

where $a_0 = 0.26$ and $a_1 = 0.000513$ for English units (specific heat in Btu per pound per degree Fahrenheit and temperature in degrees Fahrenheit) or $a_0 = 0.103$ and $a_1 = 0.00387$ for SI units [specific heat in kJ/(kg · K) and temperature in kelvins]. The specific heat of moist wood can be derived from

$$c_p = \frac{c_{p0} + 0.01Mc_{p,w}}{1 + 0.01M} + A$$

where $c_{p,w}$ is the specific heat of water [1 Btu/(lb · °F)], or 4.186 kJ/(kg · K). M is the moisture content (percent), and A is a correction factor, given by

$$A = M(b_1 + b_2T + b_3M)$$

with $b_1 = -4.23 \times 10^{4}$, $b_2 = 3.12 \times 10^{5}$, and $b_3 = -3.17 \times 10^{5}$ in English units: and $b_1 = -0.06191$, $b_2 = 2.36 \times 10^{4}$, and $b_3 = -1.33 \times 10^{-4}$ in SI units. These formulas are valid for wood below fiber saturation at temperatures between 45°F(7°C) and 297°F(147°C). And T is the temperature at which c_{p0}, is desired.

The fuel value of wood depends primarily upon its dry density, moisture content, and chemical composition. Moisture in wood decreases the fuel value as a result of latent heat absorption of water vaporization. An approximate relation for the fuel value of moist wood (Btu per pound on wet weight basis) (2,326 Btu/lb = 1 Jkg) is

$$H_w = H_D\left(\frac{100 - u/7}{100 + u}\right)$$

where H_D is higher fuel value of dry wood, averaging 8,500 Btu/lb for hardwoods and 9,000 Btu/lb for conifers, and u is the moisture content in percent. The actual fuel value of moist wood in a furnace will be less since water vapor interferes with the combustion process and prevents the combustion of pyrolytic gases. (See Sec. 7 for fuel values and Sec. 4 for combustion.)

Wood undergoes thermal degradation to volatile gases and char when it is exposed to elevated temperature. When wood is directly exposed to the standard tire exposure of ASTM E 119, the **char rate** is generally considered to be 1 $^1/_2$ in/h (38 mm/h). The temperature at the base of the char layer is approximately 550°F (300°C). A procedure for calculating the fire resistance rating of an exposed wood member can be found in recent editions of "National Design Specification" (American Forest & Paper Association, 2005 and later). Among other factors, the ignition of wood depends on the intensity and duration of exposure to elevated temperatures. Typical values for rapid ignition are 570 to 750°F (300 to 400°C). In terms of heat flux, a surface exposure to 1.1 Btu/ft^2(l3 kW/m^2) per second is considered sufficient to obtain piloted ignition. Recommended "maximum safe working temperatures" for wood exposed for prolonged periods range from 150 to 212°F(65 to 100°C). **Flame spread** values as determined by ASTM E 84 generally range from 65 to 200 for nominal 1-in- (25-mm-) thick lumber. Lists of flame spread index values for different species can be found in "Wood Handbook" and the Website of the American Wood Council. Flame spread can be reduced by impregnating the wood with fire-retardant chemicals or applying a fire-retardant coating.

The **reversible effect of temperature** on the properties of wood is a function of the change in temperature, moisture content of the wood, duration of heating, and property being considered. In general, the mechanical properties of wood decrease when the wood is heated above normal temperatures and increase when it is cooled. The magnitude of the change is greater for green wood than for dry. When wood is frozen, the change in property is reversible; i.e., the property will return to the value at the initial temperature. At constant moisture content and below about 150°F (65°C), mechanical properties are approximately linearly related to temperature. The change in property is also reversible if the wood is heated for a short time at temperatures below about 150°F. Table 6.7.5 lists the changes in properties at −58°F(−50°C) and 122°F (50°C) relative to those at 68°F (20°C).

Permanent loss in properties occurs when wood is exposed to higher temperatures for prolonged periods and then is cooled and tested at normal temperatures. If the wood is tested at a higher temperature after prolonged exposure, the actual strength loss is the sum of the reversible and permanent losses in properties. Permanent losses are higher for heating in steam than in water, and higher when heated in water than when heated in air. Repeated exposure to elevated temperatures is assumed to have a cumulative effect on wood properties. For example, at a given temperature the property loss will be about the same after six exposure of 1-year duration as it would be after a single exposure of 6 years. Figure 6.7.1 illustrates the effect of heating at l50°F(65°C) at 12 percent moisture content on the modulus of rupture relative to the strength at normal temperatures for spruce-pine-fir, Douglas-fir, and southern pine 2 × 4 s. Over the 6-year period, there was little or no change in the modulus of elasticity. Increasing the temperature would be expected to increase the permanent loss in strength; reducing the relative humidity would decrease the loss (see Green et al., 2003).

Electrical Properties

The important electrical properties of wood are **conductivity** (or its reciprocal, **resistivity**), **dielectric constant,** and **dielectric power factor** (see James, 1988).

Table 6.7.5 Approximate Middle-Trends for the Reversible Effect of Temperature on Mechanical Properties of Clear Wood at Various Moisture Conditions

Property	Moisture condition, %	Relative change in mechanical property from 68°F, % At −58°F	 At + 122°F
Modulus of elasticity parallel to grain	0	+11	−6
	12	+17	−7
	>FSP*	+50	-
Modulus of rupture	≤4	+18	-10
	11−15	+35	-20
	18−20	+60	-25
	>FSP*	+110	−25
Tensile strength parallel to grain	0−12	-	−4
Compressive strength parallel to grain	0	+20	−10
	12–45	+50	-25
Shear strength parallel to grain	>FSP*	-	−25
Compressive strength perpendicular to grain at proportional limit	0−16	-	-20
	≥10	-	-35

*Moisture content higher than the fiber saturation point (FSP).
$T_C = (T_F - 32)(0.55)$.

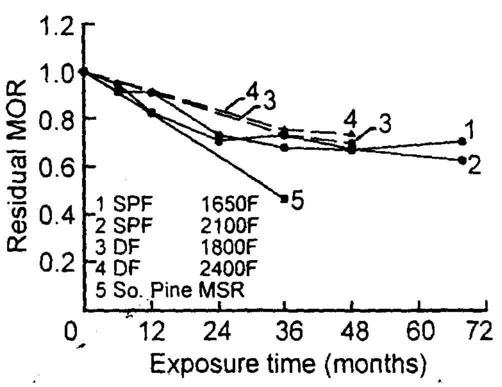

Fig. 6.7.1 Average residual MOR for solid-sawn 2 × 4 lumber exposed for various times at 66°C (150°F). 75 percent relative humidity and tested at 23°C (73°F). 67 percent relative humidity. DF. Douglas-fir; So. Pine, southern pine; SPF, spruce−pine−fir.

Resistivity approximately doubles for each 10°C decrease in temperature. As moisture content increases from zero to the fiber saturation point (FSP), the resistivity decreases by 10^{10} to 10^{13} times in an approximately linear relationship between the logarithm resistivity and moisture content. The resistivity is about 10^{14} to 10^{16} W · m for oven-dry wood and 10^3 to 10^4 W · m for wood at FSP. As the moisture content increases up to complete saturation, the decrease in resistivity is a factor of only about 50. Wood species also affect resistivity (see James), and the resistivity perpendicular to the grain is about twice that parallel to the grain. Water-soluble salts (some preservatives and tire retardants) reduce resistivity by only a minor amount when the wood has 8 percent moisture content or less, but they have a much larger effect when moisture content exceeds 10 to 12 percent.

The **dielectric constant** of oven-dry wood ranges from about 2 to 5 at room temperature, and it decreases slowly with increasing frequency. The dielectric constant increases as either temperature or moisture content increases. There is a negative interaction between moisture and frequency: At 20 Hz, the dielectric constant may range from 4 for dry wood to 106 for wet wood; at 1 kHz, from 4 dry to 5,000 wet; and at 1 MHz, from about 3 dry to 100 wet. The dielectric constant is about 30 percent greater parallel to the grain than perpendicular to it.

The **power factor** of wood varies from about 0.01 for dry, low-density woods to as great as 0.95 for wet, high-density woods. It is usually greater parallel to the grain than perpendicular. The power factor is affected by complex interactions of frequency, moisture content, and temperature (James, 1975).

The change in electrical properties of wood with moisture content has led to the development of moisture meters for nondestructive estimation of moisture content. Resistance-type meters measure resistance between two pins driven into the wood. Dielectric-type meters depend on the correlation between moisture content and either dielectric constant or power factor, and they require only contact with the wood surface, not penetration.

Wood in Relation to Sound

Transmission of sound and the vibrational properties in wood are functions of a variety of factors. The speed of sound transmission is described by the expression $v = \sqrt{E/\rho}$, in which v is the speed of sound in wood. ins; E is the dynamic Young's modulus, lb/in^2; and p is the density of the wood. slugs/in^3 (Pellerin and Rossn 2002). Various factors influence the speed of sound transmission; two of the most important factors are grain angle and the presence of degradation from decay. Hankinson's formula, cited previously, adequately describes the relationship between speed of sound transmission and grain angle. The dynamic modulus is about 10 percent higher than the static value and varies inversely with moisture changes by approximately 1.3 percent for each percentage change in moisture content.

Degradation from biological agents can significantly alter the speed at which sound travels in wood. Speed of sound transmission values are greatly reduced in severely degraded wood members. Sound transmission characteristics of wood products are used in one form of nondestructive testing to assess the performance characteristics of wood products. Because speed of sound transmission is a function of the extent of degradation from decay, this technique is used to estimate the extent of severe degradation in large timbers.

PROPERTIES OF LUMBER PRODUCTS

by Roland Hernandez and David W. Green

Visually Graded Structural Lumber

Stress-graded structural lumber is produced under two systems: visual grading and machine grading. Visual structural grading is the oldest stress grading system. It is based on the premise that the mechanical properties of lumber differ from those of clear wood because many growth characteristics of lumber affect its properties: these characteristics can be seen and judged by eye (ASTM D 245). The principal growth feature affecting lumber properties are the size and location of knots, sloping grain, and density.

Grading rules for lumber nominally 2 to 4 in (standard 38 to 89 mm) thick (dimension lumber) are published by grading agencies (listing and addresses are given in “National Design Specification,” American Forest & Paper Association, 2005 and later). For most species, allowable properties are based on test results from full-size specimens graded by agency rules, sampled according to ASTM D 2915, and tested according to ASTM D 4761. Procedures for deriving allowable properties from these tests are given in ASTM D 1990. Allowable properties for visually graded hardwoods and a few softwoods are derived from clear-wood data following principles given in ASTM D 2555. Derivation of the allowable strength properties accounts for within-species variability by starting with a nonparametric estimate of the 5th percentile of the data. Thus, 95 of 100 pieces would be expected to be stronger than the assigned property. The allowable strength properties are based on an assumed normal duration of load of 10 years. Tables 6.7.6 and 6.7.7 show the grades and allowable properties for the four most commonly used species groupings sold in the United States. The allowable strength values in bending, tension, shear, and compression parallel to the grain can be multiplied by factors for other load durations. Some commonly used factors are 0.90 for permanent (50-years) loading, 1.15 for snow loads (2 months), and 1.6 for wind/earthquake loading (10 min). The most recent edition of “National Design Specification” should be consulted for updated property values and for property values for other species and size classifications.

Allowable properties are assigned to visually graded lumber at two moisture content levels: green and 19 percent maximum moisture content (assumed 15 percent average moisture content). Because of the influence of knots and other growth characteristics on lumber properties, the effect of moisture content on lumber properties is generally less than its effect on clear wood. The C_M factors of Table 6.7.8 are for adjusting the properties in Tables 6.7.6 and 6.7.7 from 15 percent moisture content to green. The Annex of ASTM D 1990 provides formulas that can be used to adjust lumber properties to any moisture content between green and 10 percent. Below about 8 percent moisture content, some properties may decrease with decreasing values, and care should be exercised in these situations (Green and Kretschmann, 1995).

Shrinkage in commercial lumber differs from that in clear wood primarily because the grain in lumber is seldom oriented in purely radial and tangential directions. Approximate formulas used to estimate shrinkage of lumber for most species are

$$S_w = 6.031 - 0.215M$$
$$S_t = 5.062 - 0.181M$$

where S_w is the shrinkage across the wide [8-in (203-mm)] face of the lumber in a 2 × 8 (standard 38 × 184 mm), S_t is the shrinkage across the narrow [2-in(51-mm)] face of the lumber, and M is moisture content (percent). As with clear wood, shrinkage is assumed to occur below a moisture content of 28 percent. Because extractives make wood less

Table 6.7.6 Base Design Values for Visually Graded Dimension Lumber*
(Tabulated design values are for normal load duration and dry service conditions)

Species and Commercial grade	Size classification, in	Design values, lb/in² Bending F_b	Tension parallel to grain F_t	Shear parallel to grain F_v	Compression perpendicular to grain $F_{c\perp}$	Compression parallel to grain F_c	Modulus of elasticity E	Grading rules agency
				Douglas-fir–Larch				
Select structural		1,500	1,000	180	625	1,700	1,900,000	WCLIB
No. 1 and better	2–4thick	1,200	800	180	625	1,550	1,800,000	WWPA
No. 1		1,000	675	180	625	1,500	1,700,000	
No. 2	2 and wider	900	575	180	625	1,350	1,600,000	
No. 3		525	325	180	625	775	1,400,000	
Stud		700	450	180	625	850	1,400,000	
Construction	2-4 thick	1,000	650	180	625	1,650	1,500,000	
Standard		575	375	180	625	1,400	1,400,000	
Utility	2–4wide	275	175	I80	625	900	1,300,000	
				Hem–Fir				
Select structural		1,400	925	150	405	1,500	1,600,000	WCLIB
No. 1 and better	2–4 thick	1,100	725	150	405	1,350	1,500,000	WWPA
No. 1		975	625	150	405	1,350	1,500,000	
No. 2	2 and wider	850	525	150	405	1,300	1,300,000	
No. 3		500	300	150	405	725	1,200,000	
Stud		675	400	150	405	800	1,200,000	
Construction	2–4 thick	975	600	150	405	1,550	1,300,000	
Standard		550	325	150	405	1,300	1,200,000	
Utility	2–4 wide	250	150	150	405	850	1,100,000	
				Spruce–Pine–Fir				
Select structural	2–4 thick	1,250	700	135	425	1,400	1,500,000	NLGA
No. 1 - No. 2		875	450	135	425	1,150	1,400,000	
No. 3	2 and wider	500	250	135	425	650	1,200,000	
Stud		675	350	135	425	725	1,200,000	
Construction	2–4thick	1,000	500	135	425	1,403	1,300,000	
Standard		550	275	135	425	1,150	1,200,000	
Utility	2–4wide	275	125	I35	425	750	1,100,000	

*Lumber dimensions: Tabulated design values are applicable to lumber that will be used under dry conditions such as in most covered structures. For 2- to 4-in-thick, lumber, the dry dressed sizes shall be used regardless of the moisture content at the time of manufacture or use. In calculating design values, the natural gain in strength and stiffness that occurs as lumber dries has been taken into consideration as well as the reduction in size that occurs when unseasoned lumber shrinks. The gain in load-carrying capacity due to increased strength and stiffnes resulting from drying more then offsets the design effect of size reductions due to shrinkage. Size factor C_F, flat-use factor C_{fu}, and wet-use factor C_M are given in Table 6.7.8

SOURCE: Table used by permission of the American Forest & Paper Association, Washington, DC.

Table 6.7.7 Design values for Visually Graded Southern Pine Dimension Lumber*
(Tabulated design values are for normal load duration and dry services conditions)

		Design values, lb/in²						
Commercial grade	Size classification, in	Bending F_b	Tension parallel to grain F_t	Shear parallel to grain F_v	Compression perpendicular to grain $F_{c\perp}$	Compression parallel to grain F_c	Modulus of elasticity E	Grading ruler agency
Dense select structural	2–4 thick	3,050	1,650	175	660	2,250	1,900,000	SPIB
Select structural		2,850	1,600	175	565	2,100	1,800,000	
Nondense select structural	2–4 wide	2,650	1,350	175	480	1,950	1,700,000	
No. 1 dense		2,000	1,100	175	660	2,000	1,800,000	
No. 1		1,850	1,050	175	565	1,850	1,700,000	
No. 1 nondense		1,700	900	175	480	1,700	1,600,000	
No. 2 dense		1,700	875	175	660	1,850	1,700.000	
No. 2		1,500	825	175	656	1,650	1,600,000	
No. 2 nondense		1,350	775	175	480	1,600	1,400,000	
No. 3 and stud		850	475	175	565	975	1,400,000	
Construction	2–4 thick	1,100	625	175	565	1,800	1,500,000	
Standard		625	350	175	565	1,500	1,300,000	
Utility	4 wide	300	175	175	565	975	1,300,000	
Dense select structural	2–4 thick	2,700	1,500	175	660	2,150	1,900,000	
Select structural		2,550	1,400	175	565	2,000	1,800,000	
Nondense select structural	5-6 wide	2,350	1,200	175	480	1,850	1,700,000	
No. 1 dense		1,750	950	175	660	1,900	1,800,000	
No. 1		1,650	900	175	565	1,750	1,700,000	
No. 1 nondense		1,500	800	175	180	1,600	1,600,000	
No. 2 dense		1,150	775	175	660	1,750	1,700,000	
No. 2		1,250	725	175	565	1,600	1,600,000	
No. 2 nondense		1,150	675	175	480	1,500	1,400,000	
No. 3 and stud		750	125	175	565	925	1,400,000	
Dense select structural	2–4 thick	2,450	1,350	175	660	2,050	1,900,000	
Select structural		2,300	1,300	175	565	1,900	1,800,000	
Nondense select structural	8 wide	2,100	1,100	175	480	1,750	1,700,000	
No. 1 dense		1,650	875	175	660	1,800	1,800,000	
No. 1		1,500	825	175	565	1,650	1,700,000	
No. 1 nondense		1,350	725	175	480	1,550	1,600,000	
No. 2 dense		1,400	675	175	660	1,700	1,700,000	
No. 2		1,200	650	175	565	1,550	1,600,000	
No. 2 nondense		1,100	600	175	480	1,450	1,400,000	
No. 3 and stud		700	400	175	565	875	1,400,000	
Dense select structural	2–4 thick	2,150	1,200	175	660	2,000	1,900,000	
Select structural		2,050	1,100	175	565	1,850	1,800,000	
Nondense select structural	10 wide	1,850	950	175	480	1,750	1,700,000	
No. 1 dense		1,450	775	175	660	1,750	1,800,000	
No. 1		1,300	725	175	565	1,600	1,700,000	
No. 1 nondense		1,200	650	175	480	1,500	1,600,000	
No. 2 dense		1,200	625	175	660	1,650	1,700,000	
No. 2		1,050	575	175	565	1,500	1,600,000	
No. 2 nondense		950	550	175	480	1,400	1,400,000	
No. 3 and stud		600	325	175	565	850	1,400,000	
Dense select structural	2–4 thick	2,050	1,100	175	660	1,950	1,900,000	
Select structural		1,900	1,050	175	565	1,800	1,800,000	
Nondense select structural	12 wide	1,750	900	175	480	1,700	1,700,000	
No. 1 dense		1,350	725	175	660	1,700	1,800,000	
No. 1		1,250	675	175	565	1,600	1,700,000	
No. 1 nondense		1,150	600	90	480	1,500	1,600,000	
No. 2 dense		1,150	575	90	660	1,600	1,700,000	
No. 2		975	550	90	565	1,450	1,600,000	
No. 2 nondense		900	525	90	480	1,350	1,100,000	
No. 3 and stud		575	325	90	565	825	1,400,000	

*For size factor C_F appropriate size adjustment factors have already been incorporated in the tabulated design values for most thicknesses of southern pine dimension lumber. For dimension lumber 4 in thick, 8 in and wider, tabulaled bending design values F_b shall be permitted to be multiplied by the size factor $C_F = 1.1$. For dimension lumber wider than 12 in, tabulated bending, tension, and compression parallel-to-grain design values for 12-in-wide lumber shall be multiplied by the size factor $C_F = 0.9$. Repetive member factor C_r, flat-use factor C_{fu}, and wet-service factor C_M are given in Table 6.7.8.

SOURCE: Table used by permission of the American Forest & Paper Association, Washington, DC.

Table 6.7.8 Adjustment Factors

Size factor C_F for Table 6.7.6 (Douglas-Fir-Larch, Hem-Fir, Spruce-Pine-Fir)

Tabulated bending, tension, and compression parallel to grain design values for dimension lumber 2 to 4 in thick shall be multiplied by the following size factors:

		F_b thickness, in			
	Width, in	2 & 3	4	F_t	F_c
Select Structural	2, 3, and 4	1.5	1.5	1.5	1.15
No. 1 and better	5	1.4	1.4	1.4	1.1
No. 1, no. 2, no. 3	6	1.3	1.3	1.3	1.1
	8	1.2	1.3	1.2	1.05
	10	1.1	1.2	1.1	1.0
	12	1.0	1.1	1.0	1.0
	14 and wider	0.9	1.0	0.9	0.9
Stud	2, 3, and 4	1.1	1.1	1.1	1.05
	5 and 6	1.0	1.0	1.0	1.0
Construction and standard	2, 3, and 4	1.0	1.0	1.0	1.0
Utility	4	1.0	1.0	1.0	1.0
	2 and 3	0.4	—	0.4	0.6

Repetitive-member factor C_r for Tables 6.7.6 and 6.7.7

Bending design values F_b for dimension lumber 2 to 4 in thick shall be multiplied by the repetitive factor C_r = 1.15, when such members are used as joists, truss chords, rafters, studs, planks, decking, or similar members which are in contact or spaced not more than 24 in on centers, are not less than 3 in number, and are joined by floor, roof, or other load-distributing elements adequate 10 support the design load.

Flat-use factor C_{fu} for Tables 6.7.6 and 6.7.7

Bending design values adjusted by size factors are based on edgewise use (load applied to narrow face). When dimension lumber is used flatwise (load applied to wide face), the bending design value F_b shall also be multiplied by the following flat-use factors:

	Thickness, in	
Width. in	2 and 3	4
2 and 3	1.0	—
4	1.1	1.0
5	1.1	1.05
6	1.15	1.05
8	1.15	1.05
10 and wider	1.2	1.1

Wet-use factor C_M for Tables 6.7.6 and 6.7.7

When dimension lumber is used where moisture content will exceed 19 percent for an extended period, design values shall be multiplied by the appropriate wet-service factors from the following table:

F_b	F_t	Fv	$F_{c\perp}$	F_c	E
0.85*	1.0	0.97	0.67	0.8†	0.9

*When $F_bC_F \leq 1150$ lb/in², $C_M = 1.0$.
†When $F_cC_F \leq 750$ lb/in², $C_M = 1.0$.
SOURCE: Used by permission of the American Forest & Paper Association, Washington, DC.

hygroscopic, less shrinkage is expected in redwood, western redcedar, and northern white cedar (Green, 1989).

The reversible effect of temperature on lumber properties appears to be similar to that on clear wood. For simplicity, "National Design Specification" uses conservative factors to account for reversible reductions in properties as a result of heating to 150°F(65°C) or less (Table 6.7.9). No increase in properties is taken for temperatures colder than normal because in practice it is difficult to ensure that the wood temperature remains consistently low. Permanent effects of temperature are not given in "National Design Specification" (see Green et al., 2003).

Table 6.7.9 Temperature Factors C_t for Short-term Exposure (Reversible Effect)

Design values	In-service moisture conditions	C_t: T ≤ 100°F	C_t: 100°F < T ≤ 125°F	C_t: 125°F < T ≤ 150°F
E_t, E	Green or dry	1.0	0.9	0.9
Fb, Fv, Fc, and $F_{c\perp}$	≤ 19% green	1.0	0.8	0.7
		1.0	0.7	0.5

SOURCE: Used by permission of the American Forest & Paper Association, Washington, DC

Mechanically Graded Structural Lumber

Machine-stress-rated (MSR) lumber and machine-evaluated lumber (MEL) are two types of mechanically graded lumber. The three basic components of both mechanical grading systems are (1) sorting and prediction of strength through machin-measured nondestructive determination of properties coupled with visual assessment of growth characteristics, (2) assignment of allowable properties based upon strength prediction, and (3) quality control to ensure that assigned properties are being obtained. Grade names for MEL start with and M designation. Grade “names” for MSR lumber are a combination of the allowable bending stress and the average modulus of elasticity; e.g., 1650f-1.4E means an allowable bending stress of 1,650 lb/in2 (11.4 MPa) and modulus of elasticity of 1.4 × 106 lb/in2 (9.7 GPa). Selected grades of mechanically graded lumber and their allowable properties are given in Table 6.7.10. Additional grades are avalable (see AF&PA, 2005).

Structural Composite Lumber

Types of Structural Composite Lumber Structural composite lumber- refers to several types of reconstituted products that have been developed to meet the demand for high-quality material for the manufacture of engineered wood products and structures. Two distinct types are commercially availble: laminated veneer lumber (LVL) and parallel strand lumber (PSL).

Laminated veneer lumber is manufactured from layers of veneer with the grain of all the layers parallel. This contrasts with plywood, which consists of adjacent layers of the grain perpendicular. Most manufacturers use sheets of $^1/_{10}$- to $^1/_6$-in- (2.5- to 4.2- mm-) thick veneer. These veneers are stacked up to the required thickness and may be laid end to end to the desired length with staggered end joiunts in the veneer. Waterproof adhesives are generally used to bond the veneer under pressure. The resulting product is a billet of lumber that may be up to 11/4 in (44 mm) thick, 4 ft (1.2 mm) wide, and 80 ft (24.4 m) long. The billets are then ripped to the desired width and cut to the desired length. The common sizes of LVL closely resemble those of sawn dimension lumber.

Parallel-strand lumber is manufactured from strands or elongated flakes of wood. One North American product is made from veneer clipped to $^1/_2$ in (13 mm) wide and up to 8 ft (2.4. m) long. Another product is made from elongated flakes and technology similar to that used to produce oriented strandboard. A third product is made from mats of interconnected strands crushed from small logs that are assembled into the desired configuration. All the products use waterproof adhesive that is cured under pressure. The size of the product is controlled during manufactured through adjustments in the amount of material and pressure applied. Parallel-strand lumber is commonly available in the same sizes as structural timbers or lumber.

Properties of Structural Composite Lumber Standard design value have not been established for either LVL or PSL. Rather, standard procedures are avaliable for developing these design values (ASTM D 5456). Commonly, each manufacturer follows these procedures and submits supporting data to the appropriate regulatory authority to establish design properties for the product. Thus, design information for LVL and PSL varies among manufacturers and is given in their product literature. Generally the engineering design properties compare favorably with or exceed those of high-quality solid dimension lumber. Example design values accepted by U.S. building codes are given in Table 6.7.11.

Glued-Laminated Timber

Structural glued-laminated timber (glulam) is an engineered, stress-rated product of a timber laminating plant. It is comprised of assemblies of suitably selected and prepared wood laminations bonded together with adhesives. The grain of all laminations os approximately parallel longitudinally. Individual laminations are typically made from nominal 2-in- (standard 38-mm-) thick lumber when used for straight or slightly cambered members, and nominal 1-in- (standard 19-mm-) thick lumber when used for curved members. Individual lamination pieces may be joined end to end to produce laminated timbers much longer than the laminating stock itself. Pieces may also be placed or glued edge to edge to make members wider than the input stock. Straight members up to 140 ft (42 m) long and more than 7 ft (2.1 m) deep have been manufactured, with size limitations generally resulting from transportation constraints. Curved members have been used in domed structures spanning over 500 ft (152 m).

The arrangement of lumber grades in the lamanated cross section depends on the anticipated loading parallel or perpendicular to the wide faces of the laminations. When loads are applied perpendicular to the wide faces of the laminations, referred to as horizontally laminated, glulam cross sections are typically designed as bending combinations. **Bending combinations** hare higher-grade laminations in the outer top and bottom layers to carry the highest stresses and lower-grade laminations in the core layers where stresses are minimal. In situations where all laminations are subjected to the same load, such as compression, tension, or in bending with loads applied parallel to the wide facer of the laminations (vertically laminated). glulam cross sections are typically designed as axial combinations. **Axial combinations** typically have the same lumber grade throughout the cross section.

Manufacture Glulam members used in structural applications in the United States must be manufactured by a laminating plant that meets the requirements of the national standard, ANSI A190.1. This standard contains requirements for production, testing, and certification of the product. Plants meeting these requirements can place their product quality mark on the glulam, which contains vital information regarding the type, species, and properties of the glulam combination. Figure 6.7.2 shows examples of glulam product quality marks and describes the features required in the mark.

Manufacturing standards cover many softwoods and hardwoods; Douglas-fir and southern pine are the most commonly used softwood species. Glulam members can be used in either dry- or wet-use conditions. Dry use, which is defined as a condition resulting in a moisture content of 16 percent or less, permits manufacturing with nonwaterproof adhesives; however, nearly all manufacturers in North America use waterproof adhesives exclusively. For wet-use conditions, these waterproof adhesives are required. For wet-use conditions in which the moisture content is expected to exceed 20 percent, pressure preservative treatment is recommended (AWPA C28). Lumber can be pressure-treated with water-based preservatives prior to gluing, provided that special procedures are followed in the manufacture. For treatment after gluing, ail-based preservatives are generally recommended.

Glulam is generally manufactured at moisture content below 16 percent. For most dry-use applications, it is important to protect the glulam timber from increases in moisture content. End sealers, surface sealers, primer coats, and wrapping may be applied at the manufacturing plant to provide protection from changes in moisture content. Protection will depend upon the final use and finish of the timber.

Special precautions are necessary during handling, storage, and erection to prevent structural damage to glulam members. Padded or non-marring slings are recommended; cable slings or chokers should be avoided unless proper blocking protects the members. Technical manuals an transit, storage, and erection of glulam members are provided by both AITC and APA-EWS.

Design Glulam members are available in standard sizes With standardized design properties. The following standard widths are established to match the widths of standard sizes of lumber, less an allowable amount for finishing the edges of the manufactured beams:

3 or 3$^1/_8$ in (76 or 79 mm)
4 or 5$^1/_8$ in (127 or 130 mm)
6$^3/_4$ in (171 mm)
8$^1/_2$ or 8$^3/_4$ in (216 or 222 mm)
10$^1/_2$ or 10$^3/_4$ in (267 or 273 mm)

standard beam depths are common multiples of lamination thickness of either 1$^3/_8$ or 1$^1/_2$ in (35 or 38 mm). There are no standard beam lengths, although most uses will be on spans where the length is from 10 to

Table 6.7.10 Design Values for Mechanically Graded Dimension Lumber
(Tabulated design values are for normal load duration and dry service conditions.)

Species and commercial grade	Size classification. in	Design values, lb/in², Bending	Tension parallel to grain	Compression parallel to grain	Modulus of elasticity	Grading rules agency
Machine-stress-rated lumber						
900f-1.0E		900	350	1,050	1,000,000	WCLIB, WWPA, NELMA, NSLB
1200f-1.2E		1,200	600	1,400	1,200,000	NLGA, WCLIB, WWPA, NELMA, NSLB
1250f-1.4E		1,250	800	1,475	1,400,000	WCLIB
1350f-1.3E		1,350	750	1,600	1,300,000	NLGA, WCLIB, WWPA, NELMA, NSLB
1400f-1.2E		1,400	800	1,600	1,200,000	NLGA
1450f-1.3E		1,450	800	1,625	1,300,000	NLGA, WCLIB, WWPA, NELMA, NSLB
1450f-1.5E		1,150	875	1,625	1,500,000	WCLIB
1500f-1.4E		1,500	900	1,650	1,400,000	NLGA, WCLIB, WWPA, NELMA, NSLB
1600f-1.4E		1,600	950	1,675	1,400,000	NLGA, WWPA
1650f-1.3E		1,650	1,020	1,700	1,300,000	NLGA, SPIB, WCLIB, WWPA, NELMA, NSLB
1650f-1.5E		1,650	1,020	1,700	1,500,000	WCLIB, WWPA
1650f-1.6E-1075f_t		1,650	1,075	1,700	1,600,000	WCLIB
1650f-1.6E		1,650	1,175	1,700	1,600,000	WCLIB
1650f-1.8E		1,650	1,020	1,750	1,800,000	WCLIB
1700f-1.6E		1,700	1,175	1,725	1,600,000	WCLIB
1750f-2.0E		1,750	1,125	1,725	2,000,000	NLGA
1800f-1.5E		1,800	1,300	1,750	1,500,000	NLGA, SPIB, WCLIB, WWPA, NELMA, NSLB
1800f-1.6E		1,800	1,175	1,750	1,600,000	WCLIB
1800f-1.8E		1,800	1,200	1,750	1,800,000	SPIB, WWPA
1950f-1.5E	2 & less in thickness	1,950	1,375	1,800	1,500,000	NLGA, SPIB, WCLIB, WWPA, NELMA, NSLB
1950f-1.7E		1,950	1,375	1,800	1,700,000	NLGA
2000f-1.6E		2,000	1,300	1,825	1,600,000	NLGA, SPIB, WCLIB, WWPA, NELMA, NSLB
2100f-1.8E	2 & wider	2,100	1,575	1,875	1,800,000	NLGA, WWPA
2250f-1.7E		2,250	1,750	1,925	1,700,000	NLGA, WCLIB, WWPA
2250f-1.8E		2,250	1,750	1,925	1,800,000	NLGA, SPIB, WCLIB, WWPA, NELMA, NSLB
2250f-1.9E		2,250	1,750	1,925	1,900,000	WCLIB, WWPA
2250f-2.0E-1600f_t		2,250	1,600	1,925	2,000,000	WCLIB, WWPA
2250f-2.0E		2,250	1,750	1,925	2,000,000	NLGA, WWPA
2400f-1.8E		2,400	1,925	1,975	1,800,000	NLGA, SPIB
2400f-2.0E		2,400	1,925	1,975	2,000,000	NLGA, SPIB, WCLIB, WWPA, NELMA, NSLB
2500f-2.2E		2,500	1,750	2,000	2,200,000	WCLIB
2500f-2.2E-1925f_t		2,500	1,925	2,000	2,200,000	WCLIB
2550f-2.1E		2,550	2,050	2,025	2,100,000	NLGA, SPIB, WCLIB, WWPA, NELMA, NSLB
2700f-2.0E		2,700	1,800	2,100	2,000,000	WCLIB
2700f-2.2E		2,700	2,150	2,100	2,200,000	NLGA, SPIB, WCLIB, WWPA, NELMA, NSLB
2850f-2.3E		2,850	2,300	2,150	2,300,000	NLGA, SPIB, WCLIB, WWPA, NELMA, NSLB
3000f-2.4E		3,000	2,400	2,200	2,000,000	NLGA, SPIB
Machine-evaluated lumber						
M-10		1,400	800	1,600	1,200,000	NLGA, SPIB
M-11		1,550	850	1,675	1,500,000	NLGA, SPIB
M-12		1,600	850	1,675	1,600,000	NLGA, SPIB
M-13		1,600	950	1,675	1,400,000	NLGA, SPIB
M-14		1,800	1,000	1,750	1,700,000	NLGA, SPIB
M-15		1,800	1,100	1,750	1,500,000	NLGA, SPIB
M-16		1,800	1,300	1,750	1,500,000	SPIB
M-17	2 & less in thickness	1,950	1,300	2,050	1,700,000	SPIB
M-18		2,000	1,200	1,825	1,800,000	SPIB
M-19	2 & wider	2,000	1,300	1,825	1,600,000	NLGA, SPIB
M-20		2,000	1,600	2,100	1,900,000	NLGA, SPIB
M-21		2,300	1,100	1,950	1,900,000	NLGA, SPIB
M-22		2,350	1,500	1,950	1,700,000	NLGA, SPIB
M-23		2,400	1,900	1,975	1,800,000	NLGA, SPIB
M-24		2,700	1,800	2,100	1,900,000	NLGA, SPIB
M-25		2,750	2,000	2,100	2,200,000	NLGA, SPIB
M-26		2,800	1,800	2,150	2,000,000	NLGA, SPIB
M-27		3,000	2,000	2,400	2,100,000	SPIB

Lumber dimensions: Tabulated design values are applicable to lumber that will be used under dry conditions such as in most covered structures. For 2- to 4-in-thick lumber, the *dry* dressed sizes shall be used regardless of the moisture content at the time of manufacture or use. In calculating design values, natural gain in strength and stiffness that occurs as lumber dries has been taken into consideration as well as reduction in size that occurs when unseasoned lumber shrinks. The gain in load-carrying capacity due to increased strength and stiffness resulting from drying more than offsets the design of size reductions due to shrinkage. **Shear parallel to grain F_v and compression perpendicular io grain F_c :** Design values for shear parallel to grain F_{vl} and compression perpendicular to grain $F_{c\perp}$ are identical to the design values given in Tahles 6.7.6 and 6.7.7 for No. 2 visually graded lumber of the appropriate species. When the F_v or $F_{c\perp}$, values shown on the grade sump differ from the dues shown in the tables, the values shown on the grade stamp shall be used for design. **Modulus of elasticity E and tension parallel to grain F_t :** For any given bending design value F_b, the average modulus of elasticity E and tension parallel to grain F_t. design value may vary depending upon species, timber source, or other variables The E and F_t values included in the F_b and E grade designations are those usually associated with each F_b level. Grade stamps may show higher or lower values if machine rating indicates the assignment is appropriate. When the E or F_t values shown on a grade stamp differ from the values in Table 6.7.10, the values shown on the grade stamp shall be used for design. The tabulated F_b and F_c values associated with the designated F_b value shall be used for design. **Additional grades are available.**

SOURCE: Table used by permission of the American Forest & Paper Association, Washington, DC.

Table 6.7.11 Example Design Values for Structural Composite Lumber

	Bending stress		Modulus of elasticity		Horizontal shear	
Product	lb/in²	MPa	×10³lb/in²	GPa	lb/in²	MPa
LVL	2,800	19.2	2,000	13.8	190	1.31
PSL, type A	2,900	20.0	2,000	13.8	210	1.45
PSL, type B	1,500	10.3	1,200	8.3	150	1.03

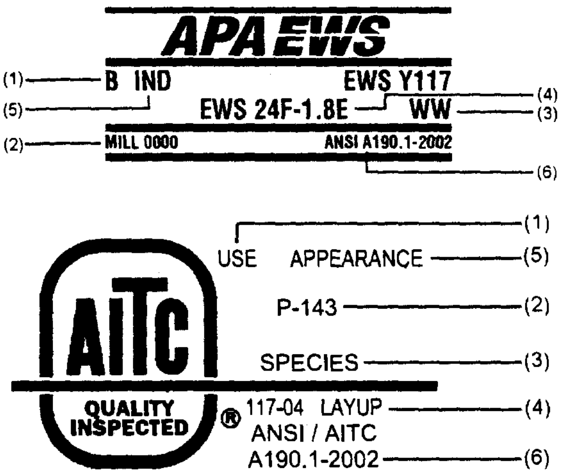

Fig. 6.7.2 Typical product quality stamps showing vital information for glulam combination. 1, structural use of member (B, simple span bending member; C, compression member; T, tension member; CB, continuous or cantilevered span bending member); 2. mill number: 3, species: 4, structural grade designation, indicating species, design bending strength and stiffness; 5, appearance grade designation (framing, industrial, architectural, or premium); 6, identification of conformance to ANSI A 190.1 standard.

20 times the depth. Technical publications containing allowable spans for various loadings of standard sizes of beams are available from either AITC or APA-EWS.

The design stresses for beams in bending for dry-use applications are Standardized in multiples of 200 lb/in² (1.4 MPa) with the range of 2,000 to 3,000 lb/in² (13.8 to 20.7 MPa). Modulus of elasticity values associated with these design stresses in bending vary from 1.6 to 2.0 × 10⁶ lb/in². A bending stress of 2,400 lb/in² (16.5 MPa) and a modulus of elasticity of 1.8 × 10⁶ lb/in² (12.4 GPa) are most commonly specified, and the designer needs to verify the availability of beams with higher values. Design properties must be adjusted for wet-use applications. Detailed information on other design properties for beams as well as design properties and procedures for arches and other uses is given in "National Design Specification" (AF&PA).

Round Timbers

Round timbers in the form of poles, piles, or construction logs represent some of the most efficient uses of forest products because of the minimum of processing required. Poles and piles are generally debarked or peeled, seasoned, graded, and treated with a preservative prior to use. Construction logs are often shaped to facilitate their use. See Table 6.7.12.

Poles The primary use of wood poles is to support utility and transmission lines. An additional use is for building construction. Each of these uses requires that the poles be pressure-treated with preservatives following the applicable AWPA standard (C1). For utility structures, pole length may vary from 30 to 125 ft (9.1 to 38.1 m). Poles for building construction rarely exceed 30 ft (9.1 m). Southern pines account for the highest percentage of poles used in the United States because of their favorable strength properties, excellent form, ease of treatment, and availability. Douglas-fir and western redcedar are used for longer lengths; other species are also included in the ANSI 05.1 standard (ANSI 1992) that forms the basis for most pole purchases in the United States.

Design procedures for the use of ANSI 05.1 poles in utility structures are described in the "National Electric Safety Code" (NESC). For building construction. design properties developed based on ASTM D 2899 (see ASTM, 1995) are provided in "Timber Construction Manual" (AITC, 1994) or ASAE EP 388.

Piles Most piles used for foundations in the United States utilize either southern pine or Douglas-fir. Material requirements for timber piles are given in ASTM D 25, and preservative treatment should follow the applicable AWPA standard (C1 or C3). Design stress and procedures are provided in "National Design Specifications."

Construction Logs Log buildings continue to be a popular form of construction because nearly any available species of wood can be used. Logs are commonly peeled prior to fabrication into a variety of shapes. There are no standardized design properties for construction logs, and when they are required, log home suppliers may develop design properties by following an ASTM standard (ASTM D 3957).

PROPERTIES OF STRUCTURAL PANEL PRODUCTS

by Roland Hernandez

Structural panel products are a family of wood products made by bonding veneer, strands, particles, or fibers of wood into flat sheets. The members of this family are (1) plywood, which consists of products made completely or in part from wood veneer; (2) flakeboard, made

Table 6.7.12 Design Stresses for Selected Species of Round Timbers for Building Construction

	Design stress					
	Bending		Compression		Modulus of elasticity	
Type of timber and species	lb/in²	MPa	lb/in²	MPa	× 10⁶ lb/in²	GPa
Poles*						
Southern pine and Douglas-fir	2,100	14.5	1,000	6.9	1.5	10.3
Western redcedar	1,400	9.6	800	5.5	0.9	6.2
Piles†						
Southern pine	2,400	16.5	1,200	8.3	1.5	10.3
Douglas-fir	2,450	16.9	1,250	8.6	1.5	10.3
Red pine	1,902	13.1	900	6.1	1.3	8.8

*From "Timber Construction Manual" (AITC, 1994).
†From "National Design Specification" (AF&PA, 2005).

from strands, wafers, or flakes; (3) particleboard, made from particles; and (4) fiberboard and hardboard, made from wood fibers. Plywood and flakeboard make up a large percentage of the panels used in structural applications such as roof, wall, and floor sheathing; thus, only those two types will be described here.

Plywood

Plywood is the name given to a wood panel composed of relatively thin layers or plies of veneer with the wood grain of adjacent layers at right angles. The outside plies are called faces or face and back plies, the inner plies with grain parallel to that of the face and back are called cores or centers, and the plies with grain perpendicular to that of the face and back are called crossbands. In four-ply plywood, the two center plies are glued with the grain direction parallel to each ply, making one center layer. Total panel thickness is typically not less than $^1/_{16}$ in (1.6 mm) or more than 3 in (76 mm). Veneer plies may vary as to number, thickness, species, and grade. Stock plywood sheets usually measure 4 by 8 ft (1.2 by 2.4 m), with the 8-ft (2.4-m) dimension parallel to the grain of the face veneers.

The alternation of grain direction in adjacent plies provides plywood panels with dimensional stability across their width. It also results in fairly similar axial strength and stiffness properties in perpendicular directions within the panel plane. The laminated construction results in a distribution of defects and markedly reduces splitting (compared to solid wood) when the plywood is penetrated by fasteners.

Two general classes of plywood, covered by separate standards, are available: construction and industrial plywood, and hardwood and decorative plywood. Construction and industrial plywood is covered by Product Standard PS 1-95; and hardwood and decorative plywood is covered by ANSI/HPVA HP-1-2004. Each standard recognizes different exposure durability classifications, which are primarily based on the moisture resistance of the glue used, but sometimes also address the grade of veneer used.

The exposure durability classifications for construction and industrial plywood specified in PS-1 are: exterior, exposure 1, intermediate glue (exposure 2), and interior. Exterior plywood is bonded with exterior (waterproof glue and is composed of C-grade or better veneers throughout. Exposure 1 plywood is bonded with exterior glue, but it may include D-grade veneers. Exposure 2 plywood is made with glue of intermediate resistance to moisture. Interior-type plywood may be bonded with interior, intermediate, or exterior (waterproof) glue. D-grade veneer is allowed on inner and back plies of certain interior-type grades.

The exposure durability classifications for hardwood and decorative plywood specified in ANSI/HPVA HP-1-2004 are, in decreasing order of moisture resistance, as follows: technical (exterior), type I (exterior), type II (interior), and type III (interior). Hardwood and decorative plywood are not typically used in applications where structural performance is a prominent concern. Therefore, most of the remaining discussion of plywood performance will concern construction and industrial plywood.

A very significant portion of the market for construction and industrial plywood is in residential construction. This market reality has resulted in the development of performance standards for sheathing and single-layer subfloor or underlayment for residential construction by APA–TheEngineered Wood Association (APA–EWA). Plywood panels conforming to these performance standards for sheathing are marked with grade stamps such as those shown in Fig. 6.7.3 (example grade stamps are shown for different agencies). As seen in this figure, the

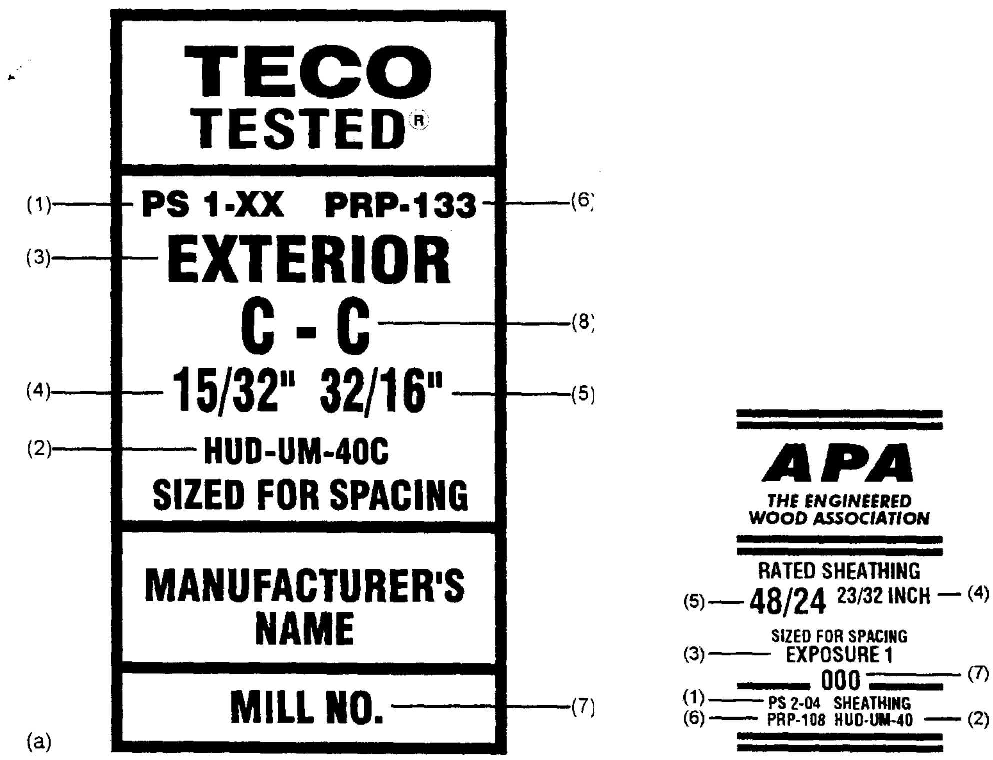

Fig. 6.7.3 Typical grade marks for *(a)* sheathing-grade plywood conforming to Product Standard PS 1-95 and *(b)* sheathing-grade structural-use panel conforming to Product Standard PS 2-95. 1, conformance to indicated product standard; 2, recognition as a quality assurance agency; 3, exposure durability classification; 4, thickness; 5, span rating; 6, conformance to performance-rated product; 7, manufacturer's name or mill number; 8, grade of face and core veneers.

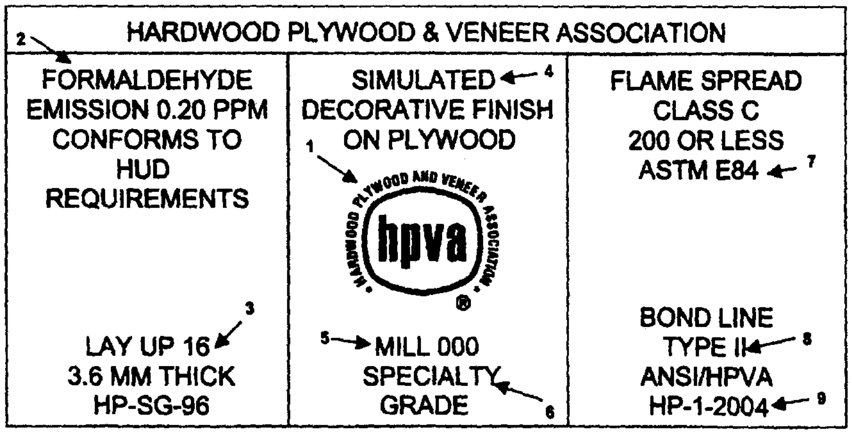

Fig. 6.7.4 Grade stamp for hardwood plywood conforming to ANSI/HPVA HP-1-2004. 1, trademark of Hardwood Plywood and Veneer Association: 2, formaldehyde emission characteristics; 3, structural description; 4, face species or finish type; 5, HPVA mill number; 6, veneer grade of face; 7, flame spread classification; 8, bondline typ; 9, standard that governs manufacture.

grade stamps must show (1) conformance to the plywood product standards; (2) recognition as a quality assurance agency by the National Evaluation Services (NES), which is affiliated with the Council of American Building Officials; (3) exposure durability classification; (4) thickness of panel; (5) span rating, 32/16, which refers to the maximum allowable roof support spacing of 32 in (813 mm) and maximum floor joist spacing of 16 in (406 mm); (6) conformance to the performance-rated standard of the agency; (7) manufacturer's name or mill number; and (8) grades of face and core veneers.

All hardwood plywood represented as conforming to American National Standard ANSI/HPVA-HP-1-2004 is identified by one of two methods: either marking each panel with the HPVA plywood grade stamp (Fig. 6.7.4) or including a written statement with this information with the order or shipment. The HPVA grade stamp shows (1) HPVA trademark; (2) fofmaldehyde emission characteristics; (3) structural description; (4) face species or finish type; (5) HPVA mill number; (6) veneer grade of face; (7) flame spread classification; (8) bondline type; and (9) standard that governs manufacture.

The span-rating system for plywood was established to simplify specification of plywood without resorting to specific structural engineering design. This system indicates performance without the need to refer to species group or panel thickness. It gives the allowable span when the face grain is placed across supports.

If design calculations are desired, a design guide is provided by APA-EWA in "Plywood Design Specifications" (PDS, 2004). The design guide contains tables of grade stamp references, section properties, and allowable stresses for plywood used in construction of buildings and similar related structures. For the design and fabrication of curved panels, plywood-lumber beams, plywood stress-skin panels, plywood sandwich panels, and all-plywood beams, information is available in supplements to the PDS standard from APA-EWA.

If calculations for the actual physical and mechanical properties of plywood are desired, formulas relating the properties of the particular wood species in the component plies to the laminated panel are provided in "Wood Handbook." These formulas could be applied to plywood of any species, provided the basic mechanical properties of the species are known. Note, however, that the formulas yield predicted actual properties (not design values) of plywood made of defect-free veneers.

Structural Flakeboards

Structural flakeboards are wood panels made from specially produced flakes—typically from relatively low-density species, such as aspen or pine—and bonded with an exterior-type water-resistant adhesive. Two major types of flakehoards are recognized, **oriented strandboard** (OSB) and **waferboard.** OSB is a flakeboard product made from wood strands (long and narrow flakes) that are formed into a mat of three to five layers. The outer layers are aligned in the long panel direction, while the inner layers may be aligned at right angles to the outer layers or may be randomly aligned. In waferboard, a product made almost exclusively from aspen wafers (wide flakes), the flakes are not usually oriented in any direction, and they are bonded with an exterior-type resin. Because flakes are aligned in OSB, the bending properties (in the aligned direction) of this type of flakeboard are generally superior to those of waferboard. For this reason, OSB is the predominant form of structural flakeboard. Panels commonly range from 0.25 to 0.75 in (6 to 19 mm) thick and are 4 by 8 ft (1 by 2 m) in surface dimension. However, thicknesses up to 1.125 in (28.58 mm) and surface dimensions up to 8 by 24 ft (2 by 7 m) are available by special order.

A substantial portion of the market for structural flakeboard is in residential construction. For this reason, structural flakeboards are usually marketed as conforming to a product standard for sheathing or single-layer subfloor or underlayment and are graded as a performance-rated product (PRP-108) similar to that for construction plywood. The Voluntary Product Standard PS 2-95 is the performance standard for wood-based structural-use panels, which includes such products as plywood, composites, OSB, and waferboard. The PS 2-95 is not a replacement for PS 1-95, which contains necessary veneer grade and glue bond requirements as well as prescriptive layup provisions and includes many plywood grades not covered under PS 2-95.

Design capacities of the APA–EWA performance-rated products, which include OSB and waferboard, can be determined by using procedures outlined in the APA–EWATechnical Note N375A. In this reference, allowable design strength and stiffness properties, as well as nominal thicknesses and section properties, are specified based on the span rating of the panel. Additional adjustment factors based on panel grade and construction are provided.

Because of the complex nature of structural flakeboards, formulas for determining actual strength and stiffness properties, as a function of the component material, are not available.

DURABILITY OF WOOD IN CONSTRUCTION

by Stan Lebow and Robert White

Biological Challenge

In the natural ecosystem, wood residues are recycled into the nutrient web through the action of wood-degrading fungi, insects, and other organisms. In some circumstances, these same natural recyclers have the potential to degrade wood used in construction. Termites and decay fungi are the most destructive, but other organisms, such as wood boring beetles and carpenter ants, can be important in some regions. Several types of marine organisms can attack wood used in brackish water and saltwater. If conditions are favorable for the survival of one or more of these wood-destroying organisms, wood that has natural durability or that has been treated with preservatives should be employed to ensure the integrity of the structure.

Conditions Favorable for Biodeterioration

Three environmental components govern the development of wood-degrading organisms within terrestrial wood construction: moisture, oxygen supply, and temperature. Of these, moisture seems most directly influenced by design and construction practices. The oxygen supply is usually adequate except for materials submerged below water or deep within the soil, and wood-degrading organisms have evolved to survive in a wide range of temperatures. For these reasons, most of the following discussion will focus on relationships between wood moisture and potential for wood deterioration.

Decay fungi require free water within the wood cells (above 20 to 25 percent moisture content) to survive. Soil provides a continuing source of moisture. Nondurable wood in contact with the ground will decay most rapidly at the ground line where moisture from soil and the supply of oxygen within the wood support growth of decay fungi. Deep within the soil, a limited supply of oxygen prevents growth of most decay fungi. As the distance above ground increases, the decreasing moisture content limits fungal growth unless the wood is wetted through exposure to rain or from water entrapped as a consequence of design or construction practices. Wood absorbs water through cut ends about 11 times faster than through lateral surfaces. Consequently, decay develops first at the joints in aboveground construction.

Extremely low oxygen content in wood submerged below water will prevent growth of decay fungi, but other microorganisms can slowly colonize submerged wood over decades or centuries of exposure. Thus, properties of such woods need to be reconfirmed when old, submerged structures are retrofitted.

Most wood-degrading insects also prefer moist wood, but their moisture requirements vary somewhat by species. Subterranean termites native to the U.S. mainland establish a continuous connection with soil to maintain adequate moisture in wood that is being attacked above ground. Formosan termites have the capacity to use sources of aboveground moisture without establishing a direct connection with the soil. Dry-wood termites survive only in tropical or neotropical areas with sufficiently high relative humidity to elevate the wood moisture content to levels high enough to provide moisture for insect metabolism. Some types of wood-boring beetles, such as powder post beetles, can colonize wood with low moisture contents. Carpenter ants initially invade wood that is moist or decayed, but may then expand into adjacent dry wood.

Methods for Protecting Wood

Protection with Good Design The most important aspect of protecting wood in construction is use of designs that minimize moisture accumulation. Many wood structures have endured for several hundred years because of sound design and construction practices. In nearly all those old buildings the wood has been kept dry by a barrier over the structure (roof plus overhang), by maintaining a separation between the ground and the wood elements (foundation), and by preventing accumulation of moisture in the structure (ventilation). Where Formosan subterranean termites occur, good designs and construction practices that eliminate sources of aboveground moisture are particularly important. Channeling of water from roof drains, collection of condensate from air conditioners, and proper installation of flashing are examples of important considerations. Other design and construction practices also help to protect wood from insect attack. Chemical or physical barriers are often used to prevent subterranean termites from moving from the soil into a building. Many beetles attack only certain species or groups of woods that may be used in speciality items such as joinery. When these species are used, it is important to use wood that is not pre-infested at the time of construction. Today's engineered wood products will last for centuries if good design practices are used. However, there are many structures where it is impractical to prevent decay and insect attack simply through design. In these situations part of or all the structure may need to be constructed with naturally durable wood species or with wood that has been treated with preservatives.

Naturally Durable Wood The heartwood of old-growth trees of certain species, such as bald cypress, redwood, cedars, and several white oaks, is naturally resistant or very resistant to decay fungi. Heartwood of several other species, such as Douglas-fir, longleaf pine, eastern white pine, and western larch, is moderately resistant to wood decay fungi. Some tropical species, such as ipe, are also imported because of their natural durability. Although decay resistance and resistance to termite attack are correlated, not all species that are decay-resistant are also resistant to termite attack. A more complete listing of naturally durable woods is given in "Wood Handbook." One limitation on the use of these species is that the durability is variable between trees and even between pieces cut from a single tree. In addition, the supply of naturally durable species is limited relative to the demand for durable wood products. Consequently, other forms of protection, such as preservative treatment, are more frequently used in current construction. Naturally durable species are not effective in preventing marine borer attack, and pressure treatment with wood preservatives is required to protect wood used in marine or brackish waters.

Preservative Treatments Wood preservatives have been used for over a hundred years. They are broadly classified as either water type or oil type based on the chemical composition of the preservative and the solvent used during the treating process. Each type of preservative has advantages and disadvantages, depending on the application. The most common oil-type preservatives are creosote, pentachlorophenol, and copper naphthenate. Because wood treated with oil-type preservatives may be oily to the touch or have a noticeable odor, it is not usually used for applications involving frequent human contact or for inhabited structures. Oil-type preservatives may offer improved water repellency and typically do not promote corrosion of fasteners. Water-based preservatives leave a dry, paintable surface and are commonly used to treat wood for residential applications such as decks and fences. They are primarily used to treat softwoods because hardwoods treated with these preservatives may not be well protected from soft-rot attack. Until recently, the most widely used water-type preservative was chromated copper arsenate (CCA). However, CCA has now been voluntarily phased out for most applications around residential areas and where human contact is expected. More recent water-based preservatives, such as alkaline copper quat or copper azole, rely primarily on copper to protect the wood. Water-based wood preservatives can increase susceptibility to corrosion. and metal fasteners used with the treated wood should be hot-dipped galvanized or stainless steel.

Borates are another type of waterborne preservative that may be used to treat interior building components for protection against insect attack. Borates should not be used where they are exposed to soil or rainfall because they are readily leached from the wood. In non-load-bearing applications such as exterior millwork around windows and doors, wood is usually protected with water-repellent preservative treatments that are applied by nonpressure processes. Standards for preservative treatment are published by the American Wood-Preservers' Association, and detailed information on wood preservation is given in "Wood Handbook." It is important to ensure that wood is being treated to standard specifications. The U.S. Department of Commerce American Lumber Standard Committee (ALSC) accredits third-party inspection agencies for treated wood products. Updated lists of accredited agencies can be found on the ALSC Website (www.alsc.og). If the wood has been treated to these specifications, it will have the quality mark or symbol of an ALSC-accredited inspection agency.

Protection from Weathering The combination of sunlight and other weathering agents will slowly remove the surface fibers of wood products. Removal of fibers can be greatly reduced by providing a wood finish; if the finish is properly maintained, the removal of fibers can be nearly eliminated. Information on wood finishes is available in Caasens and Feist. "Exterior Wood in the South."

Protection from Fire In general, proper design for fire satety allows the use of untreated wood. When there is a need to reduce the potential for heat contribution or flame spread, fire-retardant treatments are available. Although fire-retardant coatings or dip treatments are available, effective treatment often requires that the wood be pressure-impregnated with the fire-retardant chemicals. These chemicals include inorganic salts such as monoammonium and diammonium phosphate, ammonium sulfate, zinc chlorate, sodium tetraborate, and boric acid Resin polymerized after impregnation into wood is used to obtain a leach-resistant treatment. Such amino resin systems are based on urea, melamine, dicyandiamide, and related compounds. An effective treatment can reduce the ASTM E 84 flame spread to less than 25 and show no evidence of significant progressive combustion when the ASTM E 84 test is continued for an additional 20-min period. When the external source of heat is removed, the flames from fire-retardant-treated wood will generally self-extinguish. Many fire-retardant treatments reduce the generation of combustible gases by lowering the thermal degradation temperature. ASTM standards have been developed to address other performance requirements such as initial strength loss due to treatment and kiln drying, strength loss when exposed to elevated temperatures in use, excessive hygroscopicity in areas of high humidity, and loss of fire performance due to outdoor exposure to rainfall.

Effect of Aging

Long exposure of wood to the atmosphere also causes changes in the cellulose. A study by Kohara and Okamoto of sound old timbers of a softwood and hardwood of known ages from temple roof beams shows that the percentage of cellulose decreases steadily over a period up to 1,400 years while the lignin remains almost constant. These changes are reflected in strength losses (Fig. 6.7.5). Impact properties approximate a loss that is nearly linear with the logarithm of time.

Allowable Working Stresses for Preservative-Treated Lumber

Allowable working stresses for preservative-treated lumber usually need not be reduced to account for the effect of the treating process. Tests made by the USDA Forest Service, Forest Products Laboratory, of preservative-treated lumber when undergoing bending, tension, and compression perpendicular to grain show reductions in mean extreme fiber stress from a few percent up to 25 percent, but few reductions in working stresses. Compression parallel to the grain is affected less and modulus of elasticity very little. The effect on horizontal shear can be estimated by inspection for an increase in shakes and checks after treatment. AWPA Standards keep temperatures. heating periods, and pressures to a minimum for required penetration and retention, which precludes the need for adjustment in working stresses.

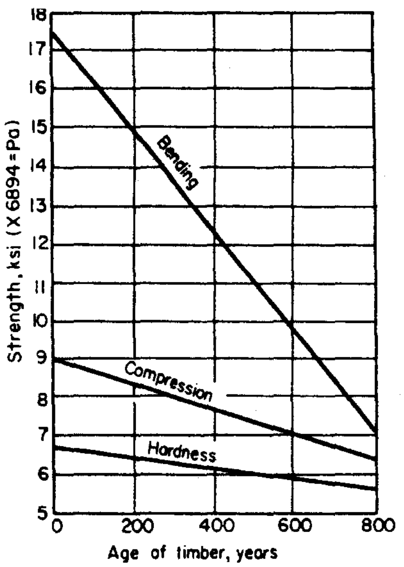

Fig. 6.7.5 Strength loss with age in a hardwood *(Zelkowa serrata). (Adapted from information in Kohara and Okamoto. 1955.)*

COMMERCIAL LUMBER STANDARDS

Standard abbreviations for lumber description and size standards for yard lumber are given in "Wood Handbook."

Cross-sectional dimensions and section properties for beams, stringers, joists, and planks are given in the "National Design Specification."

Standard patterns for finish lumber are shown in publications of the grading rules for the various lumber associations.

Information and specifications for construction and industrial plywood are given in Product Standard PS 1-95 and in ANSI/HPVA HP-1-2004 for hardwood and decorative plywood. Information and specifications for structural flakeboard are given in PS 2-95.

Marks'

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Revised by a staff of specialists

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