leaning hardwood stems or branches. Characteristics of compression wood include eccentric growth rings, a high percent of latewood per ring, higher density, intercellular spaces, helical checking of the cell walls, a large microfibril angle in the S_2, and a higher lignin content. It is often 'dull' looking or darker in color. **Figure 12a** illustrates the eccentric rings and darkening of compression wood. Tension wood has eccentric growth increments, fuzzy cut surfaces, a gelatinous almost pure cellulose layer that may replace part of the cell wall, a higher percent of thick-walled fibers, and an increased cellulose content. Macroscopic features such as eccentric rings of tension wood of ash are shown in **Figure 12b**. Wood on the opposing side of the reaction wood is also 'unusual' in that it does not possess the same features of wood in the nonleaning stem portion. As with juvenile wood, the physical properties of reaction wood are reflective of the fine structure and chemistry and are considered inferior to those of mature wood.

See also: **Tree Breeding, Practices**: Biological Improvement of Wood Properties; Genetics and Improvement of Wood Properties. **Wood Formation and Properties**: Chemical Properties of Wood; Mechanical Properties of Wood; Physical Properties of Wood; Wood Quality. **Wood Use and Trade**: History and Overview of Wood Use.

Further Reading

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Mechanical Properties of Wood

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Introduction

This article covers mechanical properties of wood and wood-based materials. Wood is a nonisotropic material with directionally dependent elastic and mechanical properties. Rules governing wood as an anisotropic, orthotropic, and transverse isotropic material are outlined. Wood materials are classified into groups based on their structure. The relationship between mechanical properties of wood and moisture, temperature, and time are also covered.

Elastic Properties

Wood is an anisotropic nonhomogeneous material. Anisotropic means that the physical properties (including mechanical) are directionally dependent. Its nonhomogeneous character is related to wood being a porous material that is not continuous but contains voids. The anisotropy is cylindrical anisotropy (**Figure 1**) but it is often, for purpose of modeling, replaced by the orthogonal anisotropy (orthotropy). This is done to achieve simplicity and to avoid coordinate transformation from a cylindrical to Cartesian system. A cylindrical coordinate system can be superimposed on the tree cross section such that the longitudinal axis is oriented along the tree axis and the radius, R, is oriented in a radial direction. Angle φ will rotate counterclockwise and mechanical properties will be a function of R and φ. Strictly speaking, wood will only loosely follow anisotropy and transformation rules due to its natural variability. If we remove a block of finite dimensions (such as cutting a board from a log) and

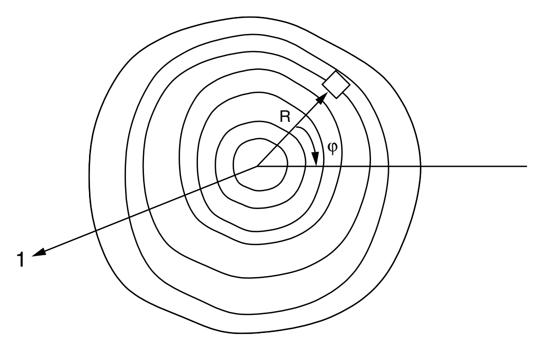

Figure 1 Cylindrical coordinate system superimposed on the tree cross-section.

let the radius, R, be relatively large with respect to the board cross-sectional dimensions (**Figure 2**) such that $R \rightarrow \infty$, we can then neglect the radius and superimpose a Cartesian coordinate system, where mechanical properties in any coordinate system rotated with respect to the original one will be a function of properties in directions 1, 2, and 3. From **Figure 2** it follows that the simplification requirements are never met and therefore discrepancies between different experimentally obtained elastic constants will occur. Orthotropic representation of wood also requires that the properties follow orthotropic symmetry rules. This means that one can superimpose three mutually perpendicular planes of symmetry and all properties (not only mechanical but also, e.g., electrical) will be symmetrical with respect to these planes. If the above assumptions are met then wood can be fully defined by 9 elastic constants (three moduli of elasticity E_1, E_2, E_3, three Poisson's ratios μ_{12}, μ_{23}, μ_{13} and three shear moduli G_{12}, G_{23}, G_{13}). The remaining constants (36 total) can be calculated using reciprocity theorem and material symmetry. Unlike isotropic materials, the shear modulus of wood is independent of other elastic parameters and must be determined experimentally. More details can be found in any standard text dealing with composite materials. The ratios of elastic moduli in longitudinal (L), radial (R), and tangential (T) directions are approximately 20 : 1.7 : 1 for softwoods and 13 : 1.7 : 1 for hardwoods. Stress, σ, can be calculated from the generalized Hooke's Law as $a_{ij}\varepsilon_j = \sigma_i$, where σ_i = stress tensor, a_{ij} = stiffness matrix, and ε_j = strain tensor, i, $j = 1, 2 \ldots 6$. Defining wood as an orthotropic material is not practical due to the large number of experimental variables that must be determined. In structural applications, it is impossible to distinguish between radial and tangential directions and wood is represented as transverse isotropic material. The transverse isotropic means that the material has isotropic properties in the transverse plane. Thus, only two moduli of elasticity (parallel and perpendicular to fibers), one shear modulus, and one Poisson's ratio are needed to define such material. One must pay attention to Poisson's ratios since values exceeding 0.5 have been reported in the literature. Such values are impossible to measure for elastic solids (value of 0.5 represents an incompressible fluid). Since wood is an inhomogeneous material with hollow cell structure, high values of expansion are possible resulting in apparent Poisson's ratio close to 0.5. Viewing wood material as rigid plastic foam can explain such high values. The values of Poisson's ratios for most common woods are listed in **Table 1**.

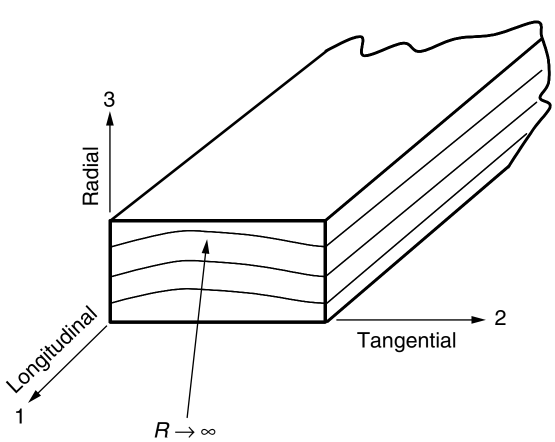

Figure 2 Orthotropic representation of solid wood cross-section.

Most wood composites are two-dimensional and can be considered as orthotropic or isotropic in two dimensions whereby the third dimension across the thickness is not considered (in two dimensional elasticity problems, the strain in the thickness is constant). **Table 2** lists various composite materials based on orientation of particles and their definitions. The elastic properties of wood composites are affected by their structure and the way the composites are manufactured. **Table 3** represents the range of elastic properties for some common wood composites.

Constitutive Equations

Wood and wood composites are generally regarded as brittle, elastic materials, with the exception of compression across fibers where large strains can be introduced without failing the material. Thus, Hooke's law can be used to describe a short-term stress–strain relationship and modulus of elasticity represents the slope of the stress–strain diagram. In compression perpendicular to fibers, the modulus of elasticity has meaning only at the pseudoelastic region of the stress–strain diagram. A typical stress–strain diagram for wood loaded in compression perpendicular to fibers direction is shown in **Figure 3**. The yield strain in compression across fibers is about 3%. The failure strains for tension and compression along fibers is in the range 2–3%. For tension across fibers, the failure strain can be less than 0.2%. Wood behavior in tension parallel, perpendicular and compression parallel to the grain is brittle and wood can be considered linearly elastic all the way up to the failure.

Strength

Strength is defined as the stress at failure. Therefore, the definition of failure plays an important role in defining strength. Because of the nonisotropic

Table 1 Poisson's ratios for various species and wood composites at approximately 12% moisture content

Species	μLR	μLT	μRT	μTR	μRL	μTL
Hardwoods						
Ash, white (*Fraxinus americana*)	0.371	0.440	0.684	0.360	0.059	0.051
Aspen, quaking (*Populus tremuloides*)	0.489	0.374	—	0.496	0.054	0.022
Balsa (*Ochroma pyramidale*)	0.229	0.488	0.665	0.231	0.018	0.009
Basswood (*Tilia americana*)	0.364	0.406	0.912	0.346	0.034	0.022
Birch, yellow (*Betula alleghaniensis*)	0.426	0.451	0.697	0.426	0.043	0.024
Cherry, black (*Prunus serotina*)	0.392	0.428	0.695	0.282	0.086	0.048
Cottonwood, eastern (*Populus deltoides*)	0.344	0.420	0.875	0.292	0.043	0.018
Mahogany, African (*Khaya grandifoliola*)	0.297	0.641	0.604	0.264	0.033	0.032
Mahogany, Honduras (*Swietenia macrophylla*)	0.314	0.533	0.600	0.326	0.033	0.034
Maple, sugar (*Acer saccharum*)	0.424	0.476	0.774	0.349	0.065	0.037
Maple, red (*Acer rubrum*)	0.434	0.509	0.762	0.354	0.063	0.044
Oak, red (*Quercus rubra*)	0.350	0.448	0.560	0.292	0.064	0.033
Oak, white (*Quercus alba*)	0.369	0.428	0.618	0.300	0.074	0.036
Sweetgum (*Liquidambar styraciflua*)	0.325	0.403	0.682	0.309	0.044	0.023
Walnut, black (*Juglans nigra*)	0.495	0.632	0.718	0.378	0.052	0.035
Yellow-poplar (*Liriodendron tulipifera*)	0.318	0.392	0.703	0.329	0.030	0.019
Softwoods						
Baldcypress (*Taxodium distichum*)	0.338	0.326	0.411	0.356	—	—
Cedar, northern white (*Thuja occidentalis*)	0.337	0.340	0.458	0.345	—	—
Cedar, western red (*Cedrela guianensis*)	0.378	0.296	0.484	0.403	—	—
Douglas-fir (*Pseudotsuga menziesii*)	0.292	0.449	0.390	0.374	0.036	0.029
Fir, subalpine (*Abies lasiocarpa*)	0.341	0.332	0.437	0.336	—	—
Hemlock, western (*Tsuga heterophylla*)	0.485	0.423	0.442	0.382	—	—
Larch, western (*Larix occidentalis*)	0.355	0.276	0.389	0.352	—	—
Pine						
Loblolly (*Pinus taeda*)	0.328	0.292	0.382	0.362	—	—
Lodgepole (*Pinus contorta*)	0.316	0.347	0.469	0.381	—	—
Longleaf (*Pinus palustris*)	0.332	0.365	0.384	0.342	—	—
Pond (*Pinus serotina*)	0.280	0.364	0.389	0.320	—	—
Ponderosa (*Pinus ponderosa*)	0.337	0.400	0.426	0.359	—	—
Red (*Pinus resinosa*)	0.347	0.315	0.408	0.308	—	—
Slash (*Pinus elliottii*)	0.392	0.444	0.447	0.387	—	—
Sugar (*Pinus lambertiana*)	0.356	0.349	0.428	0.358	—	—
Western white (*Pinus monticola*)	0.329	0.344	0.410	0.334	—	—
Redwood (*Sequoia sempervirens*)	0.360	0.346	0.373	0.400	—	—
Spruce, Sitka (*Picea sitchensis*)	0.372	0.467	0.435	0.245	0.040	0.025
Spruce, Engelmann (*Picea engelmannii*)	0.422	0.462	0.530	0.255	0.083	0.058
Plywood	0.44	0.10	0.08	0.30	0.05	0.23
Particleboard	0.02	0.27	0.02	0.25	0.30	0.23

Data from US Department of Agriculture (1999) *Wood Handbook: Wood as an Engineering Material*. Madison, WI: US Department of Agriculture Forest Service; Niemz P (1993) *Physik des Holzes und der Holzwerkstoffe*. Weinbrenner, Germany: DRW-Verlag.

Table 2 Types of wood composite materials and their representation

Material	*Representation*	*Number of elastic constants needed*[a]
Layered systems (plywood)	Orthotropic, two-dimensional	4 (E_1, E_2, G_{12}, μ_{12})
Particle-based systems with oriented particles (OSB)	Orthotropic, two-dimensional, or isotropic	4 (E_1, E_2, G_{12}, μ_{12}) 2 (E_1, μ_{12})
Particle-based with randomly oriented particles (particleboard)	Isotropic	2 (E_1, μ_{12})
Fiber-based (fiberboard)	Isotropic	2 (E_1, μ_{12})
Composite lumber products (LVL, laminated veneer lumber; LSL, laminated strand lumber)	Transverse Isotropic	4 (E_1, E_2, G_{12}, μ_{12})

[a] E_1, modulus of elasticity in the direction 1; E_2, modulus of elasticity in the direction 2; G_{12}, shear modulus; μ_{12}, Poisson's ratio.

character of wood and wood-based composites, several strength values are required to describe completely the strength of the material. These include tensile, compressive, and shear strengths. Since tensile and compressive strengths are not equal, bending strength is also used as an additional

Table 3 Elasticity properties of common wood-based composites

	E_1 *(MPa)*	E_2 *(MPa)*	μ_{12}	G_{12} *(MPa)*
Softwood plywood	6000–12000[a] 4100–10000[b]	2000–7000[a] 2500–7000[b]	0.1–0.44	
Hardwood plywood			0.1–0.44	
Oriented strandboard (OSB)				
Particleboard	1500–7000	1500–7000		
Medium density fiberboard (MDF)	1500–4500	1500–4500		
Hardboard	4000–7000	4000–7000		
Laminated veneer lumber (LVL)	13000–19000	3000–4000		
Laminated strand lumber (LSL)	13000–19000	3000–4000		

[a] Less than 5 layers.
[b] More than 7 layers.
Data from Bodig J and Jayne BA (1993) *Mechanics of Wood and Wood Composites*. Malabar, FL: Krieger; Wesche K (1988) *Baustoffe für Tragende Bauteile*, vol. 4, *Holz und Kunstoffe*, 2nd edn. Wiesbaden, Germany: Bauverlag GmbH.

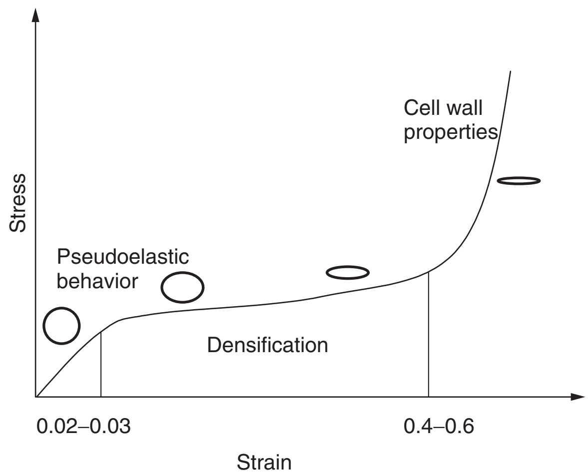

Figure 3 Typical stress–strain diagram of wood loaded in compression perpendicular to fibers.

parameter. Tensile and compressive strengths are defined in direction parallel and perpendicular to the fibers. Tensile strength in the direction perpendicular to the fibers is an unreliable quantity due to the likelihood of checks in wood. Failure can be relatively easily defined for all stresses, except for the compression perpendicular to fibers where the strength is defined as the stress at certain value of the strain. Thus, compressive strength in the direction perpendicular to fibers is a deformation-based quantity. Values of strengths for common woods are listed in **Tables 4** and **5**.

Shear strength depends on the orientation of the shear plane. Since the shear forces in an element always act in pairs, the shear stress will always act on two opposite planes in an elementary shear block. When a shear force acts in the direction perpendicular to fibers, rolling shear occurs. Shear through the thickness of wood composites (horizontal shear) is defined when shear force acts across the material thickness.

If wood or wood composites are under multiaxial stress (such as biaxial tension), a single value of strength is not sufficient to determine failure and a failure surface must be constructed. Various strength theories can be used to define the strength envelope with tensorial strength criterion being the most general. A generalized function describing the material strength can be written as $a_i\sigma_i + a_{ij}\sigma_i\sigma_j + a_{ijk}\sigma_i\sigma_j\sigma_k + \cdots = 1$. The coefficients a_i, a_{ij}, a_{ijk} represent the strength tensor components and σ_i, σ_j, σ_k are the stresses in directions 1, 2, 3 and planes 3, 4, 6. **Figure 4** shows a strength envelope for plywood loaded by in-plane forces. Note that for the most simple, two-dimensional stress state, the envelope will be in three dimensions and additional characteristic, a strength in biaxial tension, will be needed to define mutual interaction between stresses in two principal directions (along and across the face veneer fibers). Another way to determine failure is use of fracture mechanics. Fracture mechanics studies mechanisms of crack initiation, development, and growth. Several parameters are needed to describe the functions governing the various stages of crack development. The problem in applying fracture mechanics to wood and wood materials is that an infinite number of cracks of unknown dimensions is present in wood.

Variability of Mechanical Properties

Variability of mechanical properties must always be considered because variability is extremely high in wood and wood materials. For example, modulus of elasticity within a species may vary by 20–30% (variability is defined as a standard deviation divided by arithmetic average). One will always have an estimate of material characteristics (arithmetic average is one of the estimators to estimate mean, the value of which is never known). The high variability of mechanical properties requires that relatively large

Table 4 Mechanical properties[a] of common woods at 12% moisture content

Common and botanical names of species	*Specific gravity*[b]	*Static bending*		*Compression parallel to grain (kPa)*	*Compression perpendicular to grain (kPa)*	*Shear parallel to grain (kPa)*	*Tension perpendicular to grain (kPa)*
		Bending strength (kPa)	*Modulus of elasticity*[c] *(MPa)*				
Hardwoods							
Alder, red (*Alnus rubra*)	0.41	68 000	9 500	40 100	3 000	7 400	2 900
Ash							
black (*Fraxinus nigra*)	0.49	87 000	11 000	41 200	5 200	10 800	4 800
white (*Fraxinus americana*)	0.60	103 000	12 000	51 100	8 000	13 200	6 500
Aspen							
bigtooth (*Populus grandidentata*)	0.39	63 000	9 900	36 500	3 100	7 400	—
quaking (*Populus tremuloides*)	0.38	58 000	8 100	29 300	2 600	5 900	1 800
Basswood, American (*Tilia americana*)	0.37	60 000	10 100	410	32 600	2 600	6 800
Beech, American (*Fagus grandifolia*)	0.64	103 000	11 900	1 040	50 300	7 000	13 900
Birch							
paper (*Betula papyrifera*)	0.55	85 000	11 000	860	39 200	4 100	8 300
Sweet (*Betula lenta*)	0.65	117 000	15 000	1 190	58 900	7 400	15 400
Butternut (*Juglans cinerea*)	0.38	56 000	8 100	610	36 200	3 200	8 100
Cherry, black (*Prunus serotina*)	0.50	85 000	10 300	740	49 000	4 800	11 700
Chestnut, American (*Castanea dentata*)	0.43	59 000	8 500	480	36 700	4 300	7 400
Cottonwood							
balsam poplar (*Populus balsamifera*)	0.34	47 000	7 600	—	27 700	2 100	5 400
black (*Populus trichocarpa*)	0.35	59 000	8 800	560	31 000	2 100	7 200
Eastern (*Populus deltoides*)	0.40	59 000	9 400	510	33 900	2 600	6 400
Elm							
rock (*Ulmus alata*)	0.63	102 000	10 600	1 420	48 600	8 500	13 200
slippery (*Ulmus rubra*)	0.53	90 000	10 300	1 140	43 900	5 700	11 200
Hackberry (*Celtis occidentalis*)	0.53	76 000	8 200	1 090	37 500	6 100	11 000
Hickory, pecan							
bitternut (*Carya cordiformis*)	0.66	118 000	12 300	62 300	11 600	—	—
Hickory, true							
mockernut (*Carya tomentosa*)	0.72	132 000	15 300	61 600	11 900	12 000	—

continued

Table 4 Continued

Common and botanical names of species	*Specific gravity*[b]	*Static bending*		*Compression parallel to grain (kPa)*	*Compression perpendicular to grain (kPa)*	*Shear parallel to grain (kPa)*	*Tension perpendicular to grain (kPa)*
		Bending strength (kPa)	*Modulus of elasticity*[c] *(MPa)*				
Honeylocust (*Gleditsia triacanthos*)	—	101 000	11 200	51 700	12 700	15 500	6 200
Locust, black (*Robinia pseudoacacia*)	0.69	134 000	14 100	70 200	12 600	17 100	4 400
Magnolia							
cucumber tree (*Magnolia acuminata*)	0.48	85 000	12 500	43 500	3 900	9 200	4 600
Southern (*Magnolia acuminata*)	0.50	77 000	9 700	37 600	5 900	10 500	5 100
Maple							
bigleaf (*Acer macrophyllum*)	0.48	74 000	10 000	41 000	5 200	11 900	3 700
black (*Acer nigrum*)	0.57	92 000	11 200	46 100	7 000	12 500	4 600
red (*Acer rubrum*)	0.54	92 000	11 300	45 100	6 900	12 800	—
silver (*Acer saccharinum*)	0.47	61 000	7 900	36 000	5 100	10 200	3 400
sugar (*Acer saccharum*)	0.63	109 000	12 600	54 000	10 100	16 100	—
Oak, red							
black (*Quercus coccinea*)	0.61	96 000	11 300	45 000	6 400	13 200	—
Northern red (*Quercus rubra*)	0.63	99 000	12 500	46 600	7 000	12 300	5 500
Scarlet (*Quercus coccinea*)	0.67	120 000	13 200	57 400	7 700	13 000	6 000
Southern red (*Quercus rubra*)	0.59	75 000	10 300	42 000	6 000	9 600	3 500
Water (*Quercus palustris*)	0.63	106 000	13 900	46 700	7 000	13 900	6 300
Oak, white (*Quercus* spp.)							
white (*Quercus alba*)	0.68	105 000	12 300	51 300	7 400	13 800	5 500
Sweetgum (*Liquidambar styraciflua*)	0.52	86 000	11 300	43 600	4 300	11 000	5 200
Sycamore, American (*Platanus occidentalis*)	0.49	69 000	9 800	37 100	4 800	10 100	5 000
Walnut, black (*Juglans nigra*)	0.55	101 000	11 600	52 300	7 000	9 400	4 800
Willow, black (*Salix nigra*)	0.39	54 000	7 000	28 300	3 000	8 600	—
Yellow-poplar (*Liriodendron tulipifera*)	0.42	70 000	10 900	38 200	3 400	8 200	3 700
Softwoods							
Baldcypress (*Taxodium distichum*)	0.46	73 000	9 900	43 900	5 000	6 900	1 900
Cedar							

Atlantic white (*Chamaecyparis thyoides*)	0.32	47 000	6 400	32 400	2 800	5 500	1 500
Eastern redcedar (*Cedrela* spp.)	0.47	61 000	6 100	41 500	6 300	—	—
Incense (*Libocedrus decurrens*)	0.37	55 000	7 200	35 900	4 100	6 100	1 900
Northern white (*Thuja occidentalis*)	0.31	45 000	5 500	27 300	2 100	5 900	1 700
Port-Orford (*Chamaecyparis lawsoniana*)	0.43	88 000	11 700	43 100	5 000	9 400	2 800
Western redcedar (*Cedrela* spp.)	0.32	51 700	7 700	31 400	3 200	6 800	1 500
yellow (*Chamaecyparis nootkatensis*)	0.44	77 000	9 800	43 500	4 300	7 800	2 500
Douglas-fir[d]							
coast (*Pseudotsuga menziesii*)	0.48	85 000	13 400	49 900	5 500	7 800	2 300
interior West (*Pseudotsuga menziesii*)	0.50	87 000	12 600	51 200	5 200	8 900	2 400
Fir							
balsam (*Abies balsamea*)	0.35	63 000	10 000	36 400	2 800	6 500	1 200
grand (*Abies grandis*)	0.37	61 400	10 800	36 500	3 400	6 200	1 700
noble (*Abies procera*)	0.39	74 000	11 900	42 100	3 600	7 200	1 500
pacific silver (*Abies amabilis*)	0.43	75 800	12 100	44 200	3 100	8 400	—
subalpine (*Abies lasiocarpa*)	0.32	59 000	8 900	33 500	2 700	7 400	—
white (*Abies concolor*)	0.39	68 000	10 300	40 000	3 700	7 600	2 100
Hemlock							
Eastern (*Tsuga canadensis*)	0.40	61 000	8 300	37 300	4 500	7 300	—
Western (*Tsuga heterophylla*)	0.45	78 000	11 300	49 000	3 800	8 600	2 300
Larch, western (*Larix occidentalis*)	0.52	90 000	12 900	52 500	6 400	9 400	3 000
Pine							
Eastern white (*Pinus strobus*)	0.35	59 000	8 500	33 100	3 000	6 200	2 100
Jack (*Pinus banksiana*)	0.43	68 000	9 300	39 000	4 000	8 100	2 900
loblolly (*Pinus taeda*)	0.51	88 000	12 300	49 200	5 400	9 600	3 200
lodgepole (*Pinus contorta*)	0.41	65 000	9 200	37 000	4 200	6 100	2 000
longleaf (*Pinus palustris*)	0.59	100 000	13 700	58 400	6 600	10 400	3 200
Pitch (*Pinus ponderosa*)	0.52	74 000	9 900	41 000	5 600	9 400	—
pond (*Pinus serotina*)	0.56	80 000	12 100	52 000	6 300	9 500	—
ponderosa (*Pinus*	0.40	65 000	8 900	36 700	4 000	7 800	2 900

continued

Table 4 Continued

Common and botanical names of species	*Specific gravity*[b]	*Static bending*		*Compression parallel to grain (kPa)*	*Compression perpendicular to grain (kPa)*	*Shear parallel to grain (kPa)*	*Tension perpendicular to grain (kPa)*
		Bending strength	*Modulus of*				
ponderosa)							
red (*Pinus resinosa*)	0.46	76 000	11 200	41 900	4 100	8 400	3 200
shortleaf (*Pinus echinata*)	0.51	90 000	12 100	50 100	5 700	9 600	3 200
slash (*Pinus elliottii*)	0.59	112 000	13 700	56 100	7 000	11 600	—
spruce (*Pinus glabra*)	0.44	72 000	8 500	39 000	5 000	10 300	—
sugar (*Pinus lambertiana*)	0.36	57 000	8 200	30 800	3 400	7 800	2 400
Redwood (*Sequoia sempervirens*)							
old-growth	0.40	69 000	9 200	42 400	4 800	6 500	1 700
young-growth	0.35	54 000	7 600	36 000	3 600	7 600	1 700
Spruce							
black (*Picea mariana*)	0.46	74 000	11 100	41 100	3 800	8 500	—
Engelmann (*Picea engelmannii*)	0.35	64 000	8 900	30 900	2 800	8 300	2 400
red (*Picea rubens*)	0.40	74 000	11 100	38 200	3 800	8 900	2 400
Sitka (*Picea sitchensis*)	0.36	65 000	9 900	35 700	3 000	6 700	2 600
white (*Picea glauca*)	0.40	68 000	9 200	37 700	3 200	7 400	2 500
Tamarack (*Larix decidua*)	0.53	80 000	11 300	49 400	5 500	8 800	2 800

[a] Definition of properties: impact bending is height of drop that causes complete failure, using 0.71-kg hammer; compression parallel to grain is also called maximum crushing strength; compression perpendicular to grain is fiber stress at proportional limit; shear is maximum shearing strength; tension is maximum tensile strength; and side hardness is hardness measured when load is perpendicular to grain.

[b] Specific gravity is based on weight when ovendry and volume when green or at 12% moisture content.

[c] Modulus of elasticity measured from a simply supported, center-loaded beam, on a span depth ratio of 14/1.

[d] Coast Douglas-fir is defined as Douglas-fir growing in Oregon and Washington State west of the Cascade Mountains summit. Interior West includes California and all counties in Oregon and Washington east of, but adjacent to, the Cascade summit.

Data from US Department of Agriculture (1999) *Wood Handbook: Wood as an Engineering Material*. Madison, WI: US Department of Agriculture Forest Service; Niemz P (1993) *Physik des Holzes und der Holzwerkstoffe*. Weinbrenner, Germany: DRW-Verlag.

Table 5 Average parallel-to-grain tensile strength of some wood species

Common and botanical names of species	Tensile strength[a] (kPa)
Hardwoods	
Ash, European (*Fraxinus excelsior*)	130 000
Beech, American (*Fagus grandifolia*)	86 200
Beech, European (*Fagus silvatica*)	135 000
Birch, European (*Betula verrucosa*)	60 000
Hornbeam, European (*Carpinus betulus*)	135 000
Elm, cedar (*Ulmus crassifolia*)	120 700
Maple, European (*Acer pseudoplatanus*)	108 200
Maple, sugar (*Acer saccharum*)	108 200
Oak	
overcup (*Quercus* spp.)	77 900
pin (*Quercus palustris*)	112 400
European red oak (*Quercus robur*)	110 000
Poplar, balsam (*Populus balsamifera*)	51 000
Sweetgum (*Liquidambar styraciflua*)	93 800
Willow, black (*Salix nigra*)	73 100
Yellow-poplar (*Liriodendron tulipifera*)	109 600
Softwoods	
Baldcypress (*Taxodium distichum*)	58 600
Cedar	
Port-Orford (*Chamaecyparis lawsoniana*)	78 600
Western redcedar (*Cedrela* spp.)	45 500
Douglas-fir, interior North (*Pseudotsuga menziesii*)	107 600
Fir	
California red (*Abies magnifica*)	77 900
Pacific silver (*Abies amabilis*)	95 100
European (*Abies alba*)	80 000
Hemlock, western (*Tsuga heterophylla*)	89 600
Larch	
western (*Larix occidentalis*)	111 700
European (*Larix decidua*)	105 000
Pine	
Eastern white (*Pinus strobus*)	73 100
European (*Pinus sylvestris*)	100 000
loblolly (*Pinus taeda*)	80 000
ponderosa (*Pinus ponderosa*)	57 900
Virginia (*Pinus virginiana*)	94 500
Redwood	
virgin (*Sequoia sempervirens*)	64 800
young-growth (*Sequoia sempervirens*)	62 700
Spruce	
Engelmann (*Picea engelmannii*)	84 800
European (*Picea abies*)	80 000
Sitka (*Picea sitchensis*)	59 300

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

Data from US Department of Agriculture (1999) *Wood Handbook: Wood as an Engineering Material*. Madison, WI: US Department of Agriculture Forest Service; Niemz P (1993) *Physik des Holzes und der Holzwerkstoffe*. Weinbrenner, Germany: DRW-Verlag.

number of tests must be performed to obtain a reasonable estimate of parameters. Likewise, any calculation of dependent elasticity parameters based on experimental data must account for the stochastic

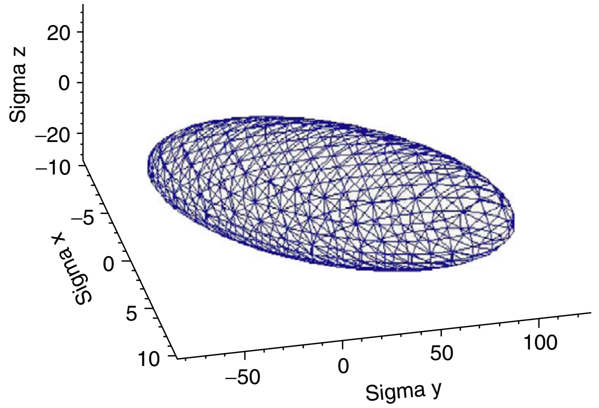

Figure 4 Typical strength surface for wood loaded by biaxial normal stress and shear.

nature of these parameters. Various sources of variability exist: for example, variability 'within' refers to the variability between specimens from within one board; variability 'between' is the variability resulting from differences between boards. **Table 6** lists the average variabilities of some mechanical properties of clear wood specimens.

Variability of mechanical properties of wood composites is significantly lower than that of solid wood but the same sources of variability exist.

Effect of Environmental Factors on Mechanical Properties

Environmental factors such as temperature, relative humidity of air (and associated equilibrium moisture content (EMC)), and their combination affect mechanical properties of wood and wood materials. Generally, the elasticity and strength parameters decrease with increased temperature and moisture content. Commonly, a linear function is used to approximate the change in mechanical properties with change in moisture content and temperature. It is assumed that moisture content change beyond fiber saturation point (FSP) will not significantly affect mechanical properties (**Figure 5**). One can calculate the mechanical property at any moisture content between 0% and FSP as

$$A_{MC} = A_{12}\left(\frac{A_{12}}{A_g}\right)^{\frac{12\text{-}MC}{M_P\text{-}12}}$$

where A_{MC} = property at desired moisture content, MC; A_{12} = property at 12% moisture content; A_g = property at MC above FSP; M_P = moisture content at which the properties of wood start to change when wood is dried from green (wet) condition (above FSP). This value can be taken as 25 for most species. The relationship between the

Table 6 Average coefficients of variation for some mechanical properties of solid wood and wood composites

Property	*Coefficient of variation (%)*			
	Solid wood	*Particleboard*	*Plywood*	*Medium density fiberboard (MDF)*
Bending strength	7–20[a]	8–10		
Modulus of elasticity in bending	9–23[a]			
Impact bending	25[b]			
Compression parallel to grain	8–20[a]		5–13[c]	
Compression perpendicular to grain	28[b]			
Shear parallel to grain, maximum shearing strength	14–22[a]		6–11[c]	
Tension parallel to grain	25[b]	12	18 6–16[c]	8
Side hardness	20[b]			
Toughness	34[b]			
Specific gravity	5–13[a]	2–6		

[a] Range of variabilities based on results of about 20 different species.
[b] Values based on results of tests of green wood from approximately 50 species. Same variation can be expected for wood at 12% moisture content.
[c] 6–27 specimens. Askhenazi EK and Ganov EV (1980) *Anizotropia Konstrukcionnych Materialov*. Leningrad, USSR: Machinostroenie.
Data from US Department of Agriculture (1999) *Wood Handbook: Wood as an Engineering Material*. Madison, WI: US Department of Agriculture Forest Service; Niemz P (1993) *Physik des Holzes und der Holzwerkstoffe*. Weinbrenner, Germany: DRW-Verlag.

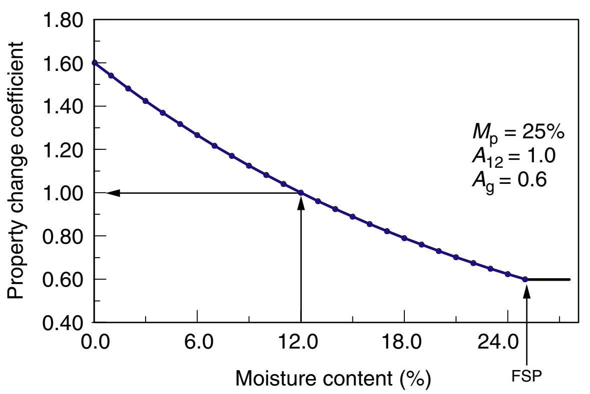

Figure 5 Effect of moisture content on mechanical properties of wood at constant temperature. For equations, see text. FSP, fiber saturation point.

MC and wood mechanical properties below FSP can also be approximated by a straight line. In general, values of mechanical properties of wood decrease with increased temperature. As with any polymeric material, the change in mechanical properties will depend on a glass transition temperature of individual wood components (*see* **Wood Formation and Properties**: Chemical Properties of Wood). The temperature effects can be either reversible (for temperatures below 100°C and relatively fast temperature changes, e.g. heating followed by immediate cooling) or irreversible (temperatures above 100°C or extended exposure to elevated temperature even below 100°C). Up to about 150°C, the decrease in elasticity and strength properties is approximately proportional to the increase in temperature and duration of heating.

Table 7 Effect of heating of Sitka spruce and Douglas-fir wood on bending strength of small clear wood (% at time = 0)

Time (hours)	*Temperature (°C)*			
	93	*120*	*150*	*175*
0	100	100	100	100
8	98	92	75	50
16	98	86	68	—
24	98	84	65	—
32	98	84	62	—

Data from US Department of Agriculture (1999) *Wood Handbook: Wood as an Engineering Material*. Madison, WI: US Department of Agriculture Forest Service.

The combined effect of moisture content and temperature is more complicated due to interaction between temperature and moisture content. **Table 7** shows the effect of temperature on bending strength of clear wood and **Figure 6** shows the effect of temperature and moisture content. Strength of wet wood decreases more rapidly with increased temperature than does strength of dry wood. **Figure 7** shows that temperature change affects various mechanical properties differently. From **Figures 6** and **7**, it follows that the time–temperature–moisture content interaction affects the rate at which mechanical properties of wood degrade. The relationships in the figures represent the trends and average properties. **Figure 8** shows the relative change in some strength and elasticity parameters of beech under elevated temperature and moisture.

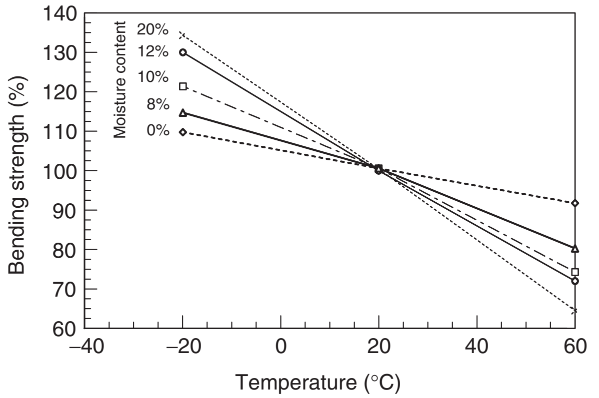

Figure 6 Combined effect of temperature and moisture on bending strength of wood. Data from Niemz P (1993) *Physik des Holzes und der Holzwerkstoffe*. Weinbrenner, Germany: DRW-Verlag and Dinwoodie JM (1981) *Timber, its Nature and Behavior*. New York: Van Nostrand Reinhold.

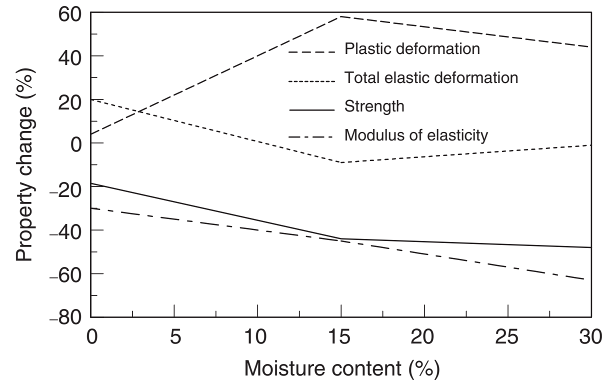

Figure 8 Relative change in mechanical properties of beech wood in bending under elevated temperature and moisture. Data from Kúdela J (1990) *Effects of Moisture Contents and Temperature on Mechanical Properties of Beech Wood*. PhD dissertation. Zvolen Slovakia: Technical University Zvolen.

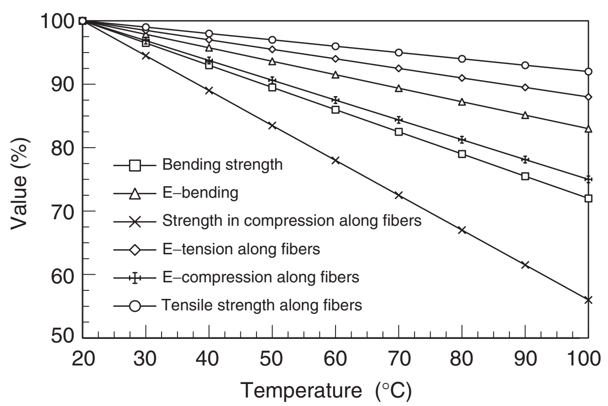

Figure 7 Effect of temperature on mechanical properties of wood. Data from Niemz P (1993) *Physik des Holzes und der Holzwerkstoffe*. Weinbrenner, Germany: DRW-Verlag.

Effect of Load History (Time) on Mechanical Properties of Wood and Wood Composites

Wood and wood materials can be considered viscoelastic materials. This means that the response of wood to the load will be affected by the load history. For example, deflection of a beam loaded by a constant load will increase with time (creep). If a fixed displacement is induced on a beam, then, over time, the load to maintain this displacement will decrease (stress relaxation). **Figure 9** shows the results of creep and stress relaxation experiments. The creep rate (or stress relaxation rate) increases with increased moisture contents (mechanosorptive creep) and temperature. Cyclic changes (temperature, moisture, or a combination of the two) further accelerate creep with increased creep rate during drying. However, wet wood will creep faster than dry wood if no changes in moisture content take place.

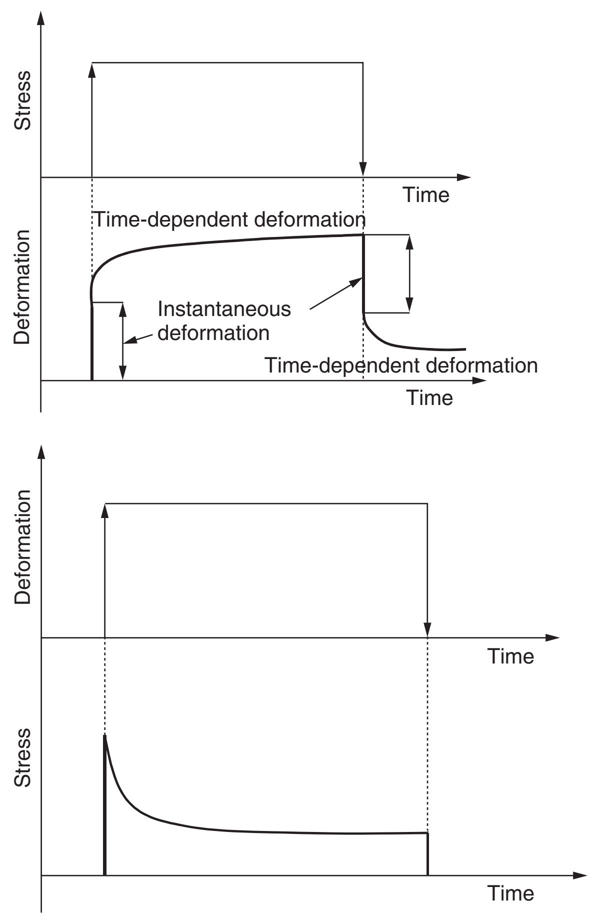

Figure 9 Creep and stress relaxation experiments.

Increase in temperature will significantly increase the creep rate. Creep can be observed in wood composites where the total creep is a sum of the creep in wood material and wood–adhesive interface. Generally, creep rate of composites with nonwater resistant adhesives can be significantly higher than the creep rate for solid wood, especially under changing moisture conditions. Time delayed failure (creep failure) can occur as a result of creep or mechanosorptive creep. Various phenomenological models are used to model creep or stress relaxation of wood and wood composites (combination of dashpots, springs, and other elements such as ratchet element or frictional element) (**Figure 10**).

Dynamic Load and Fatigue

The apparent strength of wood and wood materials increases with increased rate of loading. The effect of load rate is shown in **Figure 11**. From **Figure 11** it follows that the apparent strength under impact load will be about 120% of the strength value obtained from the static test. Material (viscous) damping of wood and wood composites is very low, generally not exceeding 3%. Fatigue of the material is defined as number of cycles at given stress level (usually as a percentage of the ultimate stress) at which the material fails. The cycles can be zero or nonzero mean cycles. **Figure 12** shows the average fatigue life of wood loaded in bending by a cyclic load. The fatigue life is influenced by the environmental factors in the same way as the static parameters (monotonic load), except for the moisture content effect that is about twice larger for dynamically loaded wood.

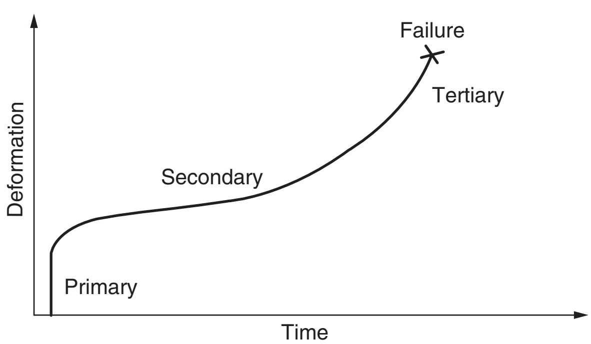

Figure 10 Primary, secondary, and tertiary stages of creep.

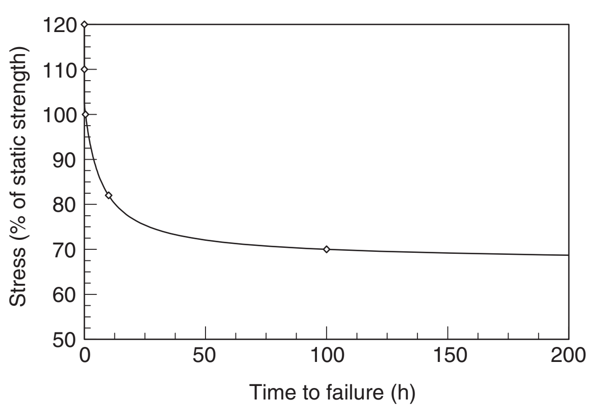

Figure 11 Time to the failure for small clear specimens of wood loaded in bending. Wood Handbook 1999.

Nonengineering Mechanical Properties

Other mechanical properties that can be defined are those associated with various end-use requirements and may include: abrasion properties, cleavage strength, nail or screw withholding capacities, dynamic impact resistance (toughness), hardness, etc. Since most of these parameters depend on testing procedures, the values have only comparative character.

Small Clear Specimens versus Full-Size Member Tests

Material properties of wood and wood composites are determined from standard tests of small clear specimens. Small clear specimens do not contain any defects such as knots or slope of grain and the values listed for small clear specimens, in most cases, will represent upper bounds for mechanical properties. In structural applications (*see* **Solid Wood Products**: Structural Use of Wood), members will contain natural defects and mechanical properties will be determined from full-size members containing the defects. The size, location, and number of the defects significantly affect the material strength and the variability of the properties.

Relationship between Mechanical Properties and Anatomical Structure of Wood

Wood anatomical structure significantly affects the mechanical properties of wood and wood

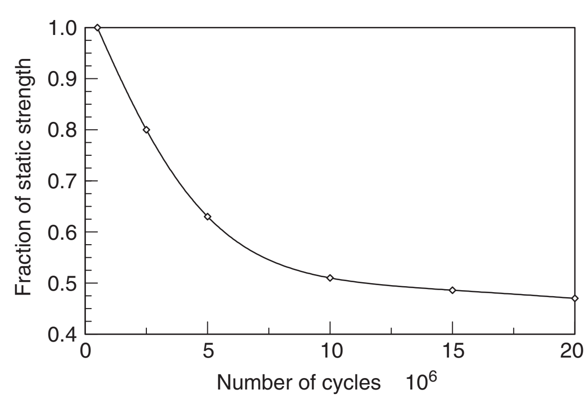

Figure 12 Fatigue life of wood. Data from Kollmann F (1952) *Technologie des Holzes und der Holzwerkstoffe*, 2nd edn. Berlin: Springer-Verlag.

composites. Parameters such as fiber length, wood density, orientation of microfibrils, and chemical composition of wood affect the properties of wood significantly. While a qualitative effect of anatomical features can be defined, the quantitative effect of these parameters is more difficult to establish. The mechanical properties are significantly affected by wood density, which is directly related to the cell wall thickness. Increasing the thickness of cell walls of latewood tracheids of pine by 36% and larch by 20% results in an increase in wood density by 18% and 20%, respectively. This increase in cell wall thickness will result in increase in compressive strength along fibers by 70–83%. **Figure 13** shows the influence of specific gravity on wood mechanical properties. The figures are based on average data and the relationships for individual species vary. The relationships are approximately linear. **Figure 14** shows the relationship between percentage of latewood and wood density and **Figure 15** demonstrates the effect of specific gravity on compressive strength. Other anatomical features, such as microfibril angle, ray size and proportion, and fiber length will significantly affect mechanical properties of solid wood. Slope of grain significantly affects mechanical properties and a simplified relationship between slope of grain and individual elastic or strength parameters known as Hankinson's formula is commonly used to estimate off-axis properties:

$$A_\alpha = \frac{A_0 A_{90}}{A_0 \sin^n(\alpha) + A_{90} \cos^n(\alpha)}$$

where A_α = property at angle α with respect to fibers, A_0 = property at zero angle with respect to fibers, A_{90} = property at 90° angle with respect to fibers, and α = angle.

Table 8 list values of exponent, n, based on the ratios of transverse and longitudinal properties $\frac{A_{90}}{A_0}$. The quantitative relationship between anatomical

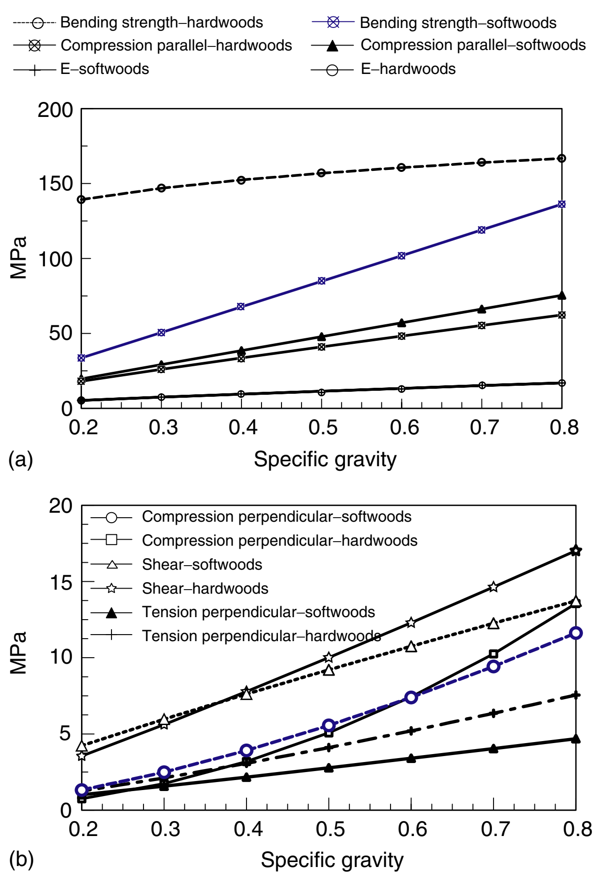

Figure 13 Effect of the specific gravity on mechanical properties of wood (oven dry weight and volume at 12% moisture content).

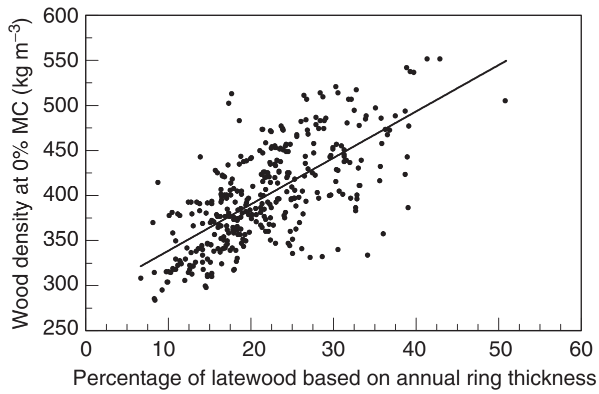

Figure 14 Effect of proportion of latewood on wood density for larch. Data from Dinwoodie JM (1981) *Timber, its Nature and Behavior*. New York: Van Nostrand Reinhold and Pozgaj A, Chovanec D, Kurjatko S and Babiak M (1993) *Structure and Properties of Wood*. Bratislava, Slovakia: Priroda Bratislava (in Slovak).

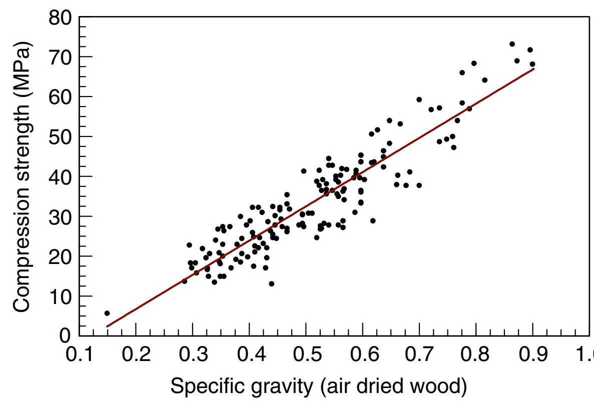

Figure 15 Effect of specific gravity on compression strength along fibers. Data from Dinwoodie JM (1981) *Timber, its Nature and Behavior*. New York: Van Nostrand Reinhold and Pozgaj A, Chovanec D, Kurjatko S and Babiak M (1993) *Structure and Properties of Wood*. Bratislava, Slovakia: Priroda Bratislava (in Slovak).

Table 8 Exponents in Hankinson's formula[a]

Property	*n*	A_{90}/A_0
Tensile strength	1.5–2	0.04–0.07
Compression strength	2–2.5	0.03–0.40
Bending strength	1.5–2	0.04–0.10
Modulus of elasticity	2	0.04–0.12
Toughness	1.5–2	0.06–0.10
Average exponent recommended for all properties	2.0	—

Wesche K (1988) *Baustoffe für tragende Bauteile*. Band 4. Holz und Kunstoffe. 2. Auflage (in German). Bauverlag GmbH. Wiesbaden und Berlin.

[a]Wood Handbook (1999) *Wood handbook: Wood as an Engineering Material*. US Forest Service, Forest Products Laboratory, Madison, WI. p. 482.

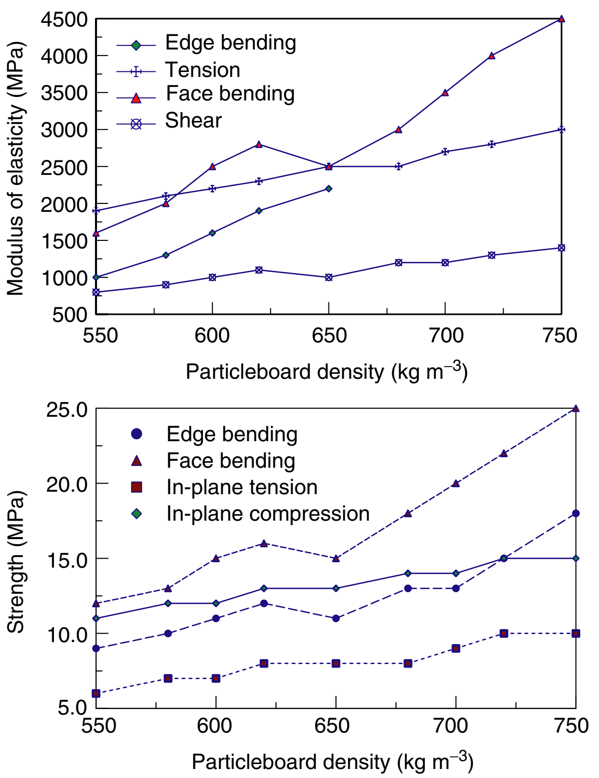

Figure 16 Effect of density on mechanical properties of particleboard. (Data from Niemz P (1993) *Physik des Holzes und der Holzwerkstoffe*. Weinbrenner, Germany: DRW-Verlag.)

features, chemical composition and wood mechanical properties is largely unknown.

Density significantly affects mechanical properties of wood composites and this is shown in **Figure 16**. All mechanical properties will increase with increased density with a linear trend.

See also: **Solid Wood Products**: Structural Use of Wood; Wood-based Composites and Panel Products. **Wood Formation and Properties**: Chemical Properties of Wood; Formation and Structure of Wood; Physical Properties of Wood. **Wood Use and Trade**: History and Overview of Wood Use.

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Physical Properties of Wood

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Introduction

This article addresses the fundamental physical properties of wood (sorptive, fluid transfer, thermal, electrical, and acoustical) that directly affect its processing and service characteristics such as sawing, drying, preservation, machining, gluing, insulation, and mechanosorptive behavior in service as a structural member or as simple panel or piece of furniture. Processing optimization and enhanced design of wood-based products is expected to result from a better understanding of how wood interacts with the environment.