10

WOOD

Wood, because of its availability, relatively low cost, ease of use, and durability, if properly maintained, continues to be an important civil engineering material. Wood is used extensively for buildings, bridges, utility poles, floors, roofs, trusses, and piles. (See Figures 10.1 and 10.2.) Civil engineering applications include both natural wood and engineered wood products, such as laminates, plywood, and strand board. In order to use wood efficiently, it is important to understand its basic properties and limitations. In the United States, the Forest Service of the Department of Agriculture has broad management responsibility for the harvesting of wood from public lands and for assisting private sources with the selection of products for harvesting. This agency has produced an excellent document describing the characteristics and properties of wood (USDA-FS, 1999).

This chapter covers the properties and characteristics of wood. In the design of a wood structure, joints and connections often limit the design elements. These are generally covered in a design class for wood construction and, therefore, are not considered in this text.

Wood is a natural, renewable product from trees. Biologically, a tree is a woody plant that attains a height of at least 6 m (20 ft), normally has a single self-supporting trunk with no branches for about 1.5 m (4 ft) above the ground, and has a definite crown. There are over 600 species of trees in the United States.

Trees are classified as either endogenous or exogenous, based on the type of growth. Endogenous trees, such as bamboo, grow with intertwined fibers. Wood from endogenous trees is not generally used for engineering applications in the United States. Exogenous trees grow from the center out by adding concentric layers of wood around the central core. This book considers only exogenous trees.

Exogenous trees are broadly classified as deciduous and conifers, producing hardwoods and softwoods, respectively. The terms *hardwood* and *softwood* are classifications within the tree family, not a description of the woods' characteristics. In general, softwoods are softer, less dense, and easier

FIGURE 10.1 Wood frame used for building structural support.

FIGURE 10.2 Wooden roller coaster.

to cut than hardwoods. However, exceptions exist such as Balsa, a very soft and lightweight wood that is technically a hardwood.

Deciduous trees generally shed their leaves at the end of each growing season. Commercial hardwood production in the U.S. comes from 40 different tree species. Hardwoods are generally used for furniture and decorative veneers, due to their pleasing grain pattern. The cost of hardwoods limits their construction application.

Conifers, also known as evergreens, have needlelike leaves and normally do not shed them at the end of the growing season. Conifers grow continuously through the crown, producing a uniform stem and homogenous characteristics (Panshin & De Zeeuw, 1980). Softwood production in the U.S. comes from about 20 individual species of conifers. Conifers are widely used for construction. Conifers grow in large stands, permitting economical harvesting. They mature rapidly, making them a renewable resource. Table 10.1 shows examples of hardwood and softwood species (USDA-FS, 1999).

10.1 Structure of Wood

Wood has a distinguished structure that affects its use as a construction material. Civil and construction engineers need to understand the way the tree grows and the anisotropic nature of wood in order to properly design and construct wood structures.

10.1.1 Growth Rings

The concentric layers in the stem of exogenous trees are called *tree rings* or *annual rings*, as shown in Figure 10.3a. The wood produced in one growing season constitutes a single growth ring. Each annual ring is composed of early wood, produced by rapid growth during the spring, and latewood from summer growth. Latewood consists of dense, dark, and thick-walled cells producing a stronger structure than early wood, as shown in Figure 10.3b. The predominant physical features of the tree stem include the *bark, cambium*, *wood*, and *pith*, as shown in Figure 10.4. The bark is the exterior covering of the tree and has an outer and an inner layer. The outer layer is dead and corky and has great variability in thickness, dependent on the species and age of the tree. The inner bark layer is the growth layer for bark but is not part of the wood section of the tree. The cambium is a thin layer of cells situated between the wood and the bark and is the location of all wood growth.

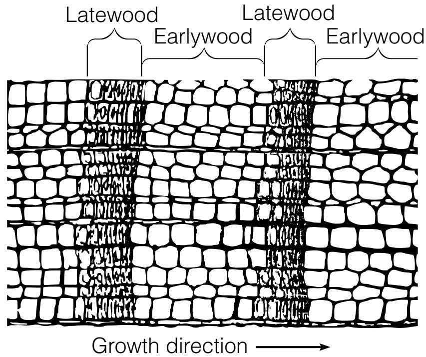
The wood section of the tree is composed of *sapwood* and *heartwood*. Sapwood functions as a storehouse for starches and as a pipeline to transport sap. Generally, faster growing species have thick sapwood regions. In

TABLE 10.1 Major Sources of Hardwood and Softwood Species by Region

Hardwoods			Softwoods		
Western	Northern and Appalachia	Southern	Western	Northern	Southern
Ash	Ash	Red alder	Incense cedar	Northern white cedar	Atlantic white cedar
Basswood	Aspen	Oregon ash	Port Orford cedar	Balsam fir	Bald cypress
American beech	Basswood	Aspen	Douglas-fir	Eastern hemlock	Fraser fir
Butternut	Buckeye	Black cottonwood	Western hemlock	Fraser fir	Southernpine
Cottonwood	Butternut	California black oak	Western larch	Jack pine	Eastern red cedar
Elm	American beech	Big leaf maple	Lodgepole pine	Eastern white pine	
Hackberry	Birch	Paper birch	Ponderosa pine	Eastern red cedar	
Pecan hickory	Black cherry	Tan oak	Sugar pine	Eastern spruces	
True hickory	American chestnut*		Western white pine	Tamarack	
Honey locust	Cottonwood		Western red cedar		
Black locust	Elm		Red wood		
Magnolia	Hackberry		Englemann spruce		
Soft maple	True hickory		Siitka spruce		
Red oak	Honey locust		Yellow cedar		
White oak	Black locust				
Sassafras	Hard maple				
Sweetgum	Soft maple				
American sycamore	Red oak				
Tupelo	White oak				
Black walnut	American sycamore				
Black willow	Black walnut				
Yellow poplar	Yellow poplar				

* Chestnut no longer harvested, but lumber from salvage timbers available.

(a)



(b)

FIGURE 10.3 Cross section of a typical tree stem: (a) annual rings (photo courtesy of American Forest & Paper Association, Washington, D.C.) and (b) earlywood and latewood.

its natural state, sapwood is not durable when exposed to conditions that promote decay. Heartwood is not a living part of the tree. It is composed of cells that have been physically and chemically altered by mineral deposits. The heartwood provides structural strength for the tree. Since the heartwood does not contain sap, it is naturally resistant to decay.

The pith is the central core of the tree. Its size varies with the tree species, ranging from barely distinguishable to large and conspicuous. The color ranges from blacks to whitish, depending on the tree species and locality. The pith structure can be solid, porous, chambered, or hollow.

10.1.2 Anisotropic Nature of Wood

Wood is an anisotropic material in that it has different and unique properties in each direction. The three axis orientations in wood are longitudinal or parallel to the grain, radial or cross the growth rings, and tangential or tangent to the growth rings, as illustrated in Figure 10.4. The anisotropic nature of wood affects physical and mechanical properties such as shrinkage, stiffness, and strength.

The anisotropic behavior of wood is the result of the tubular geometry of the wood cells. The wood cells have a rectangular cross section. The centers of the tubes are hollow, whereas the ends of the tubes are tapered. The length-to-width ratio can be as large as 100. The long dimension of the majority of cells is parallel to the tree's trunk. However, a few cells, in localized bundles, grow radially, from the center to the outside of the trunk. The preponderance of cell orientation in one direction gives wood its anisotropic characteristics. The hollow tube structure is very efficient in resisting compressive stresses parallel to its length, but readily deforms when loaded on its side. Also, fluctuations in moisture contents flex the tube walls but have little effect on the length of the tube.

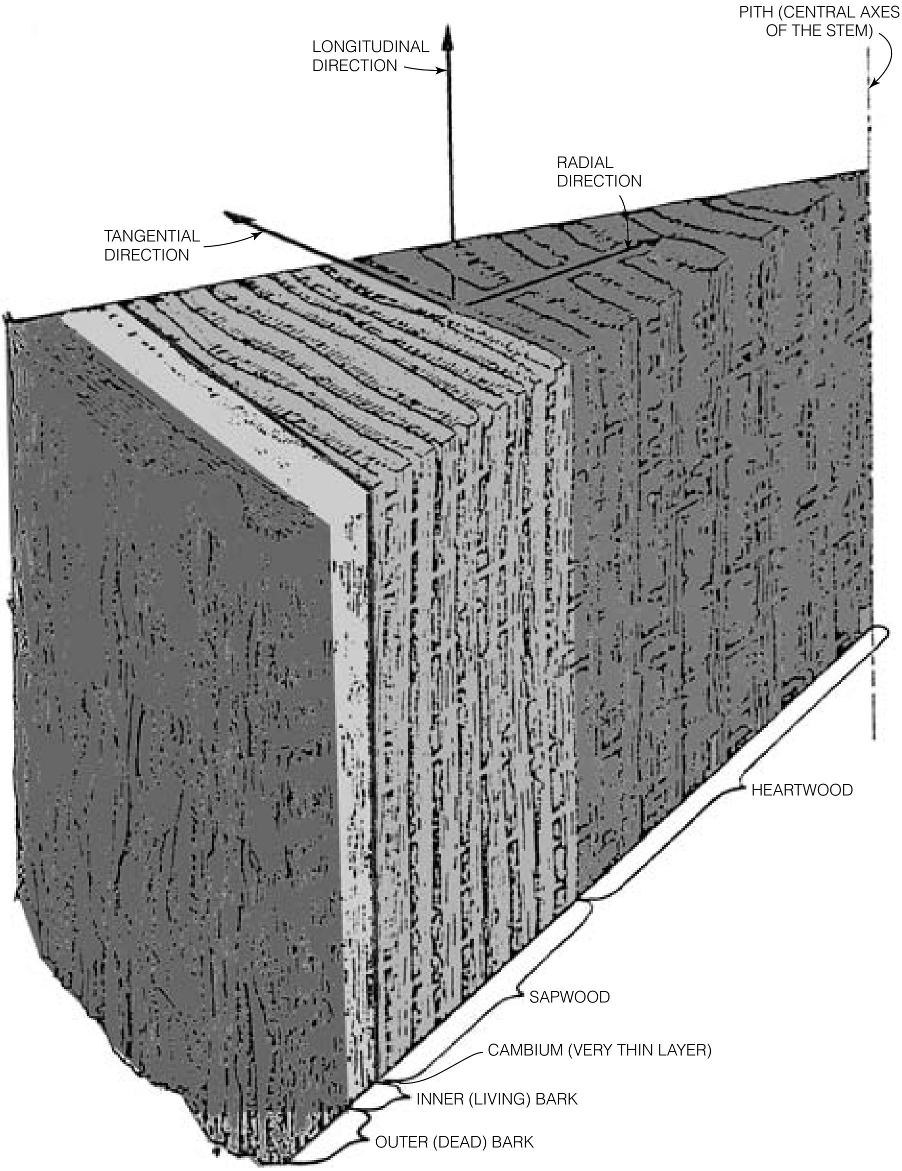


FIGURE 10.4 Main structural features of a typical tree stem.

10.2 Chemical Composition

Wood is composed of cellulose, lignin, hemicellulose, extractives, and ash producing minerals. Cellulose accounts for approximately 50 percent of the wood substance by weight (USDA-FS, 1999). The exact percent is species dependent. It is a linear polymer (aliphatic carbon compound) having a high molecular weight. The main building block of cellulose is sugar–glucose. As the tree grows, linear cellulose molecules arrange themselves into highly ordered strands, called *fibrils*. These ordered strands form the large structural elements that compose the cell walls of wood fibers.

Lignin accounts for 23% to 33% of softwood and 16% – 25% of hardwood by weight. Lignin is mostly an intercellular material. Chemically, lignin is an intractable, insoluble, material that is loosely bonded to the cellulose. Lignin is basically the glue that holds the tubular cells together. The longitudinal shear strength of wood is limited by the strength of the lignin bounds.

Hemicelluloses are polymeric units made from sugar molecules. Hemicellulose is different from cellulose in that it has several sugars tied up in its cellular structure. Hardwood contains 20% to 30% hemicellulose and softwood averages 15% to 20%. The main sugar units in hardwood and softwood are xylose and monnose, respectively.

The extractives compose 5% to 30% of the wood substance. Included in this group are tannins and other polyphenolics, coloring matters, essential oils, fats, resins, waxes, gums, starches, and simple metabolic intermediates. These materials can be removed with simple inert neutral solvents, such as water, alcohol, acetone, and benzene. The amount contained in an individual tree depends on the species, growth conditions, and time of year the tree is harvested.

The ash-forming materials account for 0.1% – 3.0% of the wood material and include calcium, potassium, phosphate, and silica.

10.3 Moisture Content

The moisture content of a wood specimen is the weight of water in the specimen expressed as a percentage of the oven-dry weight of the wood. An oven-dried wood sample is a sample that has been dried in an oven at 100°C to 105°C (212°F to 220°F) until the wood attains a constant weight. Physical properties such as weight, shrinkage, and strength depend on the moisture content of wood.

Moisture exists in wood as either *bound or free water*. Bound water is held within the cell wall by adsorption forces, whereas free water exists as either condensed water or water vapor in the cell cavities. In green wood, the cell walls are saturated. However, the cell cavities may or may not contain free water. The level of saturation at which the cell walls are completely saturated, but no free water exists in the cell cavities, is called the *fiber saturation point* (FSP). FSP varies from species to species, but is typically in the range of 21% to 32%. The FSP is of great practical significance, because the addition or removal of moisture below the FSP has a large effect on practically all physical and mechanical properties of wood, whereas above the FSP, the properties are independent of moisture content.

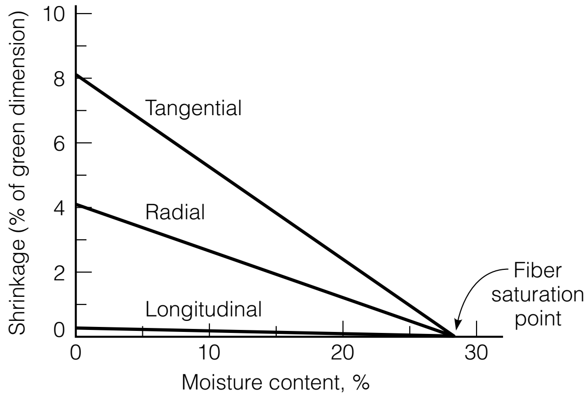


FIGURE 10.5 Relation between shrinkage and moisture content.

When the moisture content of wood is above the fiber saturation point, the wood is dimensionally stable. However, moisture fluctuations below the FSP always result in dimensional changes. Shrinkage is caused by loss of moisture from the cell walls, and conversely, swelling is caused by the gain of moisture in the cell walls. Figure 10.5 shows that the changes in wood dimensions vary from one direction to another. Dimensional changes in the radial direction are generally one-half the change in the tangential direction. Swelling and shrinkage in the longitudinal direction is minimal, typically 0.1% to 0.2% for a change in the moisture content from the FSP to oven dry. This anisotropy of dimensional changes of wood causes warping, checking, splitting, and structural performance problems, as discussed in more detail later in the chapter. It is also the reason that the sawing pattern of boards affects the amount of distortion when subjected to changes in moisture.

The moisture content in wood varies depending on air temperature and humidity. However, the natural change of moisture content is a slow process, so as atmospheric conditions change, the moisture content in wood tends to adjust to conditions near the average. The moisture content for the average atmospheric conditions is the *equilibrium moisture content (EMC)*. The Forest Service has developed values of the EMC as a function of temperature and humidity. The EMC ranges from less than 1%, at temperatures greater than 55°C (130°F) and 5% humidity, to over 20% at temperatures less than 27°C (80°F) and 90% humidity.

Sample Problem 10.1

A 250-mm wide Red Spruce plank is cut in such a way that the width is in the tangential direction of annual rings. Compute the change in width as the moisture content changes from 15% to 32%. (The fiber saturation point of Red Spruce is 27% and it shrinks 7.8% in drying from FSP to oven dry in the tangential direction.)

Solution

Swell does not occur above FSP. Increasing the moisture content from 15% to 27% causes swell. From the data given, Red Spruce swells 7.8% for a 27% change in moisture content (from zero moisture content to FSP).

$$\text{Percent swell} = (7.8/27) \times (27 - 15) = 3.5\%$$

$$\text{Change in dimension} = 250 \times (3.5/100) = 8.7 \text{ mm}$$

$$\text{New dimension} = 258.7 \text{ mm}$$

10.4 Wood Production

Trees are harvested in the fall or winter, because of their water content and environmental concerns connected with fire hazard and other plant growth. A vast industry has developed to harvest and process wood. Wood is harvested from forests as *logs*. They are transported to saw mills, where they are cut into dimensional shapes to produce a variety of products for engineering applications:

1. *Dimensional lumber* is wood from 50 mm to 125 mm (2 in. to 5 in.) thick, sawn on all four sides. Common shapes include 2 × 4, 2 × 6, 2 × 8, 2 × 10, 2 × 12, and 4 × 4.[1] These sizes refer to the rough-sawn dimensions of the lumber in inches. The rough-sawn lumber is surfaced to produce smooth surfaces; this removes 5 mm to 10 mm (1/4 in. to 3/8 in.) per side. For example, the actual dimensions of a 2 × 4 are 40 mm by 90 mm ($1\frac{1}{2}$ in. by $3\frac{1}{2}$ in.). Dimensional lumber is produced in lengths of 2.4 m to 7.2 m (8 ft. to 24 ft.) in 0.6 m (2 ft.) increments. Dimensional lumber is typically used for studs, sill and top plates, joints, beams, rafters, trusses, and decking.
2. *Heavy timber* is wood sawn on all four sides; common shapes include 4 × 6, 6 × 6, 8 × 8, and larger. As with the case of dimensional lumber, these sizes specify rough-sawn dimensions in inches. Surfacing generally removes 10 mm (3/8 in.) per side. Heavy timbers are used for heavy frame construction, landscaping, railroad ties, and marine construction.
3. *Round stock* consists of posts and poles used for building poles, marine piling, and utility poles.
4. *Engineered wood* consists of products manufactured by bonding together wood strands, veneers, lumber, and other forms of wood fiber to produce a larger and integral composite unit. These products are engineered and

1. The standards for dimensional lumber and heavy timber standards were implemented in about 1970. When remodeling older structures, the dimension of the existing lumber must be measured.

tested to have specific mechanical responses to loads. Structural engineered wood products include the following:

- structural panels including plywood, oriented strand board, and composite panels,
- glued laminated timber (glulam),
- structural composite lumber, and
- composite structural members.

5. Specialty items are milled and fabricated products to reduce on-site construction time, includes lattice, handrails, spindles, radius edge decking, turned posts, etc.

   Sawn wood production includes the following steps:

- Sawing into desired shape
- Seasoning
- Surfacing
- Grading
- Preservative treatment (optional)

Surfacing (planing) of the wood surface, to produce a smooth face, can be done before or after drying. Post drying surfacing is superior, because it removes small defects developed during the drying process. When surfacing is done before seasoning, the dimensions are slightly increased to compensate for shrinkage during seasoning.

10.4.1 Cutting Techniques

The harvested wood is cut into lumber and timber at saw mills using circular saws, band saws, or frame saws. The most common patterns for sawing a log are *plain (slash), quarter*, and *combination sawing*, as shown on Figure 10.6. (Levin, 1972).

The quality of the boards is related to the angle the growth rings make with the face of the board (i.e., the angle between the growth ring and the saw blade). There are three categories, as illustrated in Figure 10.7:

1. Flat-sawn, 45° or less
2. Rift-sawn, 45° to 80°
3. Vertical- or edge-sawn, 80° to 90°

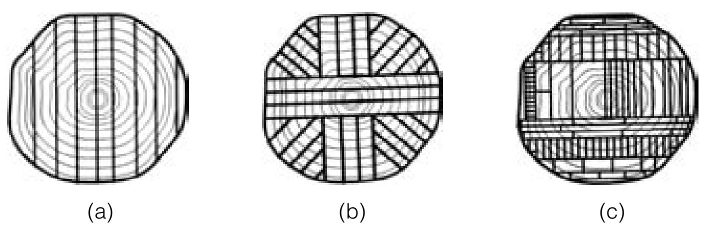


FIGURE 10.6 Common log sawing patterns: (a) plain sawing, (b) quarter sawing, and (c) combination sawing.

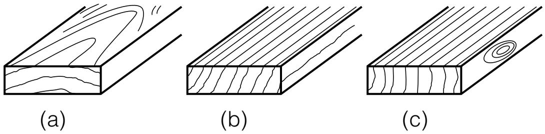


FIGURE 10.7 Types of board cut: (a) flat sawn, (b) rift sawn, and (c) vertical- or edge-sawn.

Flat-sawn boards have desirable exposure of grain for decorative applications. However, flat sawn boards tend to distort more than vertical-sawn boards in response to moisture fluctuations. Hence, vertical-sawn boards are generally better for structural applications.

The sawing pattern selected depends on the cross section of the tree, the capability of the mill, and the desired product. Plain sawing is rapid and economic, whereas quarter sawing maximizes the amount of vertical-sawn cuts. Some of the advantages of the different sawing patterns are summarized in Table 10.2 (USDA-FS, 1999).

10.4.2 Seasoning

Green wood, in living trees, contains from 30% to 200% moisture by the oven-dry weight. Seasoning removes the excess moisture from wood. For structural wood, the recommended moisture content varies from 7% in the

TABLE 10.2 Relative Advantages of Plain-sawn and Quarter-sawn Lumber

Plain-sawn	Quarter-sawn
Shrinks and swells less in thickness	Shrinks and swells less in width
Surface appearance less affected by round or oval knots,compared to effect of spike knots in quartersawn boards; boards with round or oval knots not as weak as boards with spike knots	Cups, surface checks, and splits less in seasoning and in use
Shakes and pitch pockets, when present, extend through fewer boards	Raised grain caused by separation in annual rings does not become as pronounced
Figure patterns resulting from annual rings and some other types of figure brought out more conspicuously	Figure patterns resulting from pronounced rays, interlocked grain, and wavy grain are brought out more conspicuously
Less susceptible to collapse in drying	Does not allow liquids to pass through readily in some species
Costs less because it is easy to obtain	Holds paint better in some species
	Sapwood appears in boards at edges and its width is limited by the width of the log

dry southwestern states to 14% in the damp coastal regions. However, as it leaves the mill, framing lumber typically has an average moisture content of 15%.

Wood is seasoned by air and kiln drying. Air drying is inexpensive, but slow. The green lumber is stacked in covered piles to dry. These piles of lumber are made of successive layers of boards separated by 25 mm (1 inch) strips so that air can flow between the layers. The time required for drying varies with the climate and temperature of the area. Normally, three to four months is the maximum air drying time used in the U.S. Air drying is complete when the moisture content of the wood is in equilibrium with the air humidity. The optimum moisture may not be achievable through air drying alone.

After air drying the lumber may be kiln dried. A kiln is a large oven where all variables can be closely monitored. Drying temperatures in a kiln range from 20°C to 50°C (70°F to 120°F), typically requiring 4 to 10 days. Care must be taken to slowly reduce the moisture content of wood. Drying too rapidly can result in cracking and warping. Kiln-dried lumber will take on moisture again if exposed to water; therefore, care must be used when storing and transporting wood.

10.5 Lumber Grades

The final step in wood production involves grading the lumber according to quality. Typically, lumber is graded according to the number of flaws that affect strength, durability, or workability. The most common grade-reducing qualities of lumber are knots, checks, pitch pockets, shakes, and stains. Due to the high degree of natural variability within lumber, it is nearly impossible to develop an exact, uniform set of grading standards. As a result, grading techniques and standards can, and do, vary among organizations. Organizations such as the National Bureau of Standards and the United States Department of Agriculture have spent many years trying to develop a simple, uniform method of lumber sizing, common nomenclature, and grading standards.

The following agencies are certified by the American Lumber Standards Committee Board of Review (Germantown, MD) for inspecting and grading of untreated lumber:

- Northeastern Timber Manufacturer Association (NELMA), Falmouth, MN
- Northern Hardwood and Pine Manufacturer Association (NHPMA), Green Bay, WI
- Redwood Inspection Service (RIS), San Francisco, CA
- Southern Pine Inspection Bureau (SPIB), Pensacola, FL
- West Coast Lumber Inspection Bureau (WCLIB), Portland, OR
- Western Wood Products Association (WWPA), Portland, OR
- National Lumber Grader Authority (NLGA), Ganges, B.C., Canada

Each of these agencies writes standards and specifications for particular species or combinations of species that are produced within their operating region. For example, the SPIB provides the grading rules for all species of Southern Pine, the WWPA governs grading of Ponderosa Pine, and the NLGA provides grading rules for all grades produced in Canada.

10.5.1 Hardwood Grades

The National Hardwood Lumber Association bases the grading of hardwood on the amount of usable lumber in each piece of standard length lumber. The inspection is performed on the poorest side of the material and the grade is based on the number and size of clear "cuttings" that can be produced from a given piece of lumber. Cuttings must have one face clear of strength-reducing imperfections and the other side must be sound. Based on "cutting" quantity, the wood is given a classification of *Firsts, Seconds, Selects*, and *Common* (No. 1, No. 2, No. 3A, or 3B), with Firsts being the best. Frequently, Firsts and Seconds are grouped into one grade of Firsts and Seconds, FAS.

10.5.2 Softwood Grades

Softwood for structural applications is either graded by visual inspection or is machine stress graded. The purpose of grading is to ensure that all lumber graded to a specific grade designation has at least the minimum mechanical or load-carrying capability with respect to critical design parameters. Under machine stress grading, each piece of wood is subjected to a bending stress, then based on the mechanical response, the wood is graded, as shown in Table 10.3. The grade designation identifies the minimum extreme fiber bending stress, tensile stress parallel to grain, compressive stress parallel to grain, and modulus of elasticity of the wood.

For visual classification, the basic mechanical properties of the wood are determined by testing small clear wood specimens. These results are then adjusted for allowable defects and characteristics for each class of wood. Unlike stress graded lumber, visual stress grade properties are defined for each species of softwood. Table 10.4 is an example of design values for grades of Eastern White Pine.

Visual grade designations include *Yard, Structural*, or *Factory and Shop*, with subgrades of Select, Select B, Select C, and No. 1, No. 2, and No. 3 commons, appearance, and studs. Other commonly used ratings are *Construction, Standard*, or *Utility* and combinations such as No. 2&BTR (Number 2 and Better) and STD&BTR. Not all grades are used for all species of wood.

Yard lumber frequently refers to some specialty stress grades of lumber such as those used for light structural framing. Structural lumber typically comprises pieces 50 mm to 125 mm (2 in. to 5 in.) thick and is graded according to its intended use. Grading categories include light framing, joists and planks, beams and stringers, and posts and timbers. Factory and shop lumber includes siding, flooring, casing, shingles, shakes, and finish lumber.

TABLE 10.3 Sample of Stress Grading of Softwood for Structural Applications[1,4]

Grade Designation	Design Values,[2] psi				
	Bending[3]	Tension Parallel to Grain	Compression Parallel to Grain	Modulus of Elasticity	Minimum Modulus of Elasticity
900f-1.0E	900	350	1,050	1,000,000	510,000
1650f-1.3E	1,650	1,020	1,700	1,300,000	660,000
1950f-1.5E	1,950	1,375	1,800	1,500,000	760,000
2250f-1.7E	2,250	1,750	1,925	1,700,000	860,000
2400f-2.0E	2,400	1,925	1,975	2,000,000	1,020,000
2850f-2.3E	2,850	2,300	2,150	2,300,000	1,170,000
3000f-2.4E	3,000	2,400	2,200	2,400,000	1,220,000

[1] Courtesy of American Forest & Paper Association, Washington, D.C.
[2] Stresses apply to lumber used at 19 percent maximum moisture content. When lumber is designed for use where the moisture content will exceed 19 percent for an extended period of time, the values shown herein shall be multiplied by certain *wet service* factors.
[3] Bending values are applicable to lumber loaded on edge. When loaded flatwise, these values may be increased by multiplying by certain *flat use* factors.
[4] For a complete list of grade designations and more detailed design values see reference (American Forest & Paper Association, 2005).

10.6 Defects in Lumber

Lumber may include defects that affect either its appearance, mechanical properties, or both. These defects can have many causes, such as natural growth of the wood, wood diseases, animal parasites, too rapid seasoning, or faulty processing. Common defect types are shown in Figure 10.8.

Knots are branch bases that have become incorporated into the wood of the tree trunk or another limb. Knots degrade the mechanical properties of lumber, affecting the tensile and flexural strengths. However, the presence of sound, tight knots may increase the compressive strength, hardness, and shear characteristics of the wood.

Shakes are lengthwise separations in the wood occurring between annual rings. They develop prior to cutting the lumber and could be due to heavy winds.

Wane is bark or other soft material left on the edge of the board.

Sap Streak is a heavy accumulation of sap in the fibers of the wood, which produces a distinctive streak in color.

TABLE 10.4 Example of Design Values of Eastern White Pine[1,4]

		Design Values,[2] psi						
Grade Designation	Size Classification	Bending[3]	Tension Parallel to Grain	Shear Parallel to Grain	Compression perpendicular to Grain	Compression Parallel to Grain	Modulus of Elasticity	Minimum Modulus of Elasticity
Select Structural		1,250	575	135	350	1,200	1,200,000	440,000
No. 1		775	350	135	350	1,000	1,100,000	400,000
No. 2	2" & wider	575	275	135	350	825	1,100,000	400,000
No. 3		350	150	135	350	475	900,000	330,000
Stud	2" & wider	450	200	135	350	525	900,000	330,000
Construction		675	300	135	350	1,050	1,000,000	370,000
Standard	2"–4" wide	375	175	135	350	850	900,000	330,000
Utility		175	75	135	350	550	800,000	290,000

[1]Courtesy of American Forest & Paper Association, Washington, D.C.
[2]Stresses apply to lumber used at 19 percent maximum moisture content. When lumber is designed for use where the moisture content will exceed 19 percent for an extended period of time, the values shown herein shall be multiplied by certain *wet service* factors.
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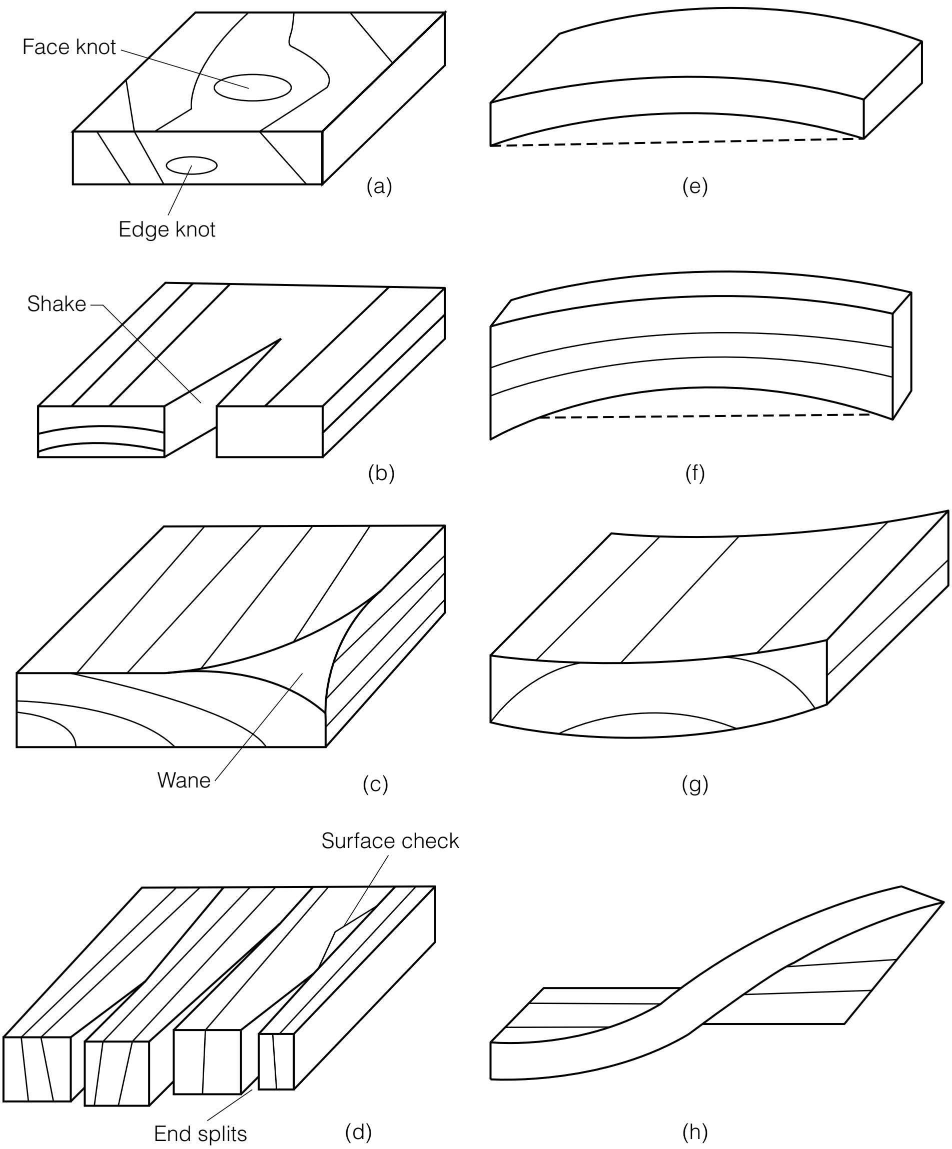


FIGURE 10.8 Common defects in lumber: (a) knots, (b) shakes, (c) wanes, (d) checks and splits, (e) bowing, (f) crooking, (g) cupping, and (h) twisting.

Reaction Wood is abnormally woody tissue that forms in crooked stems or limbs. Reaction wood causes the pith to be off center from the neutral axis of the tree. It creates internal stresses which can cause warping and longitudinal cracking.

Pitch Pockets are well-defined openings between annual rings that contain free resin. Normally, only Douglas fir, pines, spruces, and western larches have pitch pockets.

Bark Pockets are small patches of bark embedded in the wood. These pockets form as a result of an injury to the tree, causing death to a small area of the cambium. The surrounding tree continues to grow, eventually covering the dead area with a new cambium layer.

Checks are ruptures in wood along the grain that develop during seasoning. They can occur on the surface or end of a board. Surface checking results from the separation of the thinner-walled early wood cells and is confined mostly to planner surfaces. Cracks due to end checking normally follow the grain and result in end splitting.

Splits are lengthwise separations of the wood caused by either mishandling or seasoning.

Warping is a distortion of wood from the desired true plane. The four major types of warping are *bowing, crooking, cupping*, and *twisting*. Bowing is a longitudinal curvature from end to end. Crooking is the longitudinal curvature side to side. Both of these defects result from differential longitudinal shrinkage. Cupping is the rolling of both edges up or down. Twisting is the lifting of one corner out of the plane of the other three. Warping results from differential drying due to the production environment or from the release of internal tree stress.

Raised, Loosened, or Fuzzy Grain may occur during cutting and dressing of lumber.

Chipped or Torn Grain occurs when pieces of wood are scooped out of the board surface or chipped away by the action of the cutting and planning tools.

Machine Burn is an area that has been darkened by overheating during cutting.

10.7 Physical Properties

Important physical properties include specific gravity and density, thermal properties, and electrical properties.

10.7.1 Specific Gravity and Density

Specific gravity of wood depends on cell size, cell wall thickness, and number and types of cells. Regardless of species, the substance composing the cell walls has a specific gravity of 1.5. Because of this consistency, specific gravity is an excellent index for the amount of substance a dry piece of wood actually contains and is nearly constant within each species. Therefore, specific gravity, or density, is a commonly cited property and is an indicator of mechanical properties within a clear, straight-grained wood.

The dry density of wood ranges from 160 kg/m^3 (10 pcf) for balsa to 1000 kg/m^3 (65 pcf) for some species. The majority of wood types have densities in the range of 300 to 700 kg/m^3 (20 to 45 pcf). Within common domestic species, density may vary by ±10%.

10.7.2 Thermal Properties

Thermal conductivity, specific heat, thermal diffusivity, and coefficient of thermal expansion are the four significant thermal properties of wood.

Thermal Conductivity Thermal conductivity is a measure of the rate at which heat flows through a material. The reciprocal of thermal conductivity is the thermal resistance (insulating) value (R). Wood has a thermal conductivity that is a fraction of that of most metals and three to four times greater than common insulating materials. The thermal conductivity ranges from 0.06 W/(m°K) [0.34 Btu/(h-ft-°F)] for balsa to 0.17 W/(m°K) [1.16 Btu/(h-ft-°F)] for rock elm. Structural woods average 0.12 W/(m°K) [0.07 Btu/(h-ft-°F)] as compared to 200 W/(m°K) [115 Btu/(h-ft-°F)] for aluminum and 0.04 W/(m°K) [0.025 Btu/(h-ft-°F)] for wool. The thermal conductivity of wood depends on several items including (1) grain orientation, (2) moisture content, (3) specific gravity, (4) extractive content, and (5) structural irregularities such as knots.

Heat flow in wood across the radial and tangential directions (with respect to the growth rings) is nearly uniform. However, heat flow through wood in the longitudinal direction (parallel to the grain) is 2.0 to 2.8 times greater than in the radial direction.

Moisture content has a strong influence on thermal conductivity. When the wood is dry, the cells are filled with air and the thermal conductivity is very low. As the moisture content increases, thermal conductivity increases. As the moisture content increases from 0% to 40%, the thermal conductivity increases by about 30%.

Because of the solid cell wall material in heavy woods, they conduct heat faster than light woods. This relationship between specific gravity and thermal conductivity for wood is linear. Also affecting the heat transfer in wood are increases in extractive content and density (i.e., knots) which increase thermal conductivity.

Specific Heat Specific heat of a material is the ratio of the quantity of heat required to raise the temperature of the material one degree to that required to raise the temperature of an equal mass of water one degree. Temperature and moisture content largely control the specific heat of wood, with species and density having little to no effect. When wood contains water, the specific heat is increased because the specific heat of water is higher than that of dry wood. However, the value of specific heat for the wet wood is higher than just the sum of the specific heats for the wood and water combined. This increase in specific heat beyond the simple sum is due to the wood–water bonds absorbing energy. An increase in temperature increases the energy absorption of wood and results in an increase in the specific heat.

Thermal Diffusivity Thermal diffusivity is a measure of the rate at which a material absorbs heat from its surroundings. The thermal diffusivity for wood is much smaller than that of other common building materials. Generally, wood has a thermal diffusivity value averaging 0.006 mm/sec. (0.00025 in./sec.), compared with steel, which has a thermal diffusivity of 0.5 mm/sec. (0.02 in./sec.). It is because of the low thermal diffusivity that wood does not feel hot or cold to the touch, compared with other materials. The small thermal conductivity, moderate density, and moderate specific heat contribute to the low value of thermal diffusivity in wood.

Coefficient of Thermal Expansion The coefficient of thermal expansion is a measure of dimensional changes caused by a temperature variance. Thermal expansion coefficients for completely dry wood are positive in all directions. For both hard and soft woods, the longitudinal (parallel to the grain) coefficient values range from 0.009 to 0.0014 mm/m/°C (0.0000017 to 0.0000025 in./in./°F). The expansion coefficients are proportional to density and therefore are five to ten times greater across the grain than those parallel to it.

When moist wood is heated, it expands due to thermal expansion and then shrinks because of the loss of moisture (below the fiber saturation point). This combined swelling and shrinking often results in a net shrinkage. Most woods, at normal moisture levels, react in this way.

10.7.3 Electrical Properties

Air-dry wood is a good electrical insulator. As the moisture content of the wood increases, the resistivity decreases by a factor of three for each 1% change in moisture content. However, when wood reaches the fiber saturation point, it takes on the resistivity of water alone.

10.8 Mechanical Properties

Knowing the mechanical properties of wood is a prerequisite to a proper design of a wood structure. Typical mechanical properties of interest to civil and construction engineers include modulus of elasticity, strength properties, creep, and damping capacity.

10.8.1 Modulus of Elasticity

The typical stress–strain relation of wood is linear up to a certain limit, followed by a small nonlinear curve after which failure occurs, as shown on

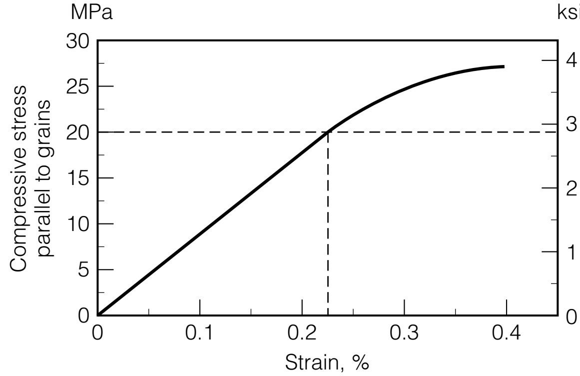


FIGURE 10.9 Typical stress strain relationship for wood.

Figure 10.9. The modulus of elasticity of wood is the slope of the linear portion of the representative stress–strain curve. The stress–strain relation of wood varies within and between species and is affected by variation in moisture content and specific gravity. Also, since wood is anisotropic, different stress–strain relations exist for different directions. The moduli of elasticity along the longitudinal, radial, and tangential axes are typically different.

10.8.2 Strength Properties

Strength properties of wood vary to a large extent, depending on the orientation of grain relative to the direction of force. For example, the tensile strength in the longitudinal direction (parallel to grain) is more than 20 times the tensile strength in the radial direction (perpendicular to grain). Also, tensile strength in the longitudinal direction is larger than the compressive strength in the same direction. Common strength properties for wood include modulus of rupture in bending, compressive strength parallel and perpendicular to the grain, and shear strength parallel to the grain. Some of the less common strength properties are tensile strength parallel to the grain, torsion, toughness, fatigue strength, and rolling shear strength.

10.8.3 Creep

Under sustained loads wood continues to deform or creep. The design values of material properties contemplate fully stressing the member to the tabulated design values for a period of 10 years and/or the application of 90% of the full maximum load continuously throughout the life of the structure. If the maximum stress levels are exceeded, the structure can deform prematurely.

10.8.4 Damping Capacity

Damping is the phenomenon in which the amplitude of vibration in a material decreases with time. Reduction in amplitude is due to internal friction within the material and resistance of the support system. Moisture content and temperature largely govern the internal friction in wood. At normal ambient temperatures, an increase in moisture content produces a proportional increase in internal friction up to the fiber-saturation point. Under normal conditions of temperature and moisture content, the internal friction in wood (parallel to the grain) is 10 times that of structural metals. Because of these qualities, wood structures dampen vibrations more quickly than metal structures of similar design.

10.9 Testing to Determine Mechanical Properties

Standard mechanical testing methods for wood are designed almost exclusively to obtain data for predicting performance. To achieve reproducibility in the testing environment, specifications include methods of material selection and preparation, testing equipment and techniques, and computational methods for data reduction. Standards for testing wood and wood composites are published by ASTM, the U.S. Department of Commerce, the National Standard Institute (NSI), and various other trade associations, such as the Western Woods Product Association.

Due to the many variables affecting the test results, it is of primary importance to correctly select the specimen and type of test. There are two main testing techniques for establishing strength parameters: the testing of representative, small, clear specimens and the testing of timbers of structural sizes.

The primary purposes for testing small, clear specimens are to obtain the mechanical properties of various species and to provide a means of control and comparison in production activities. The testing of structural timbers provides relationships among mechanical and physical properties, working stress data, correlations between environmental conditions, wood imperfections, and mechanical properties. ASTM D 143 presents the complete testing standards for small, clear wood specimens. This standard gives full descriptions of sample collection, preparation, and testing techniques. Mechanical tests included in this standard are the following:

- Static bending
- Impact bending
- Compression perpendicular to the grain
- Shear parallel to the grain
- Tension parallel to the grain
- Nail withdrawal
- Radial and tangential shrinkage
- Compression parallel to the grain
- Toughness
- Hardness
- Cleavage
- Tension perpendicular to the grain
- Specific gravity and shrinkage in volume
- Moisture determination.

Figure 10.10 shows a schematic of test specimens of wood tested in tension, compression, bending, and hardness. Static and impact bending, compression

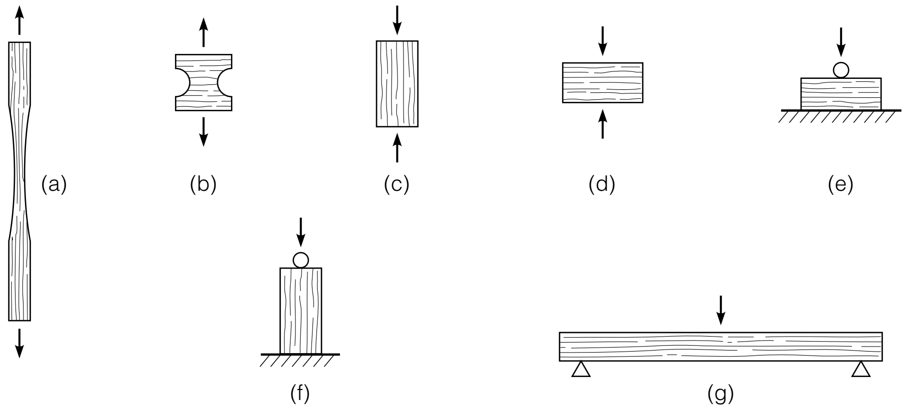


FIGURE 10.10 Test specimens of wood: (a) tension parallel to grains, (b) tension perpendicular to grains, (c) compression parallel to grains, (d) compression perpendicular to grains, (e) hardness perpendicular to grains, (f) hardness parallel to grains, and (g) bending. (© Pearson Education, Inc. Used by permission.)

and tension parallel and perpendicular to the grain, and shear parallel to the grain are commonly used.

10.9.1 Static Bending Test

The static bending test is performed on either $50 \times 50 \times 760$ mm ($2 \times 2 \times 30$ in.) or $25 \times 25 \times 410$ mm ($1 \times 1 \times 16$ in.) specimens. For the large specimens, the loading head is placed on the center of the specimen and over a span of 710 mm (28 in.), and the load is applied at a rate of 2.5 mm/min. (0.1 in./min.). For the small specimens, the loading head is placed on the center of the specimen and over a span of 360 mm (14 in.), and the load is applied at a rate of 1.3 mm/min. (0.05 in./min.). Load–deflection data are recorded to or beyond the maximum load. Within the proportional limit, readings are taken to the nearest 0.02 mm (0.001 in.). After the proportional limit, deflection readings are usually measured with a dial gage, to the limit of the gage, usually 25 mm (1 in.). Load and deflection of the first failure, the maximum load, and points of sudden change are recorded. The failure appearance is described as either brash or fibrous. Brash indicates an abrupt failure and fibrous indicates a failure showing splinters.

Sample Problem 10.2

A static bending test was performed on a $50 \times 50 \times 760$ mm wood sample according to ASTM D143 procedure (span between supports = 710 mm). If the maximum load was 2.67 kN, calculate the modulus of rupture.

Solution

$$\text{Modulus of rupture} = \frac{Mc}{I}$$

where

M = bending moment at maximum load
c = 1/2 of the specimen height
I = moment of inertia of the specimen cross section

$$\text{Reaction at each support at failure} = \frac{2.67}{2} = 1.335 \text{ kN}$$

$$\text{Bending moment at the center at failure} = 1.335 \times \left(\frac{710}{2}\right) = 473{\cdot}9 \text{ N.m}$$

$$I = \frac{(0.05)(0.05)^3}{12} = 5.21 \times 10^{-7} \text{ m}^4$$

$$\text{Modulus of rupture} = \frac{473.9 \times 0.025}{5.21 \times 10^{-7}} = 22.75 \text{ MPa}$$

10.9.2 Compression Tests

The compression test parallel to the grain is performed on either 50 × 50 × 200 mm (2 × 2 × 8 in.) or 25 × 25 × 100 mm (1 × 1 × 4 in.) specimens, as shown in Figure 10.11. The load is applied at a rate equal to 0.003 mm/mm

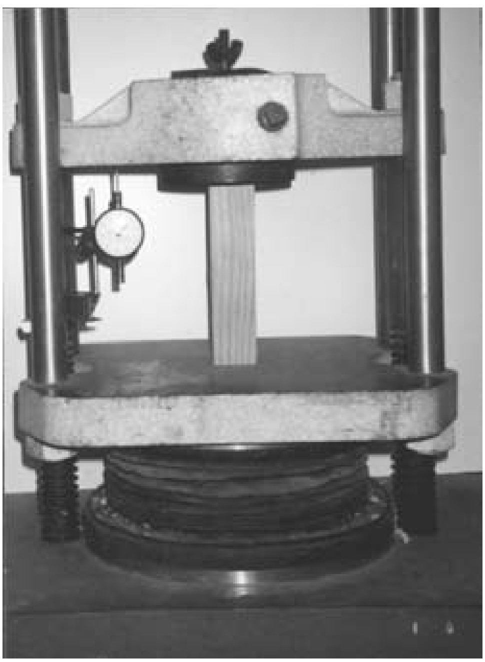


FIGURE 10.11 Compression parallel to grain test.

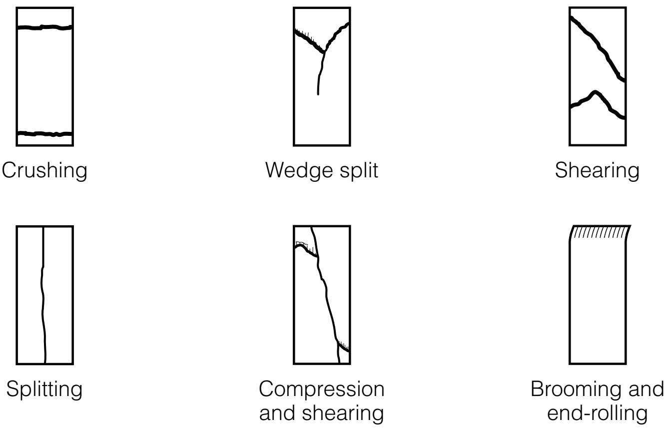


FIGURE 10.12 Types of failure in the compression-parallel-to-grain test. (ASTM D143). Reprinted with permission of ASTM.

(in./in.) of the nominal specimen length per minute. The deformations are recorded to 0.002 mm (0.0001 in.) over a gage length of not more than 150 mm (6 in.) for the large specimens or 50 mm (2 in.) for the small specimens. Load–compression readings are recorded until well past the proportional limit. The failures should occur in the center portion of the sample. If failures are occurring near the ends, the samples can be stacked such that the ends dry relative to the middle. This will increase the strength of the ends of the sample. The tests are then repeated on the conditional samples. The type of failure can be classified as crushing, wedge split, shearing, splitting, compression and shearing, and brooming and end rolling, as shown in Figure 10.12.

The compression test perpendicular to the grain is performed on $50 \times 50 \times 150$ mm ($2 \times 2 \times 6$ in.) specimens. The load is applied through a metal bearing plate 50 mm (2 in.) in width, centered across the upper surface of the specimen. The load is applied at a rate of 0.305 mm/min. (0.012 in./min.). Deflection readings are taken to the nearest 0.002 mm (0.0001 in.). Load and deformation are measured until the deformation is 2.5 mm (0.1 in.).

10.10 Design Considerations

Measurement of wood properties in the lab does not reflect all the factors which affect behavior of the material in engineering applications. For design of wood structures, the strength properties given in Tables 10.3 and 10.4 must be adjusted for the following (National Design Specification® for Wood Construction, 2005, ASTM D2555):

- Wet service
- Temperature
- Beam stability
- Size

- Volume
- Flat use
- Repetitive member
- Curvature
- Form
- Column stability
- Shear stress
- Bearing area

In addition, sustained loads will cause wood to creep. In design applications, this means that the wood can carry higher stresses of short time durations than the same wood element can carry for a long-term application. Generally, a load duration of 10 years is used for design. Typical load duration factors that would be applied to the values in Tables 10.3 and 10.4 (except for compression perpendicular to the grain) are shown in Figure 10.13. For example, if a floor joint is designed for a temporary stage that is used only for a one-day presentation, the allowable bending fiber stress can be increased by 33 percent over the allowable stress for a normal application.

10.11 Organisms that Degrade Wood

Wood can experience degradation due to attack of fungi, bacteria, insects, or marine organisms.

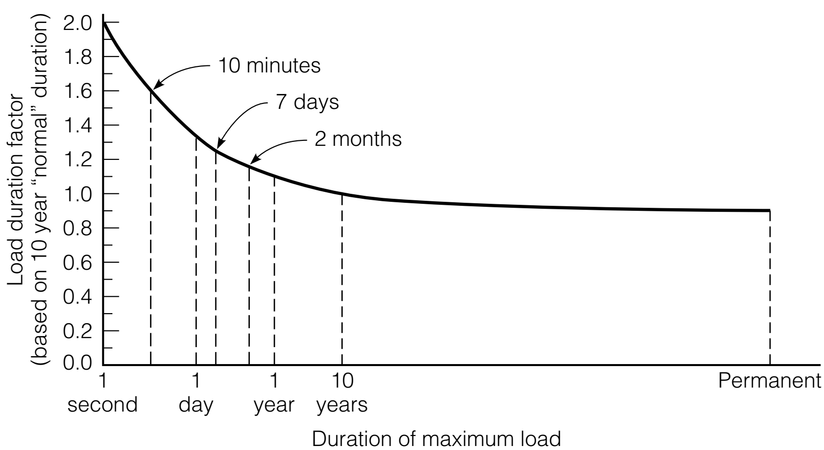


FIGURE 10.13 Adjustment factors for load duration working-stress for wood design based on 10-year nominal duration. Reprinted with permission of American Forest and Paper Association (2005.)

10.11.1 Fungi

Most forms of decay and sap stains are the result of fungal growth. Fungi need four essential conditions to exist: food, proper range of temperature, moisture, and oxygen. Fungi feed on either the cell structure or the cell contents of woody plants, depending on the fungus type. The temperature range conducive for fungal growth is from 5°C to 40°C (40°F to 100°F). Moisture content above the fiber saturation point is required for fungal growth. Fungi are plants and, as such, require oxygen for respiration. Fungi attack produces *stains* and/or *decay damage.*

To protect against fungal attack, one of the four essential conditions for growth needs be removed. The most effective protection measure is to keep the wood dry by using coatings or by correct placement during storage and in the structure. Fungi can also be contained by treating the wood fibers with chemical poisons through a pressure treatment process.

Construction procedures that limit decay in buildings include the following:

1. Building with dry lumber that is free of incipient decay and excessive amounts of stains and molds
2. Using designs that keep the wood components dry, using wood treated with preservatives
3. Using a heartwood from decay-resistant species in sections exposed to above-ground decay hazards
4. Using pressure-treated wood for components in contact with the ground.

10.11.2 Bacteria

Bacteria causes "wet wood" and "black heartwood" in living trees and a general degradation of lumber. Wet wood is a water-soaked condition that occupies the stem centers of living trees and is most common in poplar, willows, and elms. Black heartwood has characteristics similar to those of wet wood, in addition to causing the center of the stem to turn dark brown or black.

Bacterial growth is sometimes fostered by prolonged storage in contact with soils. This type of bacteria activity produces a softening of the outer wood layers, which results in excessive shrinkage when redried.

10.11.3 Insects

Beetles and *termites* are the most common wood-attacking insects. Several types of beetles, such as bark beetles, attack and destroy wood. Storage of the logs in water or a water spray prevents the parent beetle from boring. Quick drying or early removal of the bark also prevents activity by beetle attack. Damage can be prevented by proper cutting practices and dipping or spraying with an appropriate chemical solution.

Termites are perhaps the most destructive organism that attacks wood. The annual damage attributed to termites exceeds losses due to fires. Termites enter structures through wood that is close to the ground and is poorly ventilated or wet. Prevention is achieved by painting and otherwise prohibiting insect entry into areas of unprotected wood through the use of screening, sill plates, and sealing compounds.

10.11.4 Marine Organisms

Damage by marine boring organisms in the United States and surrounding oceans is principally caused by shipworms, pholads, *Limnoria*, and *Sphaeroma*. These organisms are almost totally confined to salt or brackish waters.

10.12 Wood Preservation

Paints, petroleum-based solutions, and waterborne oxides (salts) are the principle types of wood preservatives. The degree of preservation achieved depends on the type of preservative, the degree of penetration, and the amount of the chemical retained within the wood. Paints are applied on the surface, while the other preservatives are applied under pressure to increase penetration into the wood.

10.12.1 Petroleum-Based Solutions

Coal-tar creosote, petroleum creosote, creosote solutions, and pentachlorophenol solutions are the oil-based preservatives. These preservatives are very effective, but are environmentally sensitive. They are commonly used where a high degree of environmental exposure exists and human contact is not a concern. Applications include utility poles, railroad ties, and retaining walls.

10.12.2 Waterborne Preservatives

The typical solutes used in waterborne preservative mixtures are ammoniacal copper arsenate, chromated copper arsenate (CCA) and ammoniacal copper zinc arsenate. The advantages of the waterborne preservative over the oil-based are cleanliness and its ability to be painted. The disadvantage of these treatments is their removal by leaching when exposed to moist conditions over long periods of time. These preservatives are also environmentally sensitive and must be applied under carefully controlled conditions. The level of potential danger to humans from contacting wood pressure treated with CCA is controversial. Trade groups are supportive of the product, but several other agencies see potential health effects. By 2003, the wood preservation industry agreed to stop using arsenic-based preservatives for products intended for residential use or direct human contact. CCA can still be used for commercial applications and permanent foundations. Although CCA was removed from the market, the EPA is not calling for the removal of it from existing structures.

The most common replacement preservatives are ammoniacal copper quat, or ACQ, followed by copper azole, and borate. Borate may be used in home foundation sill plates and other "dry" applications, but borate-treated wood is not appropriate for outdoor uses (Forintek, 2002).

10.12.3 Application Techniques

Preservatives are applied by superficial treatment or by fluid penetration processes. Superficial treatment techniques include coatings applied by painting, spraying, or immersion. Liquid penetration into a porous solid is by capillary action and is a function of surface tension, angle of contact, time, temperature, and pressure.

Pressure-treated wood has greater resistance to degradation than surface-treated wood. The preservative is forced into the entire structure of the wood. By thoroughly treating the entire cross section of the wood, decay can be eliminated for an extended period of time. Some vendors of pressure-treated wood provide a lifetime warranty for their products when in direct contact with the ground. The key to ensuring long life is the amount of preservative retained in the wood. Table 10.5 gives the minimum retention requirements for different treatments and applications of Southern Pine lumber, timber, and plywood.

TABLE 10.5 Minimum Retention Requirements in kg/m^3 for Different Treatments and Applications of Southern Pine Lumber, Timber, and Plywood (Southern Pine Council 1990)

		Above ground	Soil and fresh water use	Permanent wood foundation	Saltwater use
Waterborne preservatives	Ammoniacal copper arsenate	4	6	10	41
	Ammoniacal copper zinc arsenate	4	7	10	41
	Chromated copper arsenate	4	7	10	41
Creosote and oil-borne preservatives	Creosote	131	163	NR*	408
	Creosote–petroleum	131	163	NR*	NR*
	Creosote solutions	131	163	NR*	408
	Pentachlorophenol	7	8	NR*	NR*

*NR: Not recommended.

**For a complete list of wood products see the American Wood Preservative Association (AWPA) standards.

10.12.4 Construction Precautions

There are a few issues that should be recognized during the design and construction with pressure-treated materials. Care should be taken to avoid inhaling saw dust during cutting of the wood. Hands should be washed after handling pressure treated wood and before consuming food or beverages. Clothes should be washed separately from other items. Waste material must be disposed of properly; it should not be burned.

Pressure-treated wood promotes corrosion of hangers and other fasteners. Generally, galvanization was adequate. However, there is some evidence that the new preservatives are even more corrosive. The higher metal corrosion rates associated with ACQ-treated wood have raised concerns with the federal Consumer Product Safety Commission (CPSC) and a Bay Area district attorney who recently issued a consumer alert (e-builder, 2005).

> "CPSC is recommending consumers use stainless steel brackets and fasteners in conjunction with ACQ-treated lumber," said commission spokesman Scott Wolfson. The CPSC is considering whether it needs to study the corrosion issue further, based on information from the connector industry and Contra Costa County. That county's district attorney, Bob Kochly, warned in a recent consumer alert that wood treated with ACQ and copper azole "may result in serious and premature corrosion … especially in wet or moist conditions unless stainless steel connectors are used."

10.13 Engineered Wood Products

Engineered wood includes a wide variety of products manufactured by bonding together wood strands, veneers, lumber, or other forms of wood fibers to produce large and integral units. These products are "engineered" to produce specific and consistent mechanical behavior and thus have consistent design properties. There is a wide variety of engineered wood products produced for many applications. Only the products used in structural applications are considered here.

An engineered product consists of wood stock material glued together with an appropriate resin or adhesive. These are predominantly wood materials, so they are liable to the same concerns as natural wood products with respect to the effects of fire, moisture, and decay. The wood stock may consist of veneers, strands, or dried lumber as shown in Table 10.6.

Veneer-based materials consist of wood plies that are glued together. A ply is a thin sheet of wood. To produce plies, logs are saturated by storage in ponds, water vats, steam vats, or water sprays. Prior to processing, the logs are moved into a boiling water bath. Next, they are debarked and sectioned into the desired width. The segments are rotated in a giant lathe and peeled into continuous sheets of veneer, or sliced, as shown in Figure 10.14. These segments of veneer are trimmed and combined into continuous rolls. Each roll of veneer is seasoned, dried to the desired moisture content. The plies,

TABLE 10.6 Classification of Engineered Wood Products

Wood stock	Class of Product	
	Structural Panels/Sheets (sheathing, flooring)	**Structural Shapes (beams, columns, headers)**
Veneer	Plywood	Laminated veneer lumber
Strands	Flakeboard	Oriented strand lumber
	Waferboard - random orientation of strands	Laminated strand lumber
	Oriented Strand Board - strands oriented, panels made in plys	Parallel strand lumber (Parallam)
Composite	COM-PLY - Wood fiber core with veneer exterior	N/A
Dried lumber	N/A	Glued laminated lumber (Glulam)

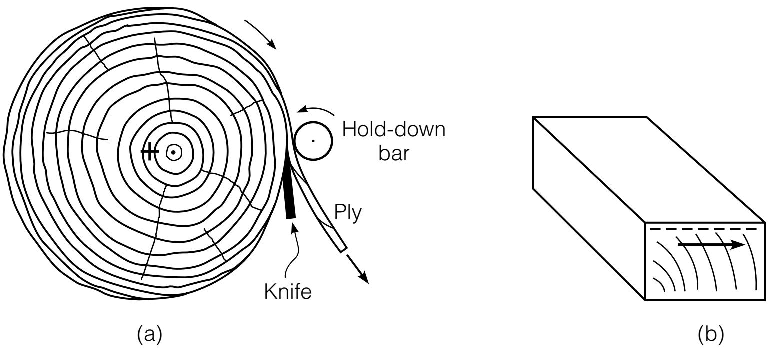


FIGURE 10.14 Cutting of plies for plywood and glulam: (a) rotary cutting and (b) slicing (© Pearson Education, Inc. Used by permission.)

cut from the veneer rolls, are assembled, glued, and pressed. The grains of the plies are alternated at 90° for plywood and they are arranged parallel for laminated veneer lumber. Plywood is made in sheets, whereas laminated veneer lumber is made in structural shapes.

Strands have uniform thickness, with a combination of length and width dimensions up to 150 mm (6″) long and 25 mm (1″) wide for panel products, and may be up to 600 mm (24″) long for structural shapes. Plies of strands are made by gluing together the strands to form plies. Structural panels are made by gluing together plies in three or five layers. These panels fall into a general class of material called flakeboard. Originally, the strands had a random orientation, producing waferboard. In the 1970s, recognition of the advantages of orientating the strands prior to gluing, then forming panels by using plies with alternating orientation of strands, led to the development of oriented strandboard (OSB). This is the dominant strand product used in the market today. It's structural characteristics compare favorably with plywood. Strandboard can also be made into structural shapes, such as beams.

Dried lumber products can be glued together (laminated) to form structural shapes to meet a wide variety of applications. Typically, either southern pine or western species of softwoods are used. The individual boards are referred to as lams, which are glued together to form the glulam product. Lams of southern pine are typically 35 mm (1 3/8 inch); Western species lams are typically 38 mm (1 1/2 inches). The widths of glulam products are typically 63 to 275 mm (2 1/2 to 10 3/4 inches), although virtually any size member can be produced.

Engineered wood products can be broadly classified as either structural panels/sheets or structural shapes as shown in Table 10.6. Panels are primarily used for sheathing, whereas structural shapes are used as beams, columns, etc. Sheet products and structural shape products can be combined to produce a variety of composite structural members, such as I-joists and T-sections.

10.13.1 Structural Panels/Sheets

Structural panel products include plywood, oriented strand board (OSB), and COM-PLY. Plywood is manufactured as a composite of veneer plies, with an alternating orientation of the grain. OSB is manufactured as a composite of strands; the strands are oriented and pressed into sheets. The OSB panel consists of three to five sheets glued together, with alternating orientation of the strands. COM-PLY is a proprietary product manufactured with a wood fiber core and veneer exterior. Panels may be used directly as sheathing, roofs, sides, and floors. Sheet panels can be cut and bonded into structural components, such as glued or nailed box beams, stressed skin panels, and structural insulated panels.

Conventional wood-based composite products are typically made with a thermosetting or heat-curing resin or adhesive that binds the wood fibers together. Adhesives are chosen based on their suitability for the particular product. Factors considered are the materials to be bonded, moisture content at time of bonding, mechanical property, durability, and cost (USDA-FS, 1999). Commonly used resin-binder systems for panels include the following:

Phenol–formaldehyde (PF) Used for materials designed for exterior exposure, including plywood, OSB, and siding.

Urea–formaldehyde (UF) typically used for manufactured products where dimensional uniformity and surface smoothness are of primary concern, such as particle board and medium density fiberboard designed for interior applications.

Melamine–formaldehyde (MF) used for decorative laminates, paper treating, and paper coating.

Isocynate as diphenylmethane di-isocynate, commonly used for OSB. Highly toxic during the manufacturing process.

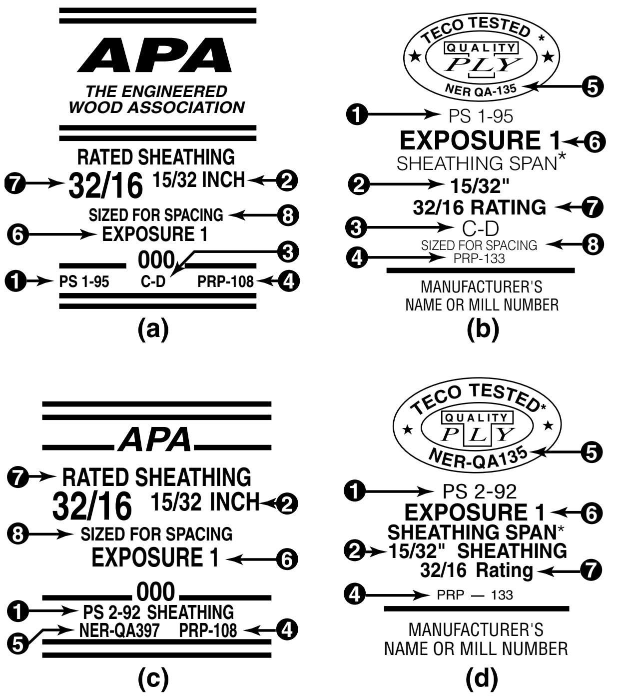
UF and PF systems are expected to continue to be the dominate wood adhesives, unless their use is curtailed due to concerns about the hazards of formaldehyde products or interruptions to the supply and manufacturing of the material. Research is underway to develop adhesives from renewable resources.

Structural panels are manufactured to meet requirements based on either the composition of the material or the stress rating of the panels. The National Institute of Standards and Technology, NIST, publishes these standards. PS 1-95 specifies the composition of structural plywood. This standard specifies wood species, grades of veneer, what repairs are permissible, and how the repairs may be made. NIST standard PS 2-92 is a performance-based standard for structural composite panels. Figure 10.15 shows typical grade stamps for plywood and OSB (USDA-FS, 1999). Figures 10.15 (a) and (b) are grade stamps for plywood showing (1) conformance of plywood to product standards, (2) nominal panel thickness, (3) grades of face and back veneers or grade name based on panel use, (4) performance-rated panel standard, (5) recognition as a quality assurance agency by the National Evaluation Service, NES, (6) exposure durability classification, (7) span rating, which refers to maximum allowable roof support spacing and maximum floor joist spacing, and (8) panel size for spacing. Figure 10.15 (c) and (d) demonstrate the typical grade stamps for OSB. The ratings are similar to those for plywood, with the exception that OSB does not have a grade rating for the face and back veneer material.

The mechanical properties of plywood are rated based on the orientation of the strength axis relative to the orientation of the supports, as shown on Figure 10.16 (Williamson, 2002). The differences in the strength properties are due to the orientation of the grains in the layers of the plywood. Similar layers occur in OSB; however, the layers are neither defined nor specified. The mechanical properties of structural panels are rated based on the orientation of the load, as shown on Figure 10.17, and several other factors (Williamson, 2002). Table 10.7 summarizes the mechanical properties of plywood and OSB used in structural sheathing applications (USDA-FS, 1999). As with natural wood products, there are several design adjustment factors that must be considered in the selection of structural panel for a specific application.

10.13.2 Structural Shapes

Three classes of engineered wood products are used to manufacture structural shapes, based on the type of wood stock: laminated veneer, strand, and glue laminated. The laminated and strand products are classified as structural composite lumber (SCL). All types of SCL products can be used in place



1. Product Standard that governs specifics of production for construction and industrial plywood
2. Nominal panel thickness subject to acceptable tolerances
3. Panel grade designation indicating minimum veneer grade used for panel face and back, or grade name based on panel use
4. Performance-rated panel standard indicating structural-use panel test procedure recognized by National Evaluation Service (NES)
5. NES report number from Council of American Building Officials (CABO)
6. Exposure durability classification: Exposure 1 indicates interior panel bonded with exterior glue suitable for uses no permanently exposed to weather
7. Span rating indicating maximum spacing of roof and floor supports for ordinary residential construction applications; 32/16 rating identifies a panel rated for use on roof supports spaced up to 813 mm (32 in.) o.c., or floor supports spaced up to 406 mm (16 in.) o.c.
8. Sized for spacing denotes panels that have been sized to allow for spacing of panel edges during installation to reduce the possibility of buckling

FIGURE 10.15 Typical grade stamp for structural panels.

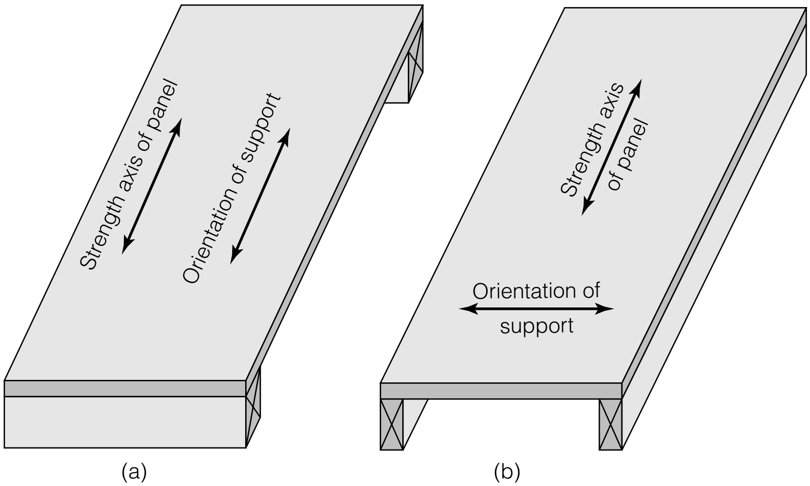


FIGURE 10.16 Strength axis of plywood.

of sawn lumber for many applications. Laminated veneer lumber (LVL) is used for scaffold planks and in flanges of prefabricated I-joists. Both LVL and parallel strand lumber (PSL) are used for headers and major load-carrying elements. The strand products are used for band joists in floor construction and as substitutes for studs and rafters in wall and roof construction (USDA-FS, 1999).

Laminated Veneer Lumber Laminated veneer lumber (LVL) was developed in the 1940s to produce high-strength parts for aircraft. It is currently a widely accepted construction material. Veneer sheets, 2.5 mm to 3.2 mm (1/10 in. to 1/8 in.) thick are glued with phenol–formaldehyde adhesive to form billets, which are 0.6 m to 1.2 m (2 ft to 4 ft) wide by 38 mm (1.5 inches) thick. The veneer sheets are all aligned with the grain parallel to the length of the member. The end joint between sheets is either staggered or overlapped to minimize any strength-reducing effect. Continuous presses are used to form sheets with lengths limited only by handling capability. Alternatively, the billets may be manufactured in 2.4 m (8 ft) lengths and enjoined with either scarf or finger joints to form longer pieces.

The veneer used to manufacture LVL must be carefully selected for uniformity. Visual grading may be used, but ultrasonic testing is commonly used to identify and sort acceptable sheets. The ultrasonic testing can rapidly detect flaws in the veneer, such as knots and splits that would limit the strength of the finished product. Since the quality of each veneer layer is controlled, the variation in product properties are less than for natural products.

LVL is manufactured to meet specific stress grade requirements. Due to the ply construction, the orientation of the member and load must be considered when selecting properties. Figure 10.18 identifies the common

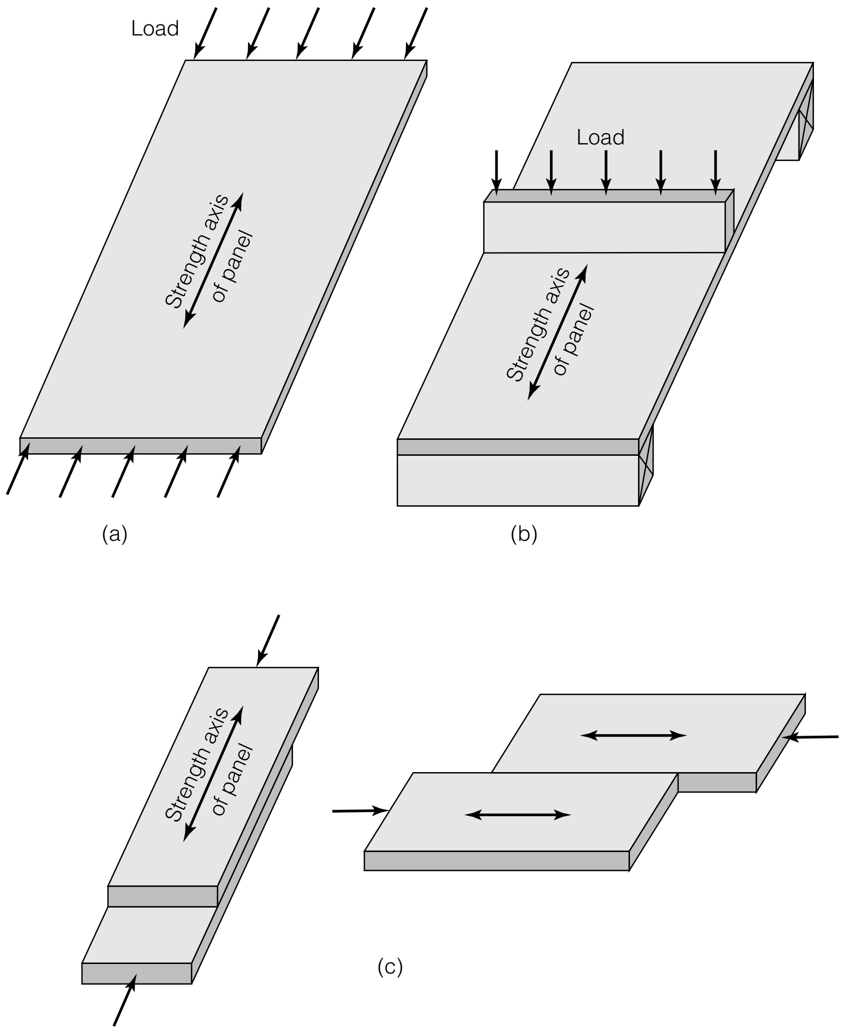


FIGURE 10.17 Load orientation conditions for determining mechanical properties of plywood.

terminology used to describe loading conditions for testing and design (Williamson, 2002). Table 10.8 is a portion of the design property table in the APA-EWS performance standard PRL-501, which covers the required properties for stress-graded LVL (APA-EWS, 2000). There are several footnotes associated with the information in this table; therefore, the cited reference should be consulted before using this information for design. The footnotes deal with modifications to the design values as a function of load conditions and duration. It should be noted that the values in Table 10.8 are for design and are therefore conservative. Table 10.9 provides characteristic test values, which are much higher than the design values for all properties other than elastic modulus in bending.

TABLE 10.7 General Properties of Plywood and OSB in Structural Sheathing Applications.

Property	Plywood	OSB	ASTM Test Method
Linear hygroscopic expansion (30–90%), %	0.15	0.15	
Linear thermal expansion in./in./F	3.4×10^{-6}	3.4×10^{-6}	
Flexure—modulus of rupture, psi	3000–7000	3000–4000	D 3043
Flexure—modulus of elasticity, psi	$1.0–1.9 \times 10^{6}$	700–1200	
Tensile strength, psi	1500–4000	1000–1500	D 3500
Compressive strength, psi	3000–5000	1500–2500	D 3501
Shear through thickness—strength, psi	600–1100	1000–1500	D 2719
Shear through thickness—modulus, psi	$68–110 \times 10^{3}$	$180–290 \times 10^{3}$	D 3044
Shear in plane of plies—strength, psi	250–300	200–300	D 2718
Shear in plane of plies—modulus, psi	$20–30 \times 10^{3}$	$20–50 \times 10^{3}$	D 2718

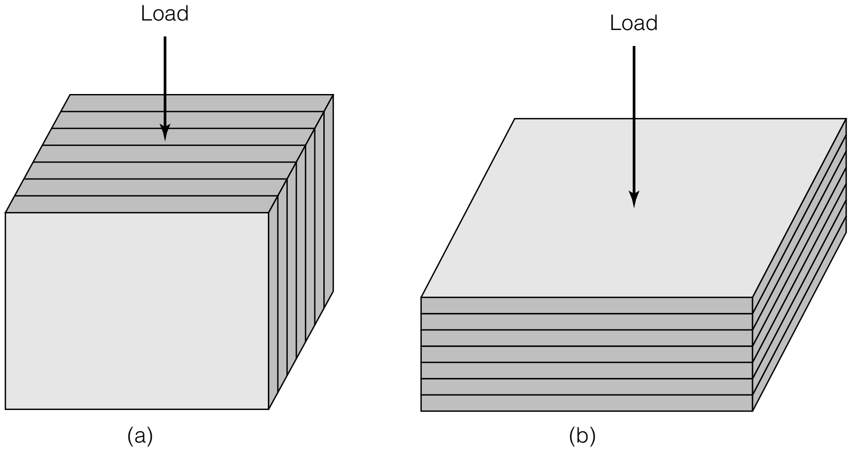


FIGURE 10.18 Axis convention used for defining loading conditions for Laminated Veneer Lumber.

TABLE 10.8 Design Properties for APA-EWS Performance Rated LVL (APA-EWS, 2000)

APA-EWS Stress Class	Bending modulus (10^6 psi)	Allowable extreme fiber stress (psi)	Allowable tensile stress parallel to grain (psi)	Compressive stress parallel to grain (psi)	Edgewise shear stress (psi)	Stress perpendicular to grain (psi)
1.5E-2250F	1.5	2250	1500	1950	220	575
1.8E-2600F	1.8	2600	1700	5400	285	700
1.9E-2600F	1.9	2600	1700	2550	285	700
2.0F-2900F	2.0	2900	1900	2750	285	750
2.1E-3100F	2.1	3100	2200	3000	285	850

Parallel and Oriented Strand Lumber As with OSB, strands of wood can be glued together into structural members. Depending on the length of strand and degree of orientation, products are classified as parallel strand lumber, laminated strand lumber, or oriented strand lumber.

Parallel strand lumber is a composite of wood strand elements, with wood fibers oriented primarily along the length of the member. The smallest dimension of the strand must be less than 6.4 mm (0.25 in.) and the average length of the strand must be 150 times the smallest dimension. Typically, the strands are 3 mm (0.125 in.) thick, 19 mm (0.75 in.) wide and 0.6 m (24 in.) long. A waterproof structural adhesive, such as phenol–resorcinol–formaldehyde,

TABLE 10.9 Characteristic Test Values for APA-EWS Performance Rated LVL (APA-EWS, 2000)

APA-EWS Stress Class	Bending modulus (10^6 psi)	Allowable extreme fiber stress (psi)	Allowable tensile stress parallel to grain (psi)	Compressive stress parallel to grain (psi)	Edgewise shear stress (psi)	Compressive stress perpendicular to grain (psi)
1.5E-2250F	1.5	4725	3150	3705	695	960
1.8E-2600F	1.8	5460	3570	4560	900	1170
1.9E-2600F	1.9	5460	3570	4845	900	1170
2.0F-2900F	2.0	5460	3990	5225	900	1255
2.1E-3100F	2.1	5460	4620	5700	900	1420

bonds the strands together. The strands are carefully oriented, coated with adhesive, and run through a continuous press to achieve a high density, producing billets that are typically 0.28 m by 0.48 m (11 in. by 19 in.). Length is limited only by handling capability. The billets are sawn into the desired dimensions (USDA-FS, 1999).

Currently, parallel strand lumber is a proprietary material with a single producer, marketed under the trade name Parallam (Trusjoist, 2003). The mechanical design properties of this product, as reported by the manufacturer, are given in Table 10.10.

TABLE 10.10 Mechanical Properties of Parallel Strand and Laminated Strand Lumber (Trusjoist)

Property	Parallel Strand Lumber	Laminated Strand Lumber
Shear modulus of elasticity (psi)	125,000	
Modulus of elasticity (psi)	2.0×10^6	1.5×10^6
Flexural stress (psi)	2900	2250
Tension stress (psi)	2025	
Compression perpendicular to grain (psi)	750	475
Compression parallel to grain (psi)	2900	1950
Horizontal shear parallel to grain (psi)	290	400

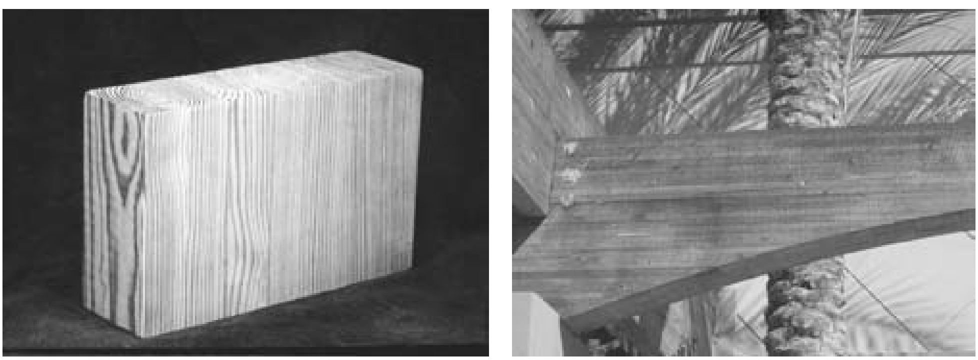
Laminated strand lumber (LSL) and oriented strand lumber (OSL) are extensions of the technology used to produce oriented strand board. They are manufactured using similar processes, with the primary difference being in the length of the strands—approximately 300 mm (12 in.) and 150 mm (6 in.) for LSL and OSL, respectively. As shown in Table 10.10, the mechanical properties of LSL are somewhat less than those of PSL. The mechanical properties of OSL are less than those of LSL (USDA-FS, 1999).

Glued–Laminated Timbers Laminated timbers are composed of two or more layers of dimensional lumber glued together with the grain of all layers laid parallel. Almost any species can be used when its mechanical and physical properties are suited for the design requirements. However, softwoods, such as Douglas fir and southern pine, are most commonly used for laminated structural timbers.

Glued–laminated wood, commonly called "glulam," is used for structural beams and columns, furniture, sports equipment, and decorative wood finishes, as shown in Figure 10.19. In such cases, glued-laminated wood is preferred over large one-piece members for many reasons, including the following:

- ease of manufacturing of large structural members from standard commercial sized lumber
- the opportunity to design large members that vary in cross section along their length, as required by the application
- specialized design to meet architectural appeal, opportunity to use lower grades of wood within the less stressed areas of the member
- minimization of checking and other seasoning defects associated with curing large one-piece members

Assembly of the laminates into full-depth members is a critical stage in manufacturing. Laminations are planed to strict tolerances just before gluing to ensure the final assembly will be rectangular and that pressure



(a) (b)

FIGURE 10.19 Examples of glued-laminated wood.

will be applied evenly. Prequalified adhesives, typically phenol–resorcinol, are applied to the gluing face. The laminations are laid up and clamped as an assembly while the glue cures. The adhesive is allowed to cure at room temperature for 6 to 24 hours, or, in some newer processes, radio-frequency curing is used to reduce the time to a few minutes (USDA-FS, 1999).

Glued–laminated wood is designed and produced to have consistent and uniform properties. Due to the laminated structured, the glulam can be laid up to optimize the use of the wood products. For example, glulams designed as bending members are laid up with higher quality wood at the edges of the beam and lower quality wood in the center, as shown in Figure 10.20. Bending members used for cantilevers or continuous members over multiple spans have a balanced layup, since both the top and bottom of the beam carry tensile loads. However, glulams designed for simple spans, which are designed to have only tension at the bottom and compression at the top of the beam, have unbalanced designs, with the higher quality wood at the bottom of the member. This is an unbalanced design and these members are carefully labeled to minimize the risk of installing the beam in an incorrect orientation.

Glulams are produced in four appearance grades:

Industrial grade is suitable where the glulam will not be exposed to view and appearance is not a concern.

Framing grade members match the width of conventional framing for use as door and window headers.

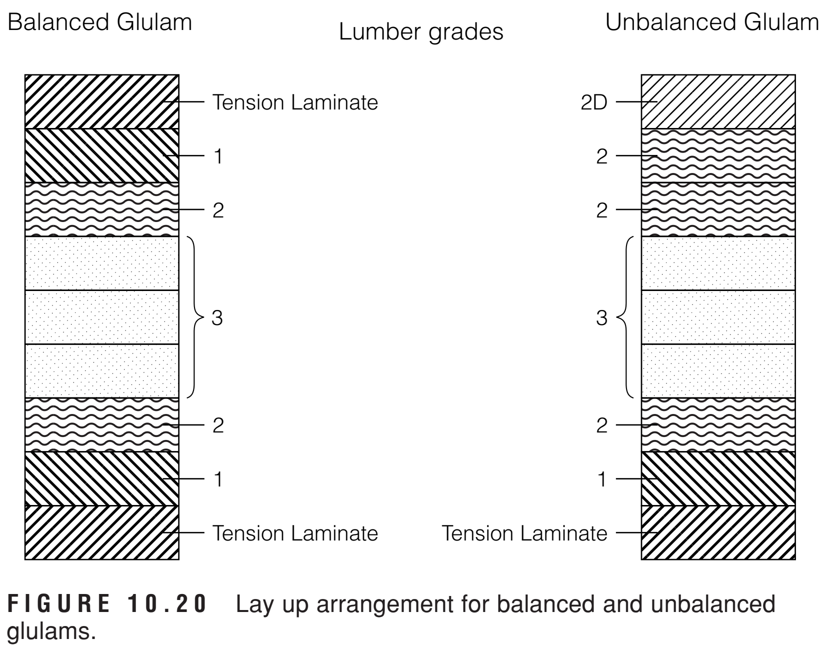


FIGURE 10.20 Lay up arrangement for balanced and unbalanced glulams.

Architectural grade is suitable where appearance is an important requirement.
Premium grade is the highest grade and is used when appearance is of the utmost importance.

Appearance grades do not modify design values, grades of lumber used, or other provisions governing the manufacture or use of glued laminate timber.

Glulams are specified by stress class, based on minimum values for their flexural strength and elastic modulus, as shown in Table 10.11 (APA-EWS, 2004). The design values in this table are for members with four or more laminations. The stress grade classification does not designate the species used

TABLE 10.11 Stress Classes of Glulams (APA-EWS, 2004)

Stress Class	Extreme Fiber in Bending: Tension Zone Stressed in Tension (psi)	Extreme Fiber in Bending: Compression Zone Stressed in Tension[1], (psi)	Compression Perpendicular to grain (psi)	Shear Parallel to Grain[3] (psi)	Modulus of Elasticity (10^6 psi)
16F-1.3E	1600	925	315	195	1.3
20F-1.5E	2000	1100	425	210	1.5[5]
24F-1.7E	2400	1450	500	210	1.7
24F-1.8E	2400	1450[2]	650	265[4]	1.8
26F-1.8E	2600	1950	650	265[4]	1.9
28F-1.8E	2800	2300	740	300	2.1[6]
30F-2.1E SP[7]	3000	2400	740	300	2.1[6]
30F-2.1E LVL[8]	3000	3000	510[9]	300	2.1

Notes:
[1]For balanced layups, bending stress when compression zone is stressed in tension shall be equal to the bending stress when tension zone is stressed in tension for the stress class. Designer shall specify when balanced layup is required.
[2]Negative bending stress, is permitted to be increased to 1850 psi for Douglas-fir and to 1950 psi for southern pine for specific combinations. Designer shall specify when these increased stresses are required.
[3]For noon-prismatic members, notched members, and members subjected to impact or cyclic loading, the design value for shear shall be multiplied by a factor of 0.72.
[4]Shear Parallel to Grain (Horizontal) = 300 psi for glulam made of southern pine.
[5]Modulus of Elasticity may be increased to 1.8×10^6 psi for glulam made of Canadian spruce-fir-pine or Eastern spruce.
[6]Modulus of Elasticity = 2.0×106 psi for members with more than 15 laminations except for 30F hybrid LVL glulam.
[7]Limited to a maximum of 6 inches except for hybrid LVL glulam.
[8]Requires the use of an outermost LVL lamination on the top and bottom.
[9]Compressive perpendicular to grain stress can be increased to the published value for the outer most LVL lamination.

TABLE 10.12 Design Value Properties of Select Glulams Produced by APA-EWS Members (APA-EWS, 2004).

			Bending (Loaded perpendicular to wide faces of laminations)					
			Extreme Fiber in Bending		Compression Perpendicular to Grain		Shear Parallel to Grain	Modulus of Elasticity
			Tension Zone Stressed in Tension	Compression Zone Stressed in Tension	Tension Face	Compression Face		
Combination Symbol	Species Outer/ Core	Balanced/ Unbalanced	(psi)	(psi)	(psi)	(psi)	(psi)	(10^6 psi)
Western Species								
EWS 20F-E/ES1	ES/ES	B	2000	2000	560	560	200	1.8
EWS 24F-E/ES1	ES/ES	U	2400	1700	560	560	200	1.7
EWS 24F-V4	DF/DF	U	2400	1850	650	650	265	1.8
EWS 24F-V8	DF/DF	B	2400	2400	650	650	265	1.8
Southern Pine								
EWS 24F-V3	SP/SP	U	2400	1950	740	740	300	1.8
EWS 24F-V5	SP/SP	B	2400	2400	740	740	300	1.7

TABLE 10.12 (Continued)

	Bending (Loaded perpendicular to wide faces of laminations)				Axial Loaded		
	Extreme Fiber in Bending	Compression Perpendicular to Grain	Shear Parallel to Grain	Modulus of Elasticity	Tension Parallel to Grain	Compression Parallel to Grain	Modulus of Elasticity
Combination Symbol	(psi)	(psi)	(psi)	(10^6 psi)	(psi)	(psi)	(10^6 psi)
Western Species							
EWS 20F-E/ES1	1100	300	175	1.5	1050	1150	1.6
EWS 24F-E/ES1	1100	300	175	1.5	1050	1150	1.6
EWS 24F-V4	1450	560	230	1.6	1100	1650	1.7
EWS 24F-V8	1450	560	230	1.6	1100	1650	1.7
Southern Pine							
EWS 24F-V3	1750	650	265	1.6	1150	1650	1.7
EWS 24F-V5	1750	650	265	1.5	1150	1650	1.6

or whether the wood in the laminate is visually graded or stress graded. Species may be specified in combination with these stress classes to obtain the required design properties. The presence of a stress classification does not ensure that the material is available. In addition, higher design values for some properties may be obtained by specifying a specific combination of laminations. Table 10.12 presents a partial list of allowable design stresses for glulams, with four or more laminations, used as bending members that are commonly produced by members of the APA-EWS. The species of wood in this table are

ES: Eastern spruce
DF: Douglas fir
SP: Southern pine

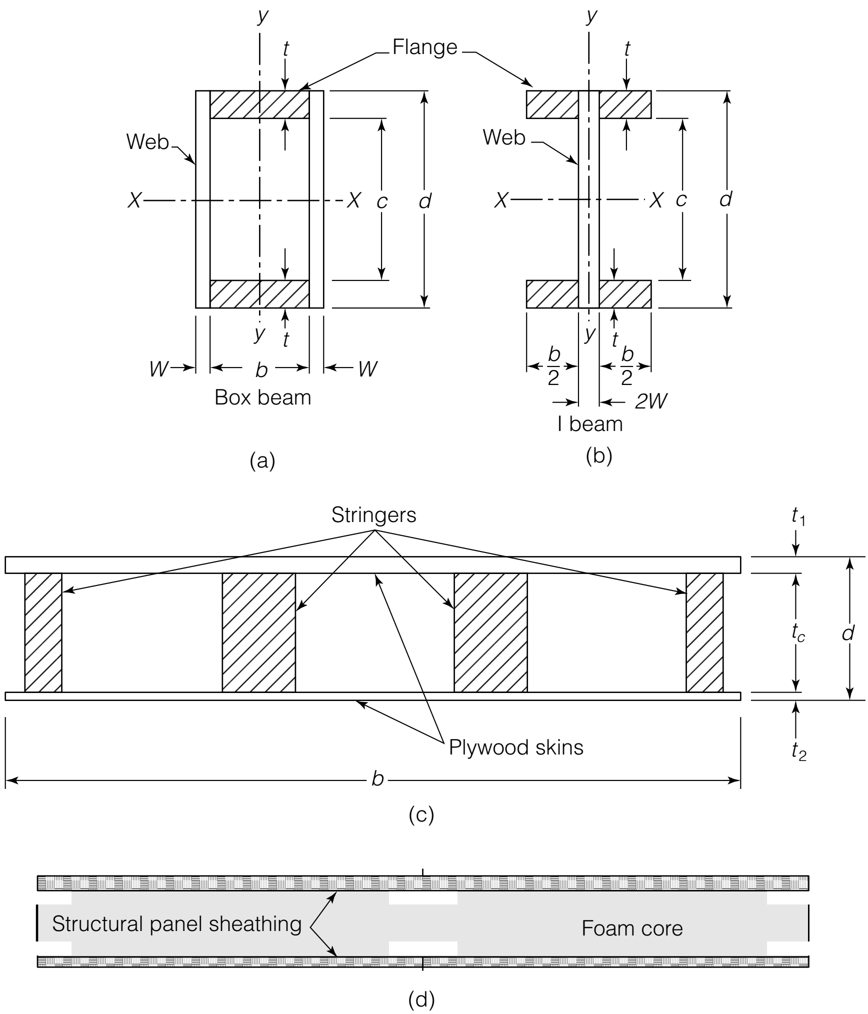


FIGURE 10.21 Composite structural members (a) box beam, (b) I-beam, (c) stressed skin panel, and (d) structural insulated panel.

It should be noted that there are many footnotes associated with this table, and before use of this information, the reader should consult the cited reference (APA-EWS, 2004). Table 10.12 addresses design values only for bending members. A similar table is available in the cited reference for design values for members subjected to axial tension or compression.

10.13.3 Composite Structural Members

As with natural wood products, glued products can be combined in a variety of ways to produce structural elements. Typical examples of manufactured composite members (Figure 10.21) are

I-beams
Box beams
Stressed skinned panels
Structural insulated panels

For example, I-beams are produced by gluing flange elements to an oriented strand board web, as shown in Figure 10.21(b). The flange elements may be either dimensional lumber or, more commonly, laminated veneer lumber.

As manufactured products, the properties of the elements are frequently specified based on the performance of the member, rather than being based on the individual material components. For example, I-joists are specified based on the spacing of the joists and the depth of the member. Standards for composite structural members may be developed by national organizations, such as ASTM, or by trade associations concerned with the proper use of the products they promote.

SUMMARY

Wood is an extremely flexible building material. Historically, natural wood products were the only option available to the engineer. However, modern forestry practices limit the size of natural products that are available. The need to increase the efficiency of using wood products has led to the development of engineered wood products. These products are frequently more economical than natural wood, particularly when large dimensions are required. In addition, by careful control of the manufacturing process, engineered woods can be produced that have characteristics superior to natural wood. The characteristics of engineered wood products depend on the wood stock used, the quality of the adhesive, and the manufacturing process. Several factors make wood unique when compared to the other materials used in civil engineering, including anisotropy, moisture sensitivity, creep, and the existence of defects in wood products. Furthermore, when wood is exposed to the environment, care must be taken to prevent degradation due to fungi, bacteria, and insects.

QUESTIONS AND PROBLEMS

10.1 What are the two main classes of wood? What is the main use of each class? State the names of two tree species of each class.

10.2 What is the difference between early wood and latewood? Describe each.

10.3 A simple lab test for specific gravity on two samples of lumber indicate that sample A has $G = 1.12$ and sample B has $G = 1.03$. Based on this information alone, which wood sample would you choose as a structural member for your construction project. Briefly explain why.

10.4 Discuss the anisotropic nature of wood. How does this phenomenon affect the performance of wood?

10.5 Briefly describe the chemical composition of wood.

10.6 The moisture content of wood test was performed according to ASTM D4442 procedure and produced the following data:

Weight of specimen in the green condition = 266.7 g.
Weight of oven-dry specimen = 152.1 g.
Calculate the moisture content of the given wood.

10.7 What is the fiber saturation point? What is the effect of the fiber saturation point on the shrinkage of wood in the different directions? How does this phenomenon affect the properties of lumber?

10.8 A stud had dimensions of 38.1 mm $\times$ 88.9 mm $\times$ 2.438 m and a moisture content of 150% when it was prepared. After seasoning, the moisture content was reduced to 7%. If the tangential, radial, and longitudinal directions of the grains are on the same order as the dimensions indicated above, what are the dimensions of the seasoned stud if the moisture-shrinkage relation follows Figure 10.5?

10.9 A wood timber with a diameter of 1 inch has a moisture content of 5%. The fiber saturation point (FSP) for this wood is 28%. The wood shrinks or swell is 1% in the radial direction for every 5% change in moisture content below FSP.

a. What would be the percent change in the wood's diameter if the wood's moisture is increased to 43%?
b. Would the wood swell or shrink?
c. What would be the new diameter?

10.10 Wood is cut at sawmills into a variety of products, with different sizes and shapes for engineering applications. What are these products?

10.11 Construction lumber can be cut from the tree using one of two methods or a combination of them. Name these two methods and show a sketch of each. What is the main advantage of each method?

10.12 Why are the actual dimensions of lumber different from the nominal dimensions? Explain.

10.13 What are the factors considered in grading lumber? What are the main grades of hardwoods and softwoods?

10.14 State five different imperfections that may be found in lumber, and briefly define them.

10.15 Sketch the typical stress–strain curve for wood. On the graph, show the modulus of elasticity.

10.16 Compute the modulus of elasticity of the wood species whose stress–strain relation is shown in Figure 10.9, using both the SI and English units. Compare the results with the typical values shown in Table 1.1 and comment about the results.

10.17 List five different tests used to evaluate the mechanical properties of wood.

10.18 A wood specimen was subjected to bending until failure by applying a load in the middle of its span. The specimen has a cross section of 1 in. × 1 in. and a span of 14 in. The load and the deflection in the middle of the span were recorded as shown in Table P10.18.

a. Using a computer spreadsheet program, plot the load–deflection relationship.
b. Plot the proportional limit on the graph.
c. Calculate the modulus of rupture (flexure strength).

Table P10.18

Load (lb)	Deflection (in.)
0	0
8	0.149
16	0.227
28	0.295
60	0.365
111	0.404
156	0.437
198	0.468
243	0.502
286	0.537
328	0.581
365	0.616

10.19. A wood specimen having a square cross section of 2 in. × 2 in. was tested in bending by applying a load at the middle of the span, where the span was 28 in. The deflection under the load was measured at different load levels as shown in Table P10.19.

Table P10.19

Load (lb)	Deflection (10^{-3} in.)
0	0
100	27.9
200	55.6
300	83.2
400	111.2
500	140.0
600	166.7
700	194.3
800	222.2
900	250.1
1000	275.4
1100	314.8
1200	359.5
1300	405.0
1400	468.6 (failure)

a. Using a computer spreadsheet program plot the load–deflection relationship.
b. Plot the proportional limit on the graph.
c. Calculate the modulus of rupture (flexure strength).
d. Does the modulus of rupture computed in (c) truly represent the extreme fiber stresses in the specimen? Comment on the assumptions used to compute the modulus of rupture and the actual response of the wood specimen.

10.20 A wood specimen was prepared with actual dimensions of 1 in. × 1in. × 4 in. and grains parallel to its length. The specimen was subjected to compression parallel to the grains to failure. The load–deformation results are as shown in Table P10.20.
a. Using a computer spreadsheet program, plot the stress–strain relationship.
b. Calculate the modulus of elasticity.
c. What is the failure stress?

10.21 A pine wood specimen was prepared with dimensions of 50 mm × 50 mm × 200 mm and grains parallel to its length. The specimen was subjected to compression parallel to the grains to failure. The load–deformation results are as shown in Table P10.21.
a. Using a computer spreadsheet program, plot the stress–strain relationship.
b. Calculate the modulus of elasticity.
c. What is the failure stress?

Table P10.20

Load (lb)	Displacement (in.)
0	0
7	0.012
10	0.068
87	0.164
530	0.180
1705	0.208
2864	0.236
3790	0.268
4606	0.300
5338	0.324
5116	0.360
4468	0.384
4331	0.413

Table P10.21

Load (kN)	Deformation (mm)
0	0
8.9	0.457
17.8	0.597
26.7	0.724
35.6	0.838
44.5	0.965
53.4	1.118
62.3	1.270
71.2	1.422
80.1	1.588
89.0	1.765
97.9	1.956
106.8	2.159
111.3	2.311

10.22 A wood specimen was prepared with dimensions of 1 in. × 1 in. × 4 in. and grains parallel to its length. The specimen was subjected to compression parallel to the grains to failure. The load (P) versus deformation (ΔL) results are as shown in Table P10.22. Using a spreadsheet program, complete the table by calculating engineering

Table P10.22

Observation No.	*P* (lb)	ΔL (in.)	σ (psi)	ε (in./in.)	u_i (psi)
0	0	0			N/A
1	720	0.020			
2	1720	0.048			
3	2750	0.076			
4	3790	0.108			
5	4606	0.140			
6	5338	0.164			
7	6170	0.200			
8	6480	0.224			
9	5400	0.253			
					u_t=

stress (σ) and engineering strain (ε). Determine the toughness of the material (u_t) by calculating the area under the stress–strain curve, namely,

$$u_t = \int_0^{\varepsilon^f} \sigma \, d\varepsilon$$

where ε_f is the strain at fracture. This integral can be approximated numerically using a trapezoidal integration technique:

$$u_t = \sum_{i=1}^{n} u_i = \sum_{i=1}^{n} \frac{1}{2}(\sigma_i + \sigma_{i-1})(\varepsilon_i - \varepsilon_{i-1})$$

10.23 A short rounded wood column with a diameter of 10 inches is to be constructed. If the failure stress is 7.3 ksi, what is the maximum load that can be applied to this column, using a factor of safety of 1.3?

10.24 For the purpose of designing wood structures, laboratory-measured strength properties are adjusted for application conditions. State five different application conditions that are used to adjust the strength properties.

10.25 What are the five types of organisms that attack wood?

10.26 What are the two types of preservatives that can be used to protect wood from decay? How are these preservatives applied?

10.27 What are the main types of engineered wood products?

10.28 What are the main advantages of engineered wood products over natural-timber members?

10.14 References

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