

4

Moisture-Related Properties of Wood and the Effects of Moisture on Wood and Wood Products

Charles Carll¹ and Alex C. Wiedenhoef¹

MOISTURE IS ARGUABLY THE MOST IMPORTANT factor affecting the performance and service life of wood and wood products. Moisture affects the dimensional movement of wood and wood products; under certain conditions, moisture change can result in major dimensional change. The integrity and strength of adhered (bonded) wood products can be compromised by swelling-induced stresses that accompany wetting. Progressive deflection over time of wood members under load is influenced by moisture conditions, particularly by large repetitive fluctuations in moisture content. Mechanical connections between wood members can be compromised by exposure to elevated moisture conditions or by significant moisture cycling. It is widely recognized that the structural integrity of wood can be irreversibly degraded by biological attack. In some cases biological infestation does not influence structural integrity but nevertheless influences serviceability. For many insect pests and all fungi, moisture conditions higher than the preferred in-service conditions are either required for infestation, or increase the likelihood of infestation.

Although wood, wood products, and wood construction can be degraded by elevated moisture levels or by greatly fluctuating moisture conditions, the vast majority of residential structures built in North America over the past three centuries were constructed primarily of wood, and most of these have performed reliably. Wood and wood products dried to an appropriate level, and maintained within a reasonable range of fluctuating moisture conditions will perform nearly indefinitely. In contrast, wooden buildings constructed without consideration of moisture control may rapidly suffer moisture-induced damage, leading to excessive repair and maintenance costs; in extreme cases the damage may even justify premature demolition.

The central topic of this chapter is how moisture affects the properties and behaviors of wood and wood-based products used in building construction. Physical properties and behaviors are discussed, as are structural behaviors, and what may be considered biological behaviors (specifically, the likelihood of biological infestation by microbes and insects). The order of discussion is that outlined in the previous sentence, namely physical first, then structural, then biological. Before the chapter delves into its central topic, it provides background information on wood and on adhered

(bonded) wood products. The information presented on wood includes discussion of wood structure, composition and basic characteristics, with an emphasis on structure. The information presented on bonded wood products follows a similar discussion path, but inasmuch as these are manufactured products, the emphasis is on product classification, composition, fabrication, and characteristics. Information concerning contemporary wood products is presented, as is information on wood products produced in past decades. The intent is to provide information applicable to buildings of various ages, not just to recently-constructed buildings.

The chapter also presents recommendations and guidelines for in-service moisture content. The recommendations are reiterated values from the literature, and take the form of not-to-exceed values. The recommendations are applicable to prevention of biological infestation; there is evidence that these recommended values also roughly correspond with values that have structural performance implications, irrespective of biological infestation. The guidelines, in contrast to the recommendations, relate to limitation of fluctuation in moisture content. The guidelines provide a basis that allows the reader to develop their own project-specific limitations on moisture fluctuation.

Structure of Wood

Axial and Radial Systems

Wood, whether a hardwood (from a broad-leaved tree such as a maple or an oak) or a softwood (from a needle-leaved tree such as a pine or a spruce) is a complex composite. It is composed of a staggering number of cells arranged in a regular, organized fashion into two cell systems, the axial (or longitudinal) system, and the radial system [Fig. 1(a)]. The axial system runs parallel to the long axis (i.e., up and down the trunk) and is the collection of cells that people often refer to as “the grain” of the wood. The axial system is responsible for the bulk of the mechanical function of wood, holding aloft the branches and leaves, and the long-distance transport of water (sap) from the roots up to the leaves. It is made of cells that are generally 100 to 200 times longer than they are wide. The radial system runs in a horizontal direction in a standing tree, that is, at a right angle to the axial system. The radial system, formed of individual collections of cells called rays,

¹ *Forest Products Technologist and Botanist, respectively, USDA Forest Service, Forest Products Laboratory, Madison, WI.*

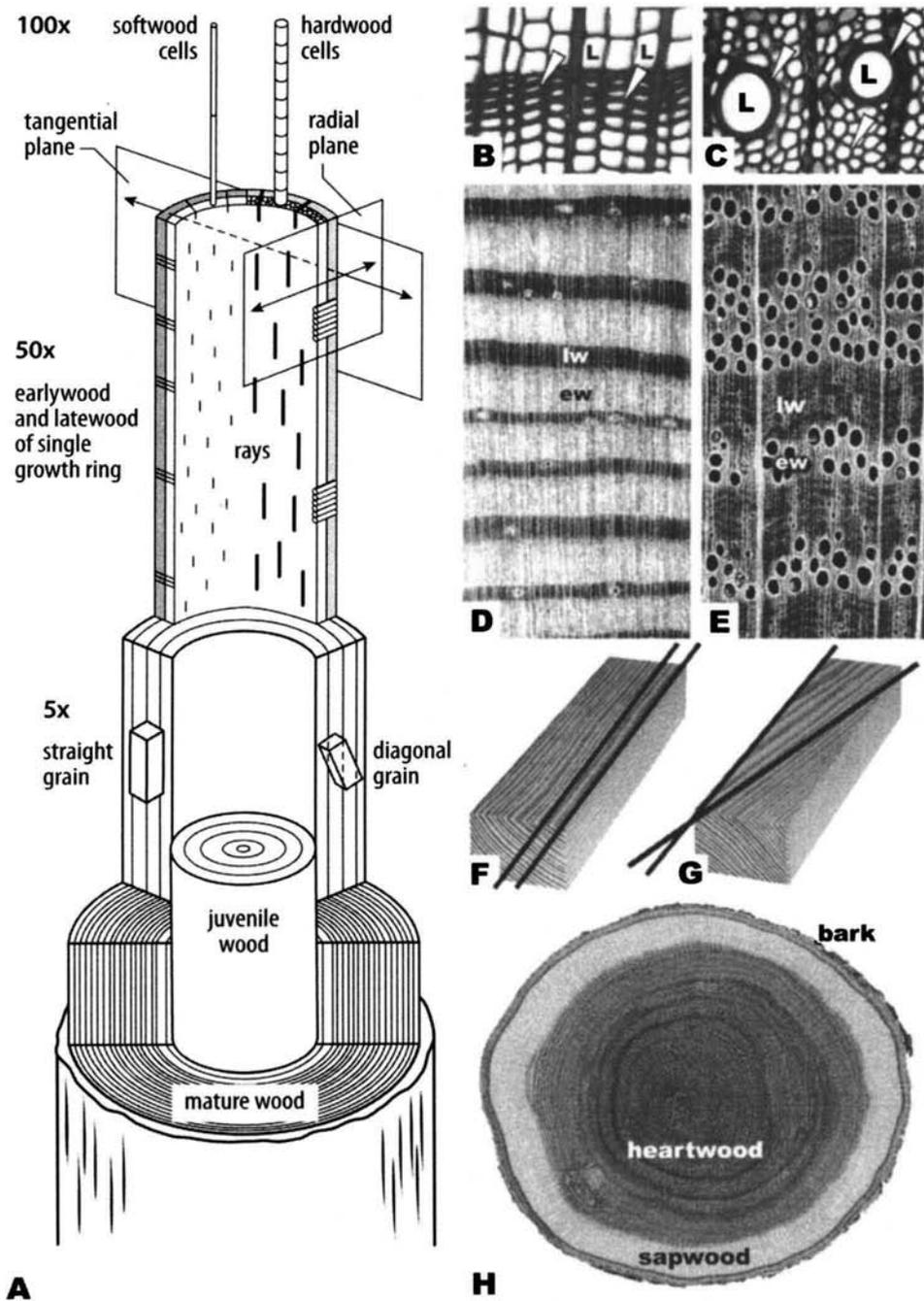


Fig. 1—(a) Illustration of a cut-away tree at various magnifications; it is intended to correspond roughly with the images to its right. At the top, at an approximate magnification of 100 \times , a softwood cell and several hardwood cells are illustrated, to give a sense of scale between the two. One tier lower is a single growth ring of a softwood (left) and a hardwood (right), as well as an indication of the radial and tangential planes. The magnification is approximately 50 \times . The next tier, at approximately 5 \times magnification, illustrates many growth rings together, and how one might produce a straight-grained rather than a diagonal-grained board. The lowest tier includes an illustration of the relative position of juvenile and mature wood in the tree, at a 1 \times magnification. (b,c) Light microscopic views of the lumina (L) and cell walls (arrowheads) of a softwood (B) and a hardwood (C). (d,e) Hand-lens views of growth rings, each composed of earlywood (ew) and latewood (lw) in a softwood (D) and a hardwood (E). (f) A straight-grained board; note that the line along the edge of the board is parallel to the line along the grain of the board. (g) A diagonal-grained board. Note that the two lines are markedly not parallel. This board has a slope of about 1 in 7. (h) The gross anatomy of a tree trunk, showing bark, sapwood, and heartwood.

runs in a pith-to-bark direction, although most rays do not extend continuously from the pith to the bark. The radial system is responsible largely for moving sugar and chemicals laterally within the trunk of the tree; its component cells are much shorter than those of the axial system.

To give some context to this discussion of cell systems and cell shapes, a one foot long 2 by 4 of Douglas-fir has on the order of 400 million cells; about 200 million of them are cells of the axial system, and the other 200 million are cells of the radial system. Despite the fact that the number of cells is nearly equal in the two systems, in Douglas-fir over 92 % of the total volume of the wood is made up of cells in the axial system [1]. This demonstrates numerically that cells of the radial system are much smaller than those of the axial system, particularly in softwoods.

Cell Wall, Lumen, and Moisture

Much as wood is made of cells occurring in two systems, any individual cell itself has two major domains; the cell wall and the lumen [Fig. 1(b) and 1(c)]. The cell wall comprises the physical matter of wood, and is formed primarily of layers of cellulose, hemicellulose, and lignin. Cellulose and hemicellulose are strongly hygroscopic (water-adsorbing), and water adsorption results in increases in the distances between the polymer chains and causes the swelling of the wall. Lignin is both an encrusting and matrix compound in the cell wall, providing rigidity to the wall, and constraining the cellulose and hemicellulose as they react to changes in moisture conditions. Lignin is also hygroscopic, but to a substantially lesser degree than cellulose or hemicellulose. It is the moisture relations within the cell walls that affect the movement (shrinkage and swelling) of wood and wood products. Shrinkage and swelling occur mostly in the thickness of the cell wall, resulting in a change in cell diameter. There are only tiny changes in the length of cells of normal wood with changes in moisture.

The moisture that is adsorbed to the hygroscopic portions of the cell wall is referred to as bound water. A given piece of wood has a finite number of sites in cell walls where water can bind; when all cell wall sites are occupied, the wood is said to have reached fiber saturation, beyond which further addition of water imparts no further change in the dimension of the cells. Thus, the range of moisture conditions across which wood responds with dimensional change is from completely dry up to the fiber saturation point (FSP). Although the concept of FSP is useful for explanatory purposes, transitory and spatial variations in moisture conditions make determination of a distinct FSP elusive. Tsoumis [2] uses the term "region of fiber saturation" to reflect such uncertainty.

The second domain of a cell in wood, the lumen (plural lumina), is the air space inside the cell where once the living contents of the cell resided [Fig. 1(b) and 1(c)]. In the living tree, the lumen was the domain of the cell through which the water flowed to travel from the roots to the leaves. In the case of wood and wood products, the lumen imparts void space in the bulk volume of wood. If it were not for the lumina, all woods would have a density of about 1.5 times that of water. In the context of moisture relations, the lumen is the space where liquid water accumulates when moisture is added after the FSP is reached. This liquid water, called free water,

does not affect the dimensional movement of wood, but its presence greatly increases the susceptibility of wood to biological attack.

The relationship between bound water, free water, and wood is analogous to the various hydration states of a dish sponge. A perfectly dry dish sponge is relatively hard and inflexible. As the amount of water in the sponge increases, the sponge softens and swells. Swelling and softening occurs as water enters, occupies, and enlarges spaces within the sponge tissue. After a certain transition point (what is by analogy, FSP), all spaces within the sponge tissue are occupied. This is the familiar feeling a well-wrung sponge; it is quite moist, but no water can be squeezed from it. Adding water to the sponge after this point results in filling of internal spaces with water (by analogy, free water), displacing air. The sponge becomes heavier and wetter, but its size and flexibility undergo no further change.

Cell-to-Cell Connections

The cells of the axial system are connected to each other, and are also connected to the cells of the radial system via tiny thin areas in the walls, called pits. These pits come in a variety of shapes and sizes, and their relative resistances to the flow of water can play an important part in wood-moisture relations. Inasmuch as the axial system comprises most of wood's volume and the cells of the axial system are much longer than they are wide, it is not surprising that moisture moves into, out of, and within wood most readily in this direction. For this reason most manuals and instructors insist on protecting the end grain of wood from direct access to water. Axial cells are nonetheless tiny compared to the scale of structural lumber; an axial cell of a softwood will generally range from 2–6 mm in length. If water taken up at the end grain could get no farther than one cell-length into a board, it would make little difference whether end grain were exposed. Water taken up by the end grain, however, can pass from cell to cell through the pits. Conduction through pits allows water to propagate for centimetres into a board end, and thus greatly increases the amount of water taken up by the board.

Growth Rings and Grain Angle

In our progressive understanding of the organization of wood, the next important scale is that of the growth ring. Virtually everyone is familiar with the idea of growth rings in trees; in the temperate world, each year another layer of wood is added to the circumference of the tree, increasing its girth and providing a simple means to determine the age and relative growth rate of the tree. In tropical areas of the world, growth rings may be correlated with wet or dry seasons; however, many tropical species do not exhibit clearly demarcated growth rings. In the case of trees from temperate regions, a given growth ring is the amount of wood produced in one year, and thus is sometimes called an annual ring.

For most species with growth rings, each ring is divided into two distinct regions, known as earlywood and latewood [Fig. 1(a), 1(d), and 1(e)]. In such cases where the two portions of the ring are distinct, the earlywood is the first-formed wood of the ring, and typically bears thin-walled cells with wide lumina that are suited for the rapid conduction of sap under conditions of plentiful soil moisture. Be-

cause wood is formed just under the bark, the earlywood is found on the interior side of the growth ring. The latewood is then added later in the growing season to the outside of the ring, and is typically formed of stronger, thicker-walled cells with narrow lumina. Virtually all woods commonly used in construction in North America have some differentiation between earlywood and latewood.

Most of the cells that form the curving arc of a growth ring are cells of the axial system; the cells forming the lines perpendicular to the growth rings are the rays of the radial system. The orientation of growth rings and rays within a board define the grain angle of the board, and can be seen thanks to the differences in wood structure between earlywood and latewood within and between growth rings. In a flat-sawn board, the arc of the growth rings are parallel to the wide face (the tangential face) of the board, and thus the rays are perpendicular to it. In a quarter-sawn board the rings are perpendicular to the wide face of the board and thus the rays are parallel to the wide face (in this case, the radial face) of the board. The rays are responsible for the pronounced figure called ray-fleck that is characteristic on the wide faces of quarter-sawn hard maple, oak, or sycamore boards (or the narrow faces of flat-sawn boards of these species). The distinction between tangential and radial directions is important, as will be discussed later, in determining the ways in which wood changes dimension with changes in moisture.

Slope of Grain, Spiral Grain, and Interlocked Grain

Ideally, the axial cells of a growth ring in a piece of lumber would be oriented perfectly parallel to the long axis of the board. There are two main ways in which the cells of the axial system deviate from this idealized condition.

The first deviation from perfect straightness is due to the nature of the shape of the tree. Though we often think of the trunk of a tree as a cylinder, it is in fact a collection of conical layers of wood, with each cone widest at the base of the trunk tapering to a point at the top of the tree. Each growth ring is a continuous sheath of wood superimposed on the previous year's cone. As the diameter of a tree increases, each layer comes closer and closer to the idealized, vertical condition. The orientation of cells in the tree can make it difficult to cut a straight-grained piece of wood from a tapered log; if one saws parallel to the pith, growth rings will be at an angle to the face of the board that is cut, resulting in a condition called diagonal grain [Fig. 1(a), 1(f), and 1(g)]. Diagonal grain can be minimized or eliminated by cutting parallel to the bark of the tree, particularly in cases where the diameter of the tree is fairly small, and thus taper tends to be high. Boards with diagonal grain often behave differently from boards with straight grain with changes in moisture.

The second common deviation from a perfectly vertical orientation of axial cells in the growth ring is called spiral grain. Spiral grain occurs when the wood cells within a growth ring are formed at a slight angle from vertical, resulting in a helical orientation about the trunk of the tree. If the angle from vertical is small (for example, less than one degree), spiral grain is not likely to be noticed in lumber. As the angle from vertical increases, however, the deviation becomes more pronounced, and spiral grain may be noticeable in a board cut from such a log. A log containing spiral grain

will not yield straight-grained lumber, regardless of how the lumber is sawn from the log. In some cases, spiral grain can occur in alternation within the same tree; for the first few years the wood may be laid down in a right-handed helix, then the next few years in a left-handed helix, and so on, switching every few years. In such a case, the wood is referred to as having interlocked grain. This condition can produce boards with an aesthetically striking figure, particularly in quarter-sawn material. Species such as African mahogany (*Khaya* spp.) often have interlocked grain, and produce interesting axial ribbonlike patterned boards. Wood with spiral or interlocked grain may show abnormal dimensional change with change in moisture.

Sapwood, Heartwood, and Natural Durability

Two regions of the trunk of the tree are germane to our discussion of wood; the heartwood and the sapwood [Fig. 1(h)]. Each of these regions is a collection of one to many growth rings. The heartwood, if present, always occurs in the center of the tree, and the sapwood is always the layer adjacent to the bark. Although there are many differences between heartwood and sapwood in the context of tree physiology, in the context of water relations of wood there are only two major differences; the closing of pits between cells and the accumulation of heartwood chemicals called extractives.

At the cell structural level, there is no appreciable difference between the anatomy or cell wall chemistry of cells in the heartwood compared to those in the sapwood. In a simple sense, the formation of heartwood is an ongoing process by which growth rings are decommissioned from transporting water to the leaves and are instead loaded to various degrees with extractives. As a given growth ring loses its transport function, it dries somewhat and in this process many of the pits in the cells close, thus making the wood less conductive of fluids. At the same time this drying is taking place, extractives are also being deposited, sometimes effectively sealing the pits closed. Such pit closure reduces the ability of the wood to allow fluid movement. If one is attempting to force preservatives into wood to increase the insect- and decay-resistance, a high proportion of sapwood is desirable, as the closed and often sealed pits of the heartwood greatly limit the penetration of the preservative into the board. In contrast, sapwood is much more prone to rapid wetting, and thus to more extreme fluctuation in moisture content in service.

Extractives are what impart the desirable colors to the heartwood of such species as cherry or walnut. Extractives give the cedars their pleasant odors, and extractives impart the great natural durability to the timber of black locust. Woods such as teak or *lignum vitae*, famous for their good performance in association with water, derive their utility from the quality, quantity, and type of extractives accumulated in their heartwood. In pines, spruces, larches, and Douglas-fir, accumulation of resinous extractives can affect appearance and performance of the wood.²

Within a species that has colored decay-resistant heartwood, coloration may provide a rough indication of the degree of decay resistance. Across species, however, heartwood

² Resinous extractives are found in both the sapwood and heartwood of these woods, but their compositions and amounts [3], and their distribution within the wood structure differ between sapwood and heartwood.

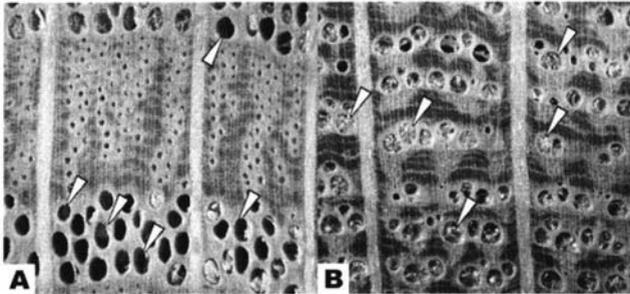


Fig. 2—Hand-lens views of two species of oak. (a) A species in the red oak group, with characteristic open vessels (arrowheads), making the wood highly permeable. (b) A species in the white oak group, showing vessels occluded with cellular ingrowths (arrowheads), rendering the wood highly impermeable. Note that the growth rate of the wood in A is much greater than that of B.

coloration should not be considered an indicator of resistance to biological attack. Some darkly colored heartwood has low resistance to biological attack, whereas nearly colorless heartwood (such as that of northern white cedar), or lightly colored heartwood (such as that of Alaska yellow-cedar) can be appreciably resistant to attack.

In some species, there are additional changes during heartwood formation that greatly affect the ultimate applications to which a wood might be suited. In species of oak, there is an important distinction between the heartwood formation process in the red oak group and that of the white oak group. In the former case, heartwood formation is much as described above; pits may close or become plugged or sealed during the deposition of extractives, and the wood dries out somewhat in the standing tree, but the overall permeability in these species is not greatly reduced [Fig. 2(a)]. In the white oak group, however, special cell wall ingrowths proliferate in the lumina of the largest conducting cells [Fig. 2(b)]. These ingrowths tightly plug the conducting cells and effectively seal the wood, and block the free flow of fluid. It is for this reason that the white oaks are used in shipbuilding and cooperage, and the red oaks are shunned. The red oaks do not form these plugs, and thus the permeability of red oak heartwood remains high. For this reason, the red oaks are commonly treated with creosote to produce railroad ties, and white oaks are not. By choosing the correct wood for the application, people have long been able to maximize the material benefits inherent in the diversity of wood structure.

Additional ways in which the relatively lower permeability of heartwood affects wood-moisture relations is in lumber drying and moisture cycling. Lower wood permeability often results in slower and more difficult drying of heartwood lumber by production mills. Conversely, the low permeability of heartwood can result in reduced fluctuation in moisture content under intermittent wetting or under fluctuating humidity conditions, and thus be a desirable trait.

Juvenile, Mature, and Reaction Wood

The bulk of our discussion of wood structure and chemistry to this point has implicitly assumed that we are speaking of mature wood cut from trees which had not been exposed to conditions that might have resulted in substantial trunk

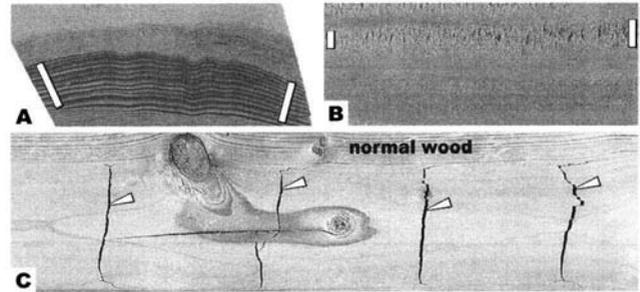


Fig. 3—(a) Wide band, spanning many rings, of compression wood (between the bars) as seen on the end-grain of a board. The wood outside the bars is mature, normal wood. (b) Fuzzy grain (between the bars) caused by incomplete cutting of tension wood fibers during planing. A partial band of fuzzy grain can be seen at the top edge of the image. (c) Dramatic longitudinal shrinkage of compression wood resulting in cross-grain checking (arrowheads). The normal wood at the top of the board does not exhibit this behavior.

lean. Such an assumption is not always valid; juvenile wood (formed early in the life of the trunk) and reaction wood (formed as a reaction to lean) are found to varying degrees in contemporary lumber.

Depending upon species, the first 5–25 years of growth can be considered juvenile wood. Juvenile wood was formed when the stem was of small diameter [Fig. 1(a)], and height-growth was rapid. The shape of juvenile wood cells often differs somewhat from that of mature wood cells, and the relative proportions and distribution of major chemical constituents in the cell wall (cellulose, hemicellulose, and lignin) can be significantly different [4]. It is thought that structural and chemical differences are responsible for the most significant undesirable property of juvenile wood; relatively large longitudinal shrinkage [5,6]. This aspect will be discussed in detail in the section on wood dimensional stability.

Reaction wood occurs in both hardwoods and softwoods, although the nature of the chemical and structural cell changes are different in each. Reaction wood in softwoods is known as compression wood due its position of formation, on the underside of the lean. Compression wood cells are generally shorter and misshapen compared to normal cells, have thick walls with a high percentage of lignin, and appear as dark bands on the end-grain of a board [Fig. 3(a)]. Though the density of compression wood is high, its relative strength is low. Compression wood tends to have high longitudinal shrinkage compared to normal wood, often resulting in cracks across the grain if only part of the board is compression wood [Fig. 3(c)].

In hardwoods, reaction wood is formed on the upper side of the lean, and is called tension wood. Tension wood is characterized by the formation of special cells with drastically altered cell wall characteristics. A common symptom of tension wood is fuzzy grain as seen on the longitudinal surface of a planed board [Fig. 3(b)]; the fuzzing effect is caused by the failure of the soft, specialized wall layers to be cut cleanly by planer knives.

Adhered (Bonded) Wood Products

Bonded Wood Products in Building Construction

Construction plywood panels have been widely used since the mid 1950s as sheathing and structural subflooring. Oriented strand board (OSB) panels have been used in these applications for about two decades. OSB currently commands a larger share of this market than plywood. Plywood and OSB panels used as sheathing or subflooring transfer loads to and between the building's framing members, and provide racking resistance to wall, roof, or floor systems. Plywood and OSB are also used in fabrication of structural frame components of buildings, for example, as web members of box beams or I-joists or as the facings of structural insulated panels. Glued laminated (glulam) timbers have been used for decades as structural frame elements in buildings. "Structural composite lumber" is a collective term that includes laminated veneer lumber (LVL), parallel strand lumber (PSL), laminated strand lumber (LSL), and oriented strand lumber (OSL), fabricated to serve as framing material [7]. Structural composite lumber evolved from plywood and OSB manufacturing technologies. Plywood, OSB, glued laminated timbers and structural composite lumber are fabricated from pieces of wood, (collectively termed wood constituents), bonded into integral panels or members with adhesives. For the past two decades, waterproof (or nearly waterproof) synthetic polymeric adhesives have been used.³ Plywood, OSB, and structural composite lumber are fabricated with waterproof adhesives and are hot-pressed. Glulam timbers are fabricated with either waterproof or nearly waterproof adhesives. They may be pressed with application of radio-frequency energy to heat the gluelines, but the wood laminations are not heated to as high temperatures as are attained by the wood constituents in structural panels or in structural composite lumber during hot pressing. The wood constituents in structural bonded wood products (plywood, OSB, glulam, and structural composite lumber) are, for the most part, indistinguishable chemically from the wood raw material from which they were derived. Composition of structural bonded wood products is, by mass, roughly 90 % or more chemically-unmodified wood. Glued laminated timbers and plywood and OSB are usually sold as commodity products. Structural composite lumber is usually marketed on a proprietary basis.

Wood-based panels are also used in largely nonstructural roles in building construction. Wood fiberboard panels at densities of between 200 and 450 kg/m³ are sometimes used as wall sheathing. Wood fiberboard sheathing panels usually incorporate resinous or asphaltic materials to inhibit water absorption. Wood fiberboards at densities of between 500 and 800 kg/m³ (hardboards) are sometimes used as wall cladding material (siding) or as exterior trim; these typically incorporate thermosetting waterproof adhesive, the amount depending on the manufacturing method. In North America, particleboard and medium density fiberboard (MDF) (at densities of roughly 640 to 850 kg/m³) are

usually bonded with urea-formaldehyde (UF) adhesives. Urea-formaldehyde bonds are not waterproof, and UF-bonded particleboard and MDF are therefore used in interior locations. These products are commonly used in kitchen and bathroom countertops, where exposed faces and edges are overlaid with laminate to isolate the board from wetting. UF-bonded particleboard is sometimes used as mobile home floor decking; with this exception, UF-bonded particleboard is not used structurally in buildings in North America. The core material in laminated interior flooring, which may be subject to wetting in limited amounts, is usually specially-made particleboard or, more commonly, specially-made MDF fabricated with a comparatively water-resistant bonding system (often incorporating melamine resin). Laminated interior flooring is sold as a proprietary product, the specially-made MDF or particleboard core being an integral part of the finished product. Hardboard exterior trim is also sold on a proprietary basis. All other nonstructural wood-based panels are usually marketed as commodity products. Composition of nonstructural wood-based panels is, like structural bonded wood products, roughly 90 % or more wood material.

Fiber-cement board is finding widespread use as a exterior cladding (siding) material. Fiber-cement board is in some ways similar to the manufactured bonded wood products mentioned previously, but also differs in a number of important ways. In fiber-cement board, wood-derived fiber is, in mass proportion, a minor (although critically important) component. Silica and portland cement are, by mass, the major components of fiber-cement board. The fiber in fiber-cement board is unbleached pulp fiber; it is composed of individual wood cells. The separation of individual wood cells in pulp is facilitated by chemical removal of a portion of the wood's lignin; the fiber thus is not chemically identical to the wood from which it was produced. Portland cement, rather than an organic polymeric resin, is used as the binding agent. Fiber-cement sidings are sold as proprietary products. The moisture-related behaviors of fiber-cement siding are not addressed in this manuscript, in part because the authors could not locate such information in the research literature, and in part because the mass proportion of wood in the product is less than 50 %.

Composite materials composed of comminuted wood (commonly wood flour or fibers) and thermoplastic synthetic polymers (commonly polyolefins or polyvinyl chloride) have become widely used as exterior decking, and are also used to fabricate extruded parts for fenestration units. Wood/plastic composite materials are typically manufactured using extrusion technology developed in the plastics processing industry. The materials are sold as proprietary products. The moisture-related behaviors of wood/plastic composite materials are not addressed in this chapter; the reasons are similar to those outlined previously relating to fiber-cement siding.

Characteristics of Plywood and LVL

Plywood and LVL are fabricated from sheets of veneer, produced by lathe peeling of veneer bolts of roughly 2.5 m length. Lathe peeling yields veneer sheets with tangential-grain faces. In LVL, grain orientation in most, if not all, veneer sheets is parallel with the longest axis of the member. In

³ Glulam timbers in buildings constructed before the mid 1960s may be adhered with casein glue. Plywood in buildings constructed before the early 1970s may be adhered with soy- or blood-protein glues. These older adhered wood products are more susceptible to water-induced delamination than are contemporary bonded wood products.

contrast, plywood is of cross-laminated construction; grain orientation in face veneers is parallel with panel long dimension, but orientation of grain in some or all interior plies is perpendicular to the panel length. In 3-ply and 4-ply plywood, grain direction of all interior plies is perpendicular panel length; in 5-ply plywood, grain direction in the center ply is parallel with panel length, and grain direction in the cross band plies between the core and face plies is perpendicular to panel length. The cross-laminated construction of plywood results in roughly equivalent along-panel and across-panel moisture-induced dimensional change.

Plywood panels may have edge veneer joints within plies, but the plies do not contain end joints. LVL members in contrast, will generally be longer than the veneer bolts from which their veneer sheets were peeled; the members will thus contain butt or overlap veneer end joints in all ply layers through the member thickness. For structural reasons, veneer end joints in LVL lumber are staggered. LVL members are most commonly installed with structural loads applied edgewise (joist configuration). Therefore, provided that the veneer end joints are staggered and adhesive bonds between plies are functional, the presence of veneer end joints in LVL members is not considered of structural consequence. In summary, the wood constituents (veneers) in plywood or LVL have an along-grain dimension of somewhere between the width of a plywood sheet (commonly 1.2 m) and the length of the veneer bolt from which the veneer was peeled (commonly about 2.5 m). Veneer sheets in plywood and LVL are, in general, neatly stacked. When manufacturing commercial softwood plywood, a compaction pressure of roughly 1.2 MPa (175 psi) will bring the veneer surfaces to be bonded into sufficiently close contact for adequate bonding [8].⁴ These consolidation pressures do not exceed the compressive strength of wood perpendicular to the grain; compaction of the wood is largely restricted to projecting high spots on veneer surfaces. Plywood tends to be 5 to 10 % denser than the wood from which it was fabricated;⁵ some of the densification comes from filling voids (including cell lumina on veneer surfaces) with adhesive. With LVL, consolidation pressures and glue spreads may be higher than in plywood,⁶ and the veneers may be selected for their strength and stiffness (and thus have higher than average density). LVL may be in excess of 30 % denser than randomly-selected wood of the same species.

Construction plywood⁷ has waterproof and boil-proof⁸ bonds. This was not, however, always the case. Until its most

recent revision [15], the U.S. Product Standard for construction plywood recognized plywood classes with Interior and Intermediate (or Exposure 2) bonds. Plywood panels classed Interior were commonplace prior to the 1970s.⁹ Today, construction plywood panels are classed as either Exterior or Exposure 1. Exterior panels are intended for uses such as exterior wall cladding (siding). Exterior panels contain high grade veneers, and (with the protection afforded by exterior finishes) are expected to withstand indefinite weather exposure. Exposure 1 panels, in contrast, contain lower veneer grades. Although bonded with the same adhesives as Exterior panels, Exposure 1 panels are not intended for indefinite exterior exposure. Fabrication with waterproof and boil-proof adhesive allows Exposure 1 panels to withstand multiple cycles of wet-dry exposure as may occur during construction, allowing for jobsite delays. Exposure 1 panels may contain significant defects (e.g., knots) in their face plies. Face ply delamination at the defects can be expected if the panels are exposed indefinitely to the weather, particularly if a significant defect in a face ply happened to line up with a defect in a core or cross-band ply.

The bonds in LVL are also fully waterproof and boil-proof but, like Exposure 1 panel products, are not intended for in-service exposure to the weather. The structural frame elements of wood frame buildings are expected to be protected from weather exposure,¹⁰ insofar as they are relatively difficult to replace, and because their integrity is generally crucial to structural safety.

Characteristics of Wood Composition Materials

Maloney [16] suggested the term “wood composition material” as a collective category for a variety of materials (e.g.: fiber insulation board, hardboard, particleboard, MDF and OSB), which are fabricated of comminuted¹¹ wood, and bonded into panels or members, usually with adhesives. Fiber insulation board is the sole wood composition material in which bonding between constituents is not provided primarily by synthetic polymeric adhesive,¹² and with this exception, wood composition materials are usually denser (commonly about 30 %) than the wood from which they were fabricated [16]. Functional wood composition building materials can be economically fabricated from wood raw materials that would be unmerchantable as sawlogs or veneer logs, (for example, small-diameter trees from woodland

⁹ This sentence comes, virtually verbatim, from Baker [17].

¹⁰ Isolation of critical structural elements from the weather is a time-proven strategy in structures of many different types. The main steel suspension cables of the George Washington, Golden Gate, Mackinac, and Verrazano Narrows Bridges are enclosed in cable covers that isolate them from the weather.

¹¹ In the parlance of wood composition materials, “comminuted” means that the individual wood pieces have a dimension along the grain that is usually less than 0.2 m, with width and thickness dimensions not exceeding roughly 90 mm and roughly 1.5 mm, respectively; in other words the pieces are relatively small as compared to veneer sheets. The wood piece dimensions are frequently less than half these dimensions, but the pieces generally have length dimensions that are many times their thickness dimensions and could not be accurately characterized as minutely fine or pulverized (as some dictionary definitions of “comminuted” suggest).

¹² As indicated previously, asphalt or rosin “sizing” is commonly incorporated in fiberboard produced for use as sheathing. These materials apparently provide some bonding between fibers, but are added primarily to prevent water-induced disruption of the inter-fiber hydrogen bonds, which are responsible for the primary bonding [18].

⁴ Pressure required depends on adhesive consistency and is inversely related to smoothness and conformability of veneer surfaces [9]. Geimer et al. [10] successfully pressed smoothly cut (sliced) pine veneers into plywood using 1.03 MPa compaction pressure. Jøkerst and Lutz [11] and Jøkerst and Geimer [12] pressed plywood fabricated from lathe-cut veneers at 175 psi compaction pressure, (the same pressure cited by Baldwin [8] as adequate).

⁵ A targeted compaction of from 3 to 5 % was promulgated by Rinne [13] as necessary for assuring adequate consolidation of plywood in industrial operations, where some variation in veneer thickness is expected.

⁶ Fabrication parameters for LVL are not available [14].

⁷ Construction plywood is termed “structural plywood” in the most recent version of the Department of Commerce Product Standard.

⁸ Boil-proof adhesive bond lines will withstand immersion in boiling water for two hours without perceptible delamination. To withstand such exposure, the bond line must have sufficient elasticity to withstand strain induced by wood substrate movement, and must be chemically stable (neither dissolve nor undergo hydrolysis).

TABLE 1—Moisture content of wood in equilibrium with stated temperature and relative humidity (source: Wood Handbook).

Temperature		Moisture Content (%) at Various Relative Humidity Values																		
°C	°F	5 %	10 %	15 %	20 %	25 %	30 %	35 %	40 %	45 %	50 %	55 %	60 %	65 %	70 %	75 %	80 %	85 %	90 %	95 %
-1.1	(30)	1.4	2.6	3.7	4.6	5.5	6.3	7.1	7.9	8.7	9.5	10.4	11.3	12.4	13.5	14.9	16.5	18.5	21.0	24.3
4.4	(40)	1.4	2.6	3.7	4.6	5.5	6.3	7.1	7.9	8.7	9.5	10.4	11.3	12.3	13.5	14.9	16.5	18.5	21.0	24.3
10.0	(50)	1.4	2.6	3.6	4.6	5.5	6.3	7.1	7.9	8.7	9.5	10.3	11.2	12.3	13.4	14.8	16.4	18.4	20.9	24.3
15.6	(60)	1.3	2.5	3.6	4.6	5.4	6.2	7.0	7.8	8.6	9.4	10.2	11.1	12.1	13.3	14.6	16.2	18.2	20.7	24.1
21.1	(70)	1.3	2.5	3.5	4.5	5.4	6.2	6.9	7.7	8.5	9.2	10.1	11.0	12.0	13.1	14.4	16.0	17.9	20.5	23.9
26.7	(80)	1.3	2.4	3.5	4.4	5.3	6.1	6.8	7.6	8.3	9.1	9.9	10.8	11.7	12.9	14.2	15.7	17.7	20.2	23.6
32.2	(90)	1.2	2.3	3.4	4.3	5.1	5.9	6.7	7.4	8.1	8.9	9.7	10.5	11.5	12.6	13.9	15.4	17.3	19.8	23.3
37.8	(100)	1.2	2.3	3.3	4.2	5.0	5.8	6.5	7.2	7.9	8.7	9.5	10.3	11.2	12.3	13.6	15.1	17.0	19.5	22.9
43.3	(110)	1.1	2.2	3.2	4.0	4.9	5.6	6.3	7.0	7.7	8.4	9.2	10.0	11.0	12.0	13.2	14.7	16.6	19.1	22.4
48.9	(120)	1.1	2.1	3.0	3.9	4.7	5.4	6.1	6.8	7.5	8.2	8.9	9.7	10.6	11.7	12.9	14.4	16.2	18.6	22.0
54.4	(130)	1.0	2.0	2.9	3.7	4.5	5.2	5.9	6.6	7.2	7.9	8.7	9.4	10.3	11.3	12.5	14.0	15.8	18.2	21.5
60.0	(140)	0.9	1.9	2.8	3.6	4.3	5.0	5.7	6.3	7.0	7.7	8.4	9.1	10.0	11.0	12.1	13.6	15.3	17.7	21.0
65.6	(150)	0.9	1.8	2.6	3.4	4.1	4.8	5.5	6.1	6.7	7.4	8.1	8.8	9.7	10.6	11.8	13.1	14.9	17.2	20.4

thinning operations). Some wood composition materials are fabricated primarily from residues produced by other wood processing industries. Construction and urban wood waste is sometimes commercially utilized in the raw material mix used for fabrication of particleboard and MDF.

Comminuted wood constituents are, individually, substantially shorter, thinner, and narrower than any dimensions of the panel or member that they form. Integrity of a wood composition panel or member thus depends on a series of lap and bridge joints between the wood constituents. Inter-leaving of constituents in a wood composition material allows for formation of lap and bridge joints during pressing, but bond formation depends on constituent surfaces being brought into close contact during adhesive cure. The pressures required to bring constituents into close contact during hot-pressing result in noticeable densification of wood composition materials. Total surface area of the (comminuted) constituents in a wood composition panel is usually about an order of magnitude greater than the surface area of the constituents in a similar-sized panel or member fabricated with veneer sheets. Specific adhesive coverage (mass of adhesive per unit surface area of the wood constituents to be bonded) is not calculated for wood composition materials [9], but is recognized as being appreciably lower than in panels or members fabricated from veneer sheets. Adhesive application to the constituents in wood composition material is discontinuous, although adhesive flow during hot pressing can result in areas of more or less continuous bonding between constituents [19]. Where more or less continuous bonding has been observed, it was evident that particles had been brought into very close contact by application of substantial pressure in the direction of panel thickness. In pressing of wood composition materials, the pressure exerted changes during the pressing cycle, with peak pressure occurring as the mattress of particles or fibers first reaches its fully compacted thickness [20]. The literature suggests 2–8 MPa (300–1000 psi) as a reasonable estimated range of peak compaction pressure during production of commercial wood composition materials [21–23]. Some crushing of the cellular structure in individual wood constituents occurs during pressing of wood composition materials [24], attributable in large part to the compaction pres-

ures involved.¹³ Wang and Winistorfer [25] measured an average compaction of roughly 24% in pine flakes pressed in mattresses using a press cycle believed to be representative of commercial flakeboard production.

Insofar as the individual constituents of wood composition materials are relatively short; they collectively have appreciable end-grain area through which liquid water might be rapidly absorbed. All commercial wood composition materials therefore contain a sizing agent (most commonly petroleum wax) to inhibit liquid water absorption. The adhesive system may also influence water absorptivity of a wood composition material, and may thus be a factor in the manufacturer's choice of adhesive system. Wood composition materials can be manufactured to have low levels of liquid water absorption, for use in applications where this is important [26]. PSL, LSL, and OSL, which are wood composition materials, are (as indicated previously), bonded with waterproof and boil-proof binder systems. Adhesive contents in PSL, LSL, and OSL (and thus production costs) are commensurate with the products' relatively critical end use (and higher unit market price). Nonetheless, and as also indicated previously, PSL, LSL, and OSL are not intended for exterior use.

Moisture Content

The moisture content of wood and wood products is defined as the mass (weight) of water in the member expressed as a fraction, usually a percentage, of the oven-dry mass of the member.

Wood placed in an environment of constant atmospheric conditions and isolated from liquid water, will eventually reach a moisture content in equilibrium with that environment, termed "equilibrium moisture content" (EMC). EMC is a function of the ambient relative humidity, and, to a lesser extent, the temperature. The EMC at any set of atmospheric conditions below 100% RH, will be below the fiber saturation point. The relationship between EMC, temperature and relative humidity is shown in Table 1. At low and

¹³ In a mattress of comminuted wood constituents undergoing compaction, the compaction pressure has an uneven spatial distribution within the panel plane; this is recognized as accentuating the crushing of cellular structure within some of the constituents.

TABLE 2—Moisture contents of wood panel products in equilibrium room temperature and stated relative humidity.

RH	Constr. ply-wood APA ^a	Constr. ply-wood NIST ^b	OSB APA	OSB NIST	Particle-board (interior) MSU ^c	Particle-board (interior) NIST	Fiber-board sheathing FPL ^d	Fiber-board sheathing NIST	Hardboard FPL ^e	Hardboard siding FPL ^f
10	1.2	2.3	0.8	1.7	3	1.9		2.1–2.3		
20	2.8	3.7	1.0	3.0	5–6	3.1		2.5–3.6		
30	4.6	4.8	2.0	4.1	6.2–7.5	4.1	3.4–6.1	2.9–4.7	2.4–5.3	
40	5.8	5.9	3.6	5.3	7–9.5	5.2		3.4–5.9		5–7
50	7.0	7.2	5.2	6.6	8–10	6.3	4.4–7.7	4.0–7.4	3.2–6.8	
60	8.4	8.7	6.3	8.1	8.5–11	7.7		4.9–9.3		7–10
70	11.1	10.8	8.9	10.1	9.5–12.2	9.8		6.2–12.0		
80	15.3	13.7	13.1	12.9	10.5–14	12.2		8.4–16.6	8.5–11.5	9–13.5
90	19.4	18.5	17.2	17.3	14–16	16.5	9.2–16.5		9.0–14.9	

^aZylkowski [37] (values correspond with Zylkowski [38] in which the data are for sorption direction, dry weight measured by oven drying).

^bRichards et al. [34]: (average of adsorption and desorption for individual commercial products, dry weight measured by desiccant drying).

^cSuchsland [33] (one commercial board, range indicates hysteretic effect, dry weight measured by oven drying).

^dNordenson [39]: (range in values indicates differences between different commercial products, adsorption direction only, dry weight by oven drying).

^eMyers and McNatt [40].

^fCarll and TenWolde [35] (range indicates hysteretic effect, dry weight by oven drying).

moderate levels of relative humidity, the values in Table 1 may be applied to wood of virtually any species. At high RH levels, values in the table should not be considered precise. Spalt [27], Hedlin [28], Choong and Manwiller [29], and Ahmet et al. [30] found essentially no between-species differences in EMC value at low and moderate levels of RH. In contrast, at RH levels of 71 % or higher Choong and Manwiller [29] and Ahmet et al. [30] observed between-species differences in EMC as high as 3–4 percentage points; Hedlin [28] observed larger between-species differences at very high RH (above 95 %). Spalt [27] proposed an explanation for the relatively larger between-species differences in EMC that occur at high relative humidity levels. This explanation, in which wood extractives play a mechanistic role, was evidently supported by the subsequent works of Wangaard and Granados [31] and by Choong [32].

Wood in service is exposed to both long-term (seasonal) and shorter-term (for example, daily) atmospheric changes in relative humidity and temperature. Wood is therefore always undergoing at least slight changes in moisture content. These changes are usually gradual, and short-term fluctuations tend to influence only the wood surface. Moisture content changes can be retarded, but not prevented, by surface coatings such as paint, exterior stain, or varnish.

The EMC that wood will attain when it adsorbs atmospheric moisture from an initially drier condition is always less than the EMC that the wood would reach if it were placed in the same environment, but instead reached moisture equilibrium from an initially wetter condition. This phenomenon is known as sorption hysteresis. The ratio of adsorption EMC to desorption EMC is commonly about

0.85. The EMC that wood will reach, however, in its first desorption from the green condition (that of freshly sawn wood) is greater than in any subsequent desorption. Data in Table 1 were derived primarily under conditions described as “oscillating desorption,” which is thought to represent a condition midway between adsorption and desorption, and

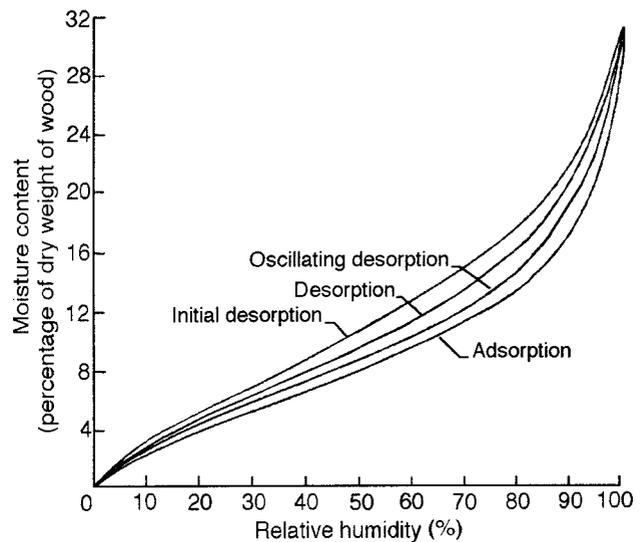


Fig. 4—Moisture content–relative humidity relationship at 20°C for wood under adsorption and various desorption conditions (source: *Wood Handbook*).

TABLE 3—Typical moisture contents of bonded wood products as shipped from production plants (courtesy APA—The Engineered Wood Association).

OSB, Particleboard and Hardboard	Plywood and Structural Composite Lumber	Glu-lam Timbers
3–5 %	6–8 %	11–12 %

TABLE 4—Equilibrium moisture content of wood, exposed to outdoor atmosphere, in several U.S. locations (source: Wood Handbook).

State	City	Equilibrium Moisture Content ^a											
		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
AK	Juneau	16.5	16.0	15.1	13.9	13.6	13.9	15.1	16.5	18.1	18.0	17.7	18.1
AL	Mobile	13.8	13.1	13.3	13.3	13.4	13.3	14.2	14.4	13.9	13.0	13.7	14.0
AZ	Flagstaff	11.8	11.4	10.8	9.3	8.8	7.5	9.7	11.1	10.3	10.1	10.8	11.8
AZ	Phoenix	9.4	8.4	7.9	6.1	5.1	4.6	6.2	6.9	6.9	7.0	8.2	9.5
AR	Little Rock	13.8	13.2	12.8	13.1	13.7	13.1	13.3	13.5	13.9	13.1	13.5	13.9
CA	Fresno	16.4	14.1	12.6	10.6	9.1	8.2	7.8	8.4	9.2	10.3	13.4	16.6
CA	Los Angeles	12.2	13.0	13.8	13.8	14.4	14.8	15.0	15.1	14.5	13.8	12.4	12.1
CO	Denver	10.7	10.5	10.2	9.6	10.2	9.6	9.4	9.6	9.5	9.5	11.0	11.0
DC	Washington	11.8	11.5	11.3	11.1	11.6	11.7	11.7	12.3	12.6	12.5	12.2	12.2
FL	Miami	13.5	13.1	12.8	12.3	12.7	14.0	13.7	14.1	14.5	13.5	13.9	13.4
GA	Atlanta	13.3	12.3	12.0	11.8	12.5	13.0	13.8	14.2	13.9	13.0	12.9	13.2
HI	Honolulu	13.3	12.8	11.9	11.3	10.8	10.6	10.6	10.7	10.8	11.3	12.1	12.9
ID	Boise	15.2	13.5	11.1	10.0	9.7	9.0	7.3	7.3	8.4	10.0	13.3	15.2
IL	Chicago	14.2	13.7	13.4	12.5	12.2	12.4	12.8	13.3	13.3	12.9	14.0	14.9
IN	Indianapolis	15.1	14.6	13.8	12.8	13.0	12.8	13.9	14.5	14.2	13.7	14.8	15.7
IA	Des Moines	14.0	13.9	13.3	12.6	12.4	12.6	13.1	13.4	13.7	12.7	13.9	14.9
KS	Wichita	13.8	13.4	12.4	12.4	13.2	12.5	11.5	11.8	12.6	12.4	13.2	13.9
KY	Louisville	13.7	13.3	12.6	12.0	12.8	13.0	13.3	13.7	14.1	13.3	13.5	13.9
LA	New Orleans	14.9	14.3	14.0	14.2	14.1	14.6	15.2	15.3	14.8	14.0	14.2	15.0
ME	Portland	13.1	12.7	12.7	12.1	12.6	13.0	13.0	13.4	13.9	13.8	14.0	13.5
MA	Boston	11.8	11.6	11.9	11.7	12.2	12.1	11.9	12.5	13.1	12.8	12.6	12.2
MI	Detroit	14.7	14.1	13.5	12.6	12.3	12.3	12.6	13.3	13.7	13.5	14.4	15.1
MN	Minneapolis-St. Paul	13.7	13.6	13.3	12.0	11.9	12.3	12.5	13.2	13.8	13.3	14.3	14.6
MS	Jackson	15.1	14.4	13.7	13.8	14.1	13.9	14.6	14.6	14.6	14.1	14.3	14.9
MO	St. Louis	14.5	14.1	13.2	12.4	12.8	12.6	12.9	13.3	13.7	13.1	14.0	14.9
MT	Missoula	16.7	15.1	12.8	11.4	11.6	11.7	10.1	9.8	11.3	12.9	16.2	17.6
NE	Omaha	14.0	13.8	13.0	12.1	12.6	12.9	13.3	13.8	14.0	13.0	13.9	14.8
NV	Las Vegas	8.5	7.7	7.0	5.5	5.0	4.0	4.5	5.2	5.3	5.9	7.2	8.4
NV	Reno	12.3	10.7	9.7	8.8	8.8	8.2	7.7	7.9	8.4	9.4	10.9	12.3
NM	Albuquerque	10.4	9.3	8.0	6.9	6.8	6.4	8.0	8.9	8.7	8.6	9.6	10.7
NY	New York	12.2	11.9	11.5	11.0	11.5	11.8	11.8	12.4	12.6	12.3	12.5	12.3
NC	Raleigh	12.8	12.1	12.2	11.7	13.1	13.4	13.8	14.5	14.5	13.7	12.9	12.8
ND	Fargo	14.2	14.6	15.2	12.9	11.9	12.9	13.2	13.2	13.7	13.5	15.2	15.2
OH	Cleveland	14.6	14.2	13.7	12.6	12.7	12.7	12.8	13.7	13.8	13.3	13.8	14.6
OK	Oklahoma City	13.2	12.9	12.2	12.1	13.4	13.1	11.7	11.8	12.9	12.3	12.8	13.2
OR	Pendleton	15.8	14.0	11.6	10.6	9.9	9.1	7.4	7.7	8.8	11.0	14.6	16.5
OR	Portland	16.5	15.3	14.2	13.5	13.1	12.4	11.7	11.9	12.6	15.0	16.8	17.4
PA	Philadelphia	12.6	11.9	11.7	11.2	11.8	11.9	12.1	12.4	13.0	13.0	12.7	12.7
SC	Charleston	13.3	12.6	12.5	12.4	12.8	13.5	14.1	14.6	14.5	13.7	13.2	13.2
SD	Sioux Falls	14.2	14.6	14.2	12.9	12.6	12.8	12.6	13.3	13.6	13.0	14.6	15.3
TN	Memphis	13.8	13.1	12.4	12.2	12.7	12.8	13.0	13.1	13.2	12.5	12.9	13.6
TX	Dallas-Ft. Worth	13.6	13.1	12.9	13.2	13.9	13.0	11.6	11.7	12.9	12.8	13.1	13.5
TX	El Paso	9.6	8.2	7.0	5.8	6.1	6.3	8.3	9.1	9.3	8.8	9.0	9.8
UT	Salt Lake City	14.6	13.2	11.1	10.0	9.4	8.2	7.1	7.4	8.5	10.3	12.8	14.9
VA	Richmond	13.2	12.5	12.0	11.3	12.1	12.4	13.0	13.7	13.8	13.5	12.8	13.0
WA	Seattle-Tacoma	15.6	14.6	15.4	13.7	13.0	12.7	12.2	12.5	13.5	15.3	16.3	16.5
WI	Madison	14.5	14.3	14.1	12.8	12.5	12.8	13.4	14.4	14.9	14.1	15.2	15.7
WV	Charleston	13.7	13.0	12.1	11.4	12.5	13.3	14.1	14.3	14.0	13.6	13.0	13.5
WY	Cheyenne	10.2	10.4	10.7	10.4	10.8	10.5	9.9	9.9	9.7	9.7	10.6	10.6

^aEquilibrium moisture content values were determined from the average of 30 or more years of relative humidity and temperature data available from the National Climatic Data Center of the National Oceanic and Atmospheric Administration [44].

is thus considered a practical compromise, suitable for situations where the direction of sorption/desorption may not be known. Hysteresis is shown in Fig. 4, as is the influence of relative humidity on EMC at constant temperature. This “sorption isotherm” also indicates that the change in EMC with changing relative humidity is comparatively modest within the range of 30 to 70 % RH, whereas change in EMC with change in relative humidity is relatively great at humidity levels in excess of 80 % RH.

Bonded wood products are by mass mostly wood and thus show EMC response to atmospheric conditions similar to that of wood. Sorption isotherms of bonded wood products have a similar shape as the sorption isotherm for wood. Like wood, bonded wood products show sorption hysteresis [33–35]. Because of the adhesives (and other additives, for example, wax) incorporated in bonded wood products, and because of the high temperatures they typically experience during pressing, these products characteristically show

TABLE 5—Recommended moisture content values for various wood items at time of installation (source: Wood Handbook).

Use of Wood	Recommended Moisture Content (%) in Various Climatological Regions					
	Most Areas of the United States		Dry Southwestern Area ^a		Damp, Warm Coastal Area ^a	
	Average ^b	Individual Pieces	Average ^b	Individual Pieces	Average ^b	Individual Pieces
Interior: woodwork, flooring, furniture, wood trim	8	6–10	6	4–9	11	8–13
Exterior: siding, wood trim, sheathing, laminated timbers	12	9–14	9	7–12	12	9–14

^aMajor areas are indicated in Fig. 5.

^bTo obtain a realistic average, test at least 10 % of each item. If the quantity of a given item is small, make several tests [44].

lower EMC values than solid wood.¹⁴ EMC values for construction plywood, OSB, wood fiberboard sheathing, hardboard, and particleboard with interior binder are presented in Table 2. This table suggests that, as with wood, variation in EMC is more pronounced at higher levels of humidity.

Initial Moisture Content of Commercial Building Materials

In freshly sawn (“green”) wood, the cell walls are completely saturated with water, and some free water is also present in cell lumina. Green construction lumber is usually dried at the producing mill before dressing (surfacing or planing) to size and subsequent grading, packaging, and shipment. Construction lumber may be air-dried at the production mill. More commonly, commercial drying operations utilize dry kilns, which accelerate the drying process. The American Softwood Lumber Standard [41] specifies that lumber grade-stamped as “S-dry” must have a moisture content at dressing of no more than 19 % (or some lower moisture content as may be specified in a grading agency rule or purchase agreement). Grading agency rules generally allow for 5 % of lumber pieces to exceed 19 % (or a specified lower) moisture content at time of dressing. The expectation is thus that most pieces of construction lumber grade-stamped as dry will be at 19 % moisture content or less as shipped from the producing mill. In some locales, most notably California, buildings

are commonly framed with lumber that was not commercially dried before dressing, and are grade-stamped with the designation “Green” or “S-Green.”

The processes inherent in manufacture of bonded wood products result in low material moisture contents. Control of constituent moisture content is essential during manufacture for adequate bond formation by adhesives.¹⁵ Furthermore, hot-pressed materials undergo drying during pressing and as hot material emerges from the press. Finally, heat exposure during manufacture, (and interaction of wood with adhesive), may also result in subtle chemical changes in the wood constituents that reduces hygroscopicity and liquid water absorptivity. Moisture contents of bonded wood products as shipped from production plants are given in Table 3.

Moisture content at time of construction is influenced by the conditions to which the materials were exposed during shipment and storage. Lumber moisture content on construction jobsites varies; in lumber grade-stamped as dry it may appreciably exceed 19 % [42]. Jobsite check of moisture content by use of a commercial moisture meter is therefore prudent. Commercial handheld moisture meters provide reliable readings provided that manufacturer’s use instructions are followed, (these generally concur with ASTM D4444 [43]), and compensation made where necessary for wood species or wood-based material, and temperature.

Anticipated Moisture Content in Service

Wood and wood products should be installed at moisture content levels as close as possible to the average moisture content they will experience in service in order to minimize dimensional change after installation. Dimensional change is usually most critical in finish carpentry (e.g., interior floors, exterior siding and soffits, and interior and exterior millwork and trim), although significant dimensional changes in framing lumber or sheathing can result in problems such as cracking of exterior cement plaster (stucco), or interior plasterboard. The in-service moisture content of exterior wood (siding and exterior trim) depends on outdoor relative humidity and exposure to rain and sun, or both. The in-service moisture content of interior wood primarily depends on indoor relative humidity. Anticipated outdoor EMC values for various locations in the United States are given in Table 4. It should be noted that the values in this

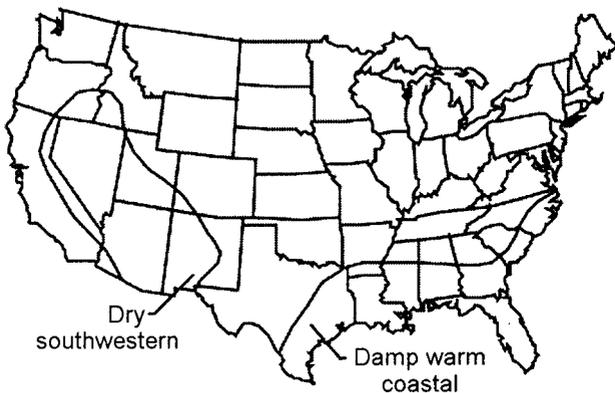


Fig. 5—Regional areas referred to in Table 5.

¹⁴ This sentence is paraphrased from Koch [36].

¹⁵ Control of moisture level into hot presses is also necessary to prevent excessive within-press steam generation that would cause explosive delamination upon press opening.

table are based on ambient atmospheric conditions and thus assume neither absorption of rainwater nor exposure to solar radiation.

Recommended moisture content values for wood items at time of installation are given in Table 5. The recommended values for exterior wood are in general accord with those in Table 4 and thus account for neither solar exposure nor appreciable absorption of rainwater. The values were developed for exterior siding, soffits, and trim. In these applications, rainwater exposure may not occur (e.g., soffits), and where it occurs (siding and trim) will primarily be from windblown rain (or roof splash), and will largely be from one (the exterior) side. In addition, exterior siding or trim is generally painted or stained; the applied finish will retard absorption of rainwater. The authors recommend that siding and trim installed on walls exposed to direct solar radiation be a couple percentage points drier than the values listed in Table 5 at installation.¹⁶ The values in Table 5 for interior wood assume that the building is well-ventilated, has no unusual moisture sources, and is not air-conditioned. Average EMC values for interior wood in air-conditioned buildings will likely be toward the low end of the range listed for individual pieces in Table 5, provided that the air-conditioning equipment has been selected and sized to provide humidity control. Wood installed in basements or crawl spaces may experience higher moisture contents than the maximum value (14 %) listed in Table 5. Seasonal peak framing lumber moisture contents approaching 20 % have been recorded in crawl spaces [47].¹⁷ With appropriate moisture control practices, wood in insulated walls and in attics should not reach moisture contents much outside the range of values listed in Table 5.

Tables 4 and 5 are not intended for application to bonded wood products. As discussed previously, these products usually have lower EMC values than the wood from which they were fabricated, and EMC values can vary from product to product. A reasonable approximation is to acclimate bonded wood products to equilibrium with 30 to 40 % RH for interior applications, and to 55 to 65 % RH for exterior applications. In applications where dimensional movement can be accommodated, wider acclimation bounds than specified above may be acceptable.

The *APA Engineered Wood Handbook* assumes that structural wood-based panels or structural composite lumber (which as discussed above have lower EMC values than wood) will not exceed 16 % MC in service. This value roughly corresponds with a 19 % MC value for wood (compare EMC values in Tables 1 and 2). As will be discussed later, a wood moisture content of 20 % (roughly the EMC at room temperature and 90 % RH) is commonly considered the “not to

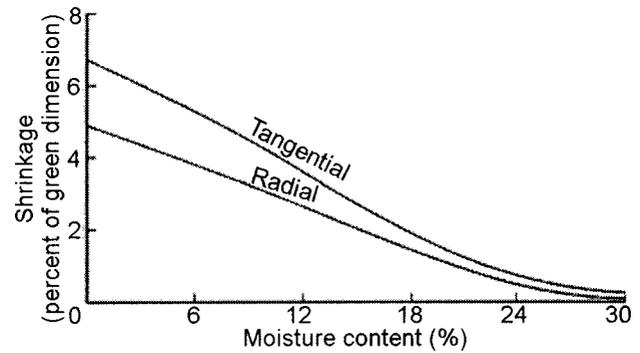


Fig. 6—Typical moisture content-shrinkage curves (source: *Wood Handbook*).

exceed” value for confidence in preventing propagation of wood-destroying fungi.

Dimensional Changes

Dimensional Stability of Wood

Below the fiber saturation point, wood changes dimension with changes in moisture content. It shrinks when losing moisture from the cell walls and swells when gaining moisture in the cell walls. Wood is orthotropic: it shrinks or swells most in the tangential direction, about half as much in the radial direction, and only slightly in the longitudinal direction. Dimensional movement of lumber has traditionally been measured as shrinkage from green (the condition at which lumber is sawn) to oven-dry. Dimensional movement is usually correlated with density, and is roughly proportional to change in moisture content. Figure 6 shows typical relationships between shrinkage and moisture content in tangential and radial directions. It indicates that the relationship between dimensional movement and moisture content is not linear over the entire moisture content range from fiber saturation to oven dry, but that it is linear from roughly 20 % moisture content to oven dry. Dimensional change of a given piece of wood depends on its density and growth characteristics. Figure 7 indicates that dimensional change can vary appreciably between pieces of wood thought to be similar. Changes in dimension in tangential or radial directions can be estimated using the following formula.

$$\Delta D = D_i [C_R (M_f - M_i)] \quad (1)$$

where ΔD is change in dimension, D_i length at initial MC, C_R dimensional change coefficient in radial anatomic direction, (alternatively, C_T , dimensional change coefficient in tangential anatomic direction), M_f moisture content (%) at end of change, and M_i moisture content (%) at start of change. Values for C_R and C_T are given in Table 6.

The coefficient values are based on dimension at 10 % MC and the assumption of a linear relationship between dimension and moisture content change over the entire hygroscopic range. The coefficients may therefore slightly underestimate dimensional movement across the range of 0–20 % moisture content, and overestimate it across the range of 20 % moisture content to fiber saturation. Variation in dimensional change between pieces of wood, (Fig. 7), suggest that Eq (1) should not be counted on to precisely predict dimensional movement of individual pieces of wood.

¹⁶ This recommendation is based on: (a) measured in-service siding moisture contents on southeast- and southwest-facing walls on buildings in Florida than were roughly 1.5 percentage points lower than on northeast-facing walls on the same buildings [45], (b) measured in-service wood-siding moisture contents on south-facing walls in southern California below 5 % [46], and (c) the lead author’s unpublished measurement of 6–9 % EMC at 22 °C and 50 % RH in wood siding removed from sun-exposed exterior walls of buildings in Wisconsin and New York (these EMC values ranged from 0–3 % lower than the value at this set of conditions shown in Table 1).

¹⁷ Crawl spaces monitored by Stiles and Custer [47] included ones that would likely have been judged “musty,” but did not include any crawl spaces which showed evidence of standing water nor any in which decay was observed.

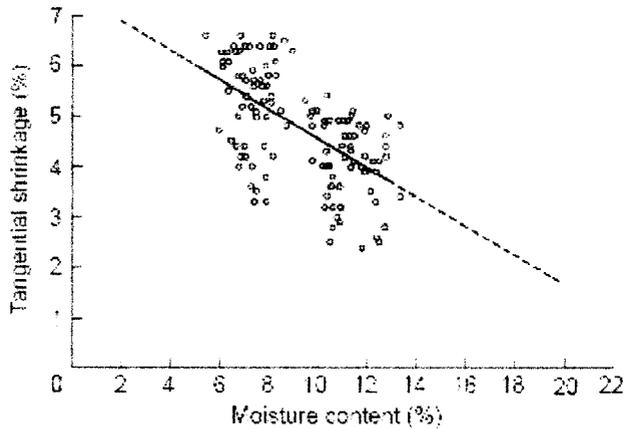


Fig. 7—Variation in individual tangential shrinkage values of several Douglas-fir boards from one locality, dried from green condition (source: *Wood Handbook*).

Movement of wood in either transverse direction (radial or tangential) can be of substantial consequence when wet framing lumber is used for floor joists in platform construction. The balloon framing technique, which was widely used in the 1920s and earlier (and which has been largely replaced by the platform framing technique), was designed to accommodate relatively large amounts of across-grain shrinkage of floor and rim joists. In construction of log buildings, attention must be paid to dimensional change in wall heights (which are across the grain direction). In log buildings with

TABLE 6—Dimensional change coefficients. C_R and C_T in radial and tangential directions respectively, for various species of wood (per percent change in moisture content) (source: *Wood Handbook*).

Species	C_R	C_T
Aspen, quaking	1.2×10^{-3}	2.3×10^{-3}
Birch, yellow	2.6×10^{-3}	3.4×10^{-3}
Cottonwood, black	1.2×10^{-3}	3.0×10^{-3}
Locust, black	1.6×10^{-3}	2.5×10^{-3}
Maple sugar	1.6×10^{-3}	3.5×10^{-3}
Red oak, commercial	1.6×10^{-3}	3.7×10^{-3}
White oak, commercial	1.8×10^{-3}	3.7×10^{-3}
Walnut, black	1.9×10^{-3}	2.7×10^{-3}
Yellow-poplar	1.6×10^{-3}	2.9×10^{-3}
Cedar, northern white	1.0×10^{-3}	2.3×10^{-3}
Cedar, western red	1.1×10^{-3}	2.3×10^{-3}
Douglas-fir, interior	1.5×10^{-3}	2.5×10^{-3}
Fir, grand	1.1×10^{-3}	2.4×10^{-3}
Hemlock, western	1.4×10^{-3}	2.7×10^{-3}
Larch, western	1.6×10^{-3}	3.2×10^{-3}
Pine, eastern white	7.1×10^{-4}	2.1×10^{-3}
Pine, jack	1.3×10^{-3}	2.3×10^{-3}
Pine, loblolly	1.7×10^{-3}	2.6×10^{-3}
Pine, ponderosa	1.3×10^{-3}	2.2×10^{-3}
Pine, slash	1.9×10^{-3}	2.7×10^{-3}
Redwood, second growth	1.0×10^{-3}	2.3×10^{-3}
Spruce, black	1.4×10^{-3}	2.4×10^{-3}
Spruce, white	1.3×10^{-3}	2.7×10^{-3}
Spruce, Sitka	1.5×10^{-3}	2.6×10^{-3}

Source: Forest-Products Laboratory [44].

gable roofs there is the potential for significant differential movement between roof eave lines and roof peaks. In log buildings there is also potential for significant differential change between the height of openings and of fenestration units installed in them; competent design of log buildings will anticipate and allow for such differential movement.

Dimensional movement in the longitudinal direction has traditionally been considered as negligible. The *Wood Handbook* [44] states that the average values of longitudinal shrinkage from green to oven-dry normally ranges between roughly 0.1 and 0.2 %. This range of values assumes that the wood contains neither juvenile nor reaction wood. Juvenile and reaction wood are, however, present to some degree in commercial lumber; softwood lumber grading rules require exclusion of neither juvenile nor compression wood. Softwood lumber grading rules also commonly allow slope of grain (observed as diagonal grain) of from 1-in-8 to 1-in-14, depending on grade. It therefore is not particularly surprising that green to OD lengthwise shrinkage values exceeding 0.3 % occur with some regularity in commercial lumber. Longitudinal shrinkage of 0.6 % has been observed in second-growth redwood [48,49], and longitudinal shrinkage as high as 2 % has been observed in rapidly-grown, second growth, southern pine [48]. The degree of longitudinal shrinkage that Ying et al. [6] observed in fast-growth loblolly pine usually exceeded 0.5 % in the first ten growth rings. Hann [5] observed longitudinal shrinkage values in baldcypress that were similar to those observed by Ying et al. [6] in loblolly pine or by Chern [49] in redwood. All researchers found that within-species longitudinal movement in second-growth material commonly varied by a factor of four or more. Predictions of longitudinal movement of any given piece of lumber are therefore likely to be imprecise. Moisture control appears to be the most reliable way to avert problems related to longitudinal movement of lumber. Hann [5] found that longitudinal movement between EMC at 80 % RH and EMC at 30 % RH was always less than half of that between the green and oven-dry conditions. Gorman [50] found that longitudinal movement of juvenile wood was a factor in seasonal arching of roof trusses, but that truss arching could often be controlled by management of moisture conditions. Percival [51] indicated that problems associated with truss arching could largely be controlled by a combination of construction practice and moisture control.

Dimensional Stability of Bonded Wood Products

Dimensional movement of glulam timbers and that of LVL members are essentially indistinguishable from that of wood under similar environmental conditions. As indicated previously, these products are manufactured under well-controlled moisture conditions, and thus usually undergo less dimensional change than construction lumber during the period from construction through the first year of building occupancy.

The dimensional movement characteristics of wood-based panels generally differ from those of wood. The three principal dimensional axes for wood-based panels are: along the panel, across the panel, and through the thickness of the panel. Proportional changes are consistently greatest through the thickness of panels. Because nominal panel thicknesses are generally 20 mm or less, high proportional

TABLE 7—Published values for within-plane dimensional movements of wood-based panel products.

Material	Source	RH Range (unless otherwise specified)	Linear Expansion Along Panel (%)	Linear Expansion Across Panel (%)
Construction plywood	Zylkowski [38]	Ovendry-soak	0.15–0.29	0.20–0.40
Construction plywood	Talbott et al. [52]	30 %–92 %	0.04–0.06	0.08
OSB	Zylkowski [38]	Ovendry-soak	0.19–0.28	0.36–0.63
OSB	Wu and Suchsland [53]	35 %–85 %	0.13–0.17	0.19–0.32
Waferboard	Alexopolous and Szabo [54]	Ovendry-soak	0.25–0.27	0.31–0.38
Waferboard Sheathing fiberboard	Talbott et al. [52]	30 %–92 %	0.15	0.19
Sheathing fiberboard	Lehmann [55]	30 %–90 %	0.37–0.53	
Sheathing fiberboard	Luxford [56]	50 %–97 %	0.20–0.47	
Sheathing fiberboard	ASTM C 208-95 [57]	50 %–90 %	(direction not specified—likely the average of along and across)	
Particleboard (interior)	Lehmann [55]	30 %–90 %	0.5–0.6 maximum allowable (average of along and across), (dependent on structural grade)	0.45–0.46 (average of along and across)
Particleboard (medium-density interior)	ANSI A208.1–1999 [58]	50 %–80 %	0.35 maximum allowable (average of along and across)	
Hardboard siding	Biblis [59]	30 %–90 %		0.19–0.29 (panel siding)
Hardboard siding	Biblis [60]	35 %–90 %	0.19–0.26 (lap siding)	
Hardboard siding	ANSI/AHA A135.6-1998 [61]	30 %–80 %	0.31–0.35 max (lap siding) (dependent on panel thickness)	0.31–0.35 max (panel siding) (dependent on panel thickness)
Hardboard siding	ANSI/AHA A135.6-1998 [61]	30 %–90 %	0.36–0.40 max (lap siding) (dependent on panel thickness)	0.36–0.40 max (panel siding) (dependent on panel thickness)

change usually does not result in large measured dimensional change. Proportional dimensional changes along and across wood-based panels generally exceed that of normal wood in the longitudinal direction, and are significantly less than that of wood in radial or tangential directions. Dimensional movement characteristics of commodity panel products can generally be found in the research literature. Dimensional movement characteristics of proprietary products, if available, must generally be obtained from the respective manufacturers.

Values in the research literature for dimensional change along the length or across the width of wood-based panels are most commonly reported as percentage increase in dimension (linear expansion) between a low humidity and a high humidity condition (in accord with ASTM D1037 [52]) or between a dry and a soaked condition. Published values are given in the Table 7.

Dimensional movement in the plane of wood-based panels, reported as a function of moisture content, is not commonly found in the research literature, but is available. Suchsland [33] and Lang and Loferski [62] have presented dimensional change coefficients per percent change in moisture content. Their measurements were taken between two moisture conditions. Using such coefficients, an equation of

the same form as Eq (1) can be used to predict dimensional change.

$$D = D_i C_{along}(M_f - M_i) \quad (2)$$

where D , D_i , M_f , and M_i are as in Eq (1) and C_{along} is dimensional change coefficient for the panel long dimension (alternatively, C_{across} for dimensional change coefficient across the panel width). Values of C_{along} and C_{across} are given in Table 8. A comparison with the dimensional change coefficient values for wood in radial and tangential directions (Table 6) indicates that proportional change across the widths of wood-based panel products is significantly less than that of wood in either radial or tangential directions.

Talbott et al. [52], Zylkowski [38], and Wu and Suchsland [63] made dimensional change measurements over multiple (more than two) different moisture conditions. Zylkowski [38] and Wu and Suchsland [63] found the relationship between dimensional movement in the plane of the panel and moisture content to be nonlinear. Within limited moisture ranges, however, linear approximations can be useful for estimating panel dimensional change. Values of C_{along} and C_{across} , derived from values reported by Zylkowski [38] are shown in Table 9.

TABLE 8—Within-plane dimensional change coefficients for panel products obtained from two-point measurement protocols.

Material	Source	Moisture Range	C_{along}	C_{across}
Construction plywood	Lang, Loferski [62]	45 % RH–95 % RH	1.8×10^{-4}	2.3×10^{-4}
OSB	Lang, Loferski [62]	45 % RH–95 % RH	2.2×10^{-4}	2.3×10^{-4}
Particleboard (interior)	Suchsland [33]	40 % RH–90 % RH	1×10^{-4} – 5.6×10^{-4} (avg. of both directions)	

The major concern with within-plane dimensional movement of wood-based panels is the potential for out-of-plane distortion (buckling), particularly between framing members. Because construction panels are relatively thin (and thus of limited stiffness) as compared with framing members, panel dimensional change along the framing members can be restrained to a significant degree by stiffness of the framing members, provided that panels are adequately fastened to them. Buckling between framing members may occur if panels are installed at appreciably lower moisture content than the framing members. Buckling at panel edges can occur (in either direction) if insufficient gaps are provided between panels at installation. Shingle ridging is associated with within-plane dimensional movement of wood-based panels in roof sheathing applications. It occurs when edge gaps between panels decrease in width and roof shingles (most commonly low-cost thin shingles) that bridge the gaps noticeably buckle as the distance between shingle nailing points decreases with panel linear expansion. Structural panels used in Exposure 1 environments have historically shown little tendency to buckle unless installed without adequate edge gaps, if inadequately fastened to framing, and if subjected to significant wetting between installation and building “dry-in,” or unless installed over wet framing lumber on walls that were enclosed while the lumber remained wet. Buckling of wall sheathing may be wholly undetectable if the wall cladding material is brick veneer or vinyl siding, whereas slight buckling or change in between-panel gaps may result in noticeable cracking of cement-plaster stucco. Visually objectionable out-of-plane distortion of wood-based panel materials used as siding or as combination sheathing/siding has occurred with some frequency. Attention to moisture content at time of installation and to build-

ing moisture control can significantly reduce the incidence of problems associated with dimensional changes in length or width of wood-based panels.

As mentioned previously, proportional dimensional changes through the thickness of wood-based panels are significantly higher than those across panel length or panel width directions. For panels fabricated of lathe-cut veneer, dimensional change through the panel thickness is roughly 40 to 50 % greater than dimensional change in the radial direction of the wood from which it was fabricated (or roughly equivalent to the dimensional change in the tangential direction). For panels fabricated of comminuted wood, but not significantly densified by pressing, (fiberboard sheathing) dimensional change in the thickness direction is not recognized as being of consequence. The ASTM/ANSI standard for fiberboard sheathing (ASTM C208 [57]) does not promulgate dimensional stability requirements in the thickness direction, and thickness swelling potential of fiberboard sheathing is apparently modest [64]. For densified wood composition materials, however, proportional dimensional movement in the thickness direction can be of appreciable magnitude, substantially exceeding that of wood in either of its transverse directions. Up to EMCs corresponding with 70 % relative humidity, thickness swelling of densified wood composition materials is roughly similar to swelling of the denser wood species in the tangential direction, and the swelling is mostly recoverable. Beyond EMCs corresponding with 80 % RH, however, swelling increases significantly and a significant portion of the swelling becomes nonrecoverable [63,65]. The proportion of swelling that is nonrecoverable continues to increase as conditions get progressively wetter. Upon exposure to soaking, thickness swelling of 35–40 % may occur in densified wood composition materials (relative to the dimension at an EMC corresponding with 50 % RH) [38]. The literature [63,65] suggests that when thickness swelling exceeds 20 %, more than half of it (around 70 %) is nonrecoverable.

Nonrecoverable (or irreversible) thickness swelling almost always occurs unevenly, being greatest at panel edges. The uneven swelling can be visually objectionable, for example, when irreversibly swollen edges of subflooring panels telegraph through floor coverings. Uneven irreversible swelling, along with surface roughening near swollen edges, results in edge wetting of laminate flooring and edge wetting of hardboard siding. Irreversible thickness swelling is generally recognized as occurring to the greatest extent when material is immersed in water for the first time, with marginal increases in irreversible swelling becoming progressively less in subsequent soaking cycles. Internal swelling stresses

TABLE 9—Within-plane dimensional change coefficients for panel products over different moisture ranges (obtained from a multi-point measurement protocol).

Material	Moisture Range	C_{along}	C_{across}
Construction plywood	4.5 %–9 % mc (EMC over 30 % to 65 % RH range)	1.3×10^{-4}	1.6×10^{-4}
Construction plywood	9 %–19 % mc	2.0×10^{-5}	3.6×10^{-5}
OSB	2 %–7 % mc (EMC over 30 % to 65 % RH range)	2.1×10^{-4}	4.2×10^{-4}
OSB	7 %–17 % mc	5.7×10^{-5}	6.1×10^{-5}

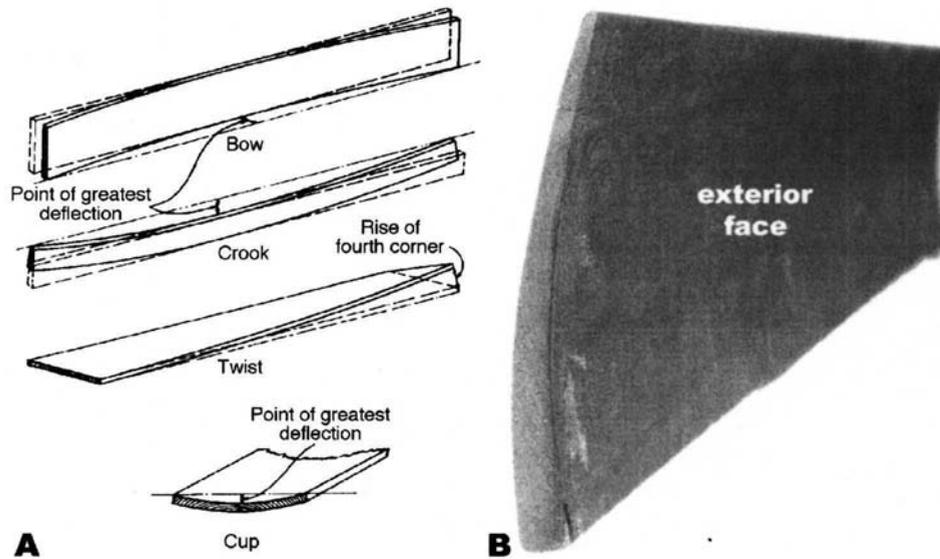


Fig. 8—(a) Types of warp. (b) Permanent cup in a piece of thin, 140-mm wide bevel wood siding that had been stained a dark color and installed on a wall with direct solar exposure.

associated with irreversible thickness swelling have, however, been shown to result in internal mechanical damage to panels [66]. Internal changes influence panel properties, with progressive property degradation occurring with repeated wetting. Progressive increase in liquid water absorptivity has been observed in OSB with repetitive wetting cycles [67]. Progressive degradation of mechanical properties with repetitive wet cycling is generally recognized as occurring at a decreasing marginal rate. Not all properties necessarily degrade at a decreasing marginal rate. In exterior exposure, edge wetting in hardboard siding has been observed to accelerate with repetitive wetting cycles, even while in-service edge thickness remained relatively steady [35]. The degree to which densified wood composition panels undergo irreversible thickness swelling can vary appreciably, even between panels bonded with similar adhesive systems [68]. Densified wood composition panels fabricated from wood fibers tend to show less irreversible thickness swelling than those fabricated from particles or flakes [68]. Appreciable differences in irreversible swelling between commercial products in the same product class have been observed [26,35,59,60].

OSB panels are Exposure 1 panels, intended to withstand weather exposure during construction, but not intended for use in exterior exposure. The amount of property degradation OSB will undergo during construction as a result of thickness swelling is not generally recognized as being of practical consequence. Owing to its incorporated sizing, the initial water-absorptivity of OSB is fairly low [69]. As indicated in Table 3, OSB is very dry as shipped from the manufacturing plant. OSB sheets are furthermore edge-sealed by manufacturers, sometimes with sealer formulated specifically for the application. For these reasons OSB edge swelling that occurs over a few months exterior exposure during building construction, is generally recognized as being less than the swelling that would be observed on an unsealed edge of the same panel if it were immersed in water

for 24 hours. Edge swelling of wood composition materials exposed to chronic water exposure (for example, indefinite weather exposure or ongoing water intrusion) is, however, likely to result in objectionable irreversible damage. Wood composition materials intended for use in exterior applications (hardboard siding or exterior trim, or resin-paper-overlaid OSB siding¹⁸) are universally recognized as being subject to objectionable water-induced damage associated with irreversible thickness swelling, unless the materials are adequately coated with a high quality exterior paint system. Edge swelling of web members in OSB-webbed I-joists has the potential to significantly compromise joist structural integrity. OSB used for I-joist web material evidently has less than half the swelling potential of sheathing-grade OSB [63].¹⁹ The importance of maintaining structural integrity, however, suggests that OSB-webbed I-joists should be protected from wetting, (during construction as well as in service).

Warp

Warp occurs when there is spatial variation in dimensional change within a wooden member. Differential dimensional change can occur across the member width, resulting in cup. It can occur along the member length on opposite wide faces, resulting in bow, or along the member length on opposite narrow faces, resulting in crook. It can also occur in a compound manner, resulting in member twist [Fig. 8(a)].

Warp that occurs during lumber manufacture and processing can be traced to two causes: (a) differences between

¹⁸ OSB siding with resin paper overlay is a proprietary product explicitly marketed as siding. It has a higher adhesive content than sheathing-grade OSB, an incorporated preservative to inhibit decay and insect infestation, and sealed back surfaces and edges

¹⁹ I-joist manufacturers have property requirements for web material and can demand that OSB manufacturers provide material that meets their requirements. These requirements are not in the realm of public information.

radial, tangential, and longitudinal shrinkage as the lumber dries, or (b) growth stresses within the tree. Warp is aggravated by irregular or distorted grain and by the presence of juvenile and reaction wood. Juvenile and reaction wood are often unevenly distributed within wood members. As mentioned in the discussion of wood anatomy, the helical angle of wood cells of the tree's axial system may change as the tree grows. This can result in differing degrees of spiral grain at different locations within a wood member, and this can be a factor in warp. Warp that has its genesis in growth stresses or in differential shrinkage upon drying from the green condition can be mitigated by drying under restraint. Commercial lumber drying operations can stack lumber and weight the stacks so that the pieces dry under restraint; the elevated temperatures involved in kiln drying aid in mitigation of warp during drying under restraint. To some degree, wet framing lumber nailed into frames and sheathed with rigid sheathing will also be held under restraint while drying in place. This approach to mitigating warp of framing lumber was used successfully before the widespread use of kiln-dried lumber, most notably in 2 by 4 construction (hip roofs of modest span and walls) sheathed with 19 mm lumber boards installed at a moisture content similar to that of the framing material. The current viability of this approach can be questioned, considering that contemporary framing lumber is more likely to contain larger proportions of juvenile wood and thus be more prone to warp, and that panel sheathing materials have largely replaced the thicker and relatively stiffer lumber board sheathing. As mentioned previously, a mismatch of relatively dry sheathing panels and relatively wet framing lumber can result in problems associated with linear expansion of the sheathing. Furthermore, drying of wet framing lumber in walls is likely to be relatively slow in contemporary construction, where enclosure often occurs rapidly, and where air leakage rates through enclosed walls are lower than commonly occurred through walls sheathed with lumber boards.

Warp sometimes occurs in service in members that were flat and straight as installed, even in members installed at moisture contents reasonably close to average long-term end-use conditions. If transient in-service moisture conditions on opposite sides of a member differ appreciably, warp may occur. Where appreciable warp occurs as a result of transient differential wetting, some of the warp is likely to be irreversible; the member may retain significant warp when the differential moisture conditions across the member are dissipated. Wood flooring installed over a wet concrete slab will warp, and much of the warp may be permanent. Wood siding that is wetted by rain and then exposed to sun is likely to undergo some degree of permanent warp [Fig. 8(b)]. The likelihood that the permanent warp will be objectionable is increased if the siding is thin, and if it is unfinished or if it is finished with a dark finish, (which will result in higher peak siding temperatures during solar exposure). Significant warp is usually more common in thinner members; the cross-sectional rigidity of thicker members is greater, and the rigidity will restrain warp. Thicker and larger members are, however, not necessarily immune to problems associated with rapid changes in surface moisture content.

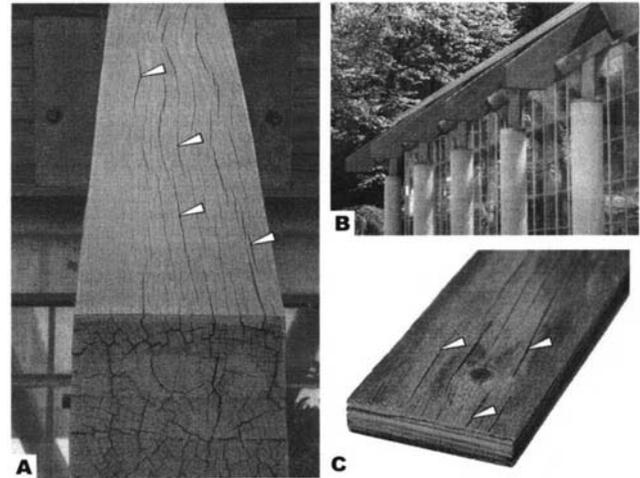


Fig. 9—(a) Top-surface checking (arrowheads) and end-checking in glued laminated beam, the end of which has been exposed to the weather. (b) Glulam beam ends exposed to the weather (the beam end shown in A is one of the five shown in this picture). (c) Surface checking in the face veneer of sheathing-grade plywood resulting from moderate weather exposure. Face veneer checking is noticeable (arrowheads) although surface defect (knot) remains tightly adhered, and virtually no surface erosion has occurred.

Surface Checking

Noticeable surface checking can occur in wood and in bonded wood products fabricated from lumber or veneers if they are exposed to rapid wetting and drying. Surface checking is related to restrained shrinkage of surface layers by inner layers during drying, and is exacerbated by intense drying conditions. The more extreme examples of in-service surface checking occur in insufficiently protected members in exterior exposure (Fig. 9), where the progressive influences of rain wetting and direct solar exposure result in rapid changes in surface moisture content. Surface checking tends to be more severe in members with relatively large cross sections [Fig. 9(a) and 9(b)]; pronounced surface checking can also occur in plywood [Fig. 9(c)]. Surface checking in members of appreciable cross section is related to significant differences in core and surface layer moisture contents under transient conditions. In plywood, checking is related to the relatively great unrestrained dimensional change potential of wood in the tangential direction (across the width of lathe-cut veneer sheets) and to restraint of that movement by core or cross-band plies.

Compression Set Shrinkage

If wood is subjected to restrained swelling it is subjected to mechanical compression. As indicated previously, moisture-induced dimensional change is proportionally least in the longitudinal direction and greatest in the tangential direction. Exertion of compressive force by restrained swelling is thus usually greatest in the tangential direction, and next greatest in the radial direction. If the compressive force results in strain beyond that at the proportional elastic limit (PEL), permanent deformation will result, and upon drying the wood will return to a smaller dimension than its dimension at the same moisture content before subjection to restrained swelling. The reduction in dimension from subjec-

tion to restrained swelling is termed compression set shrinkage, or sometimes simply as compression set. The effect of compression set is most commonly observed in loosened handles of hammers or axes, or in progressive widening of gaps between pieces of tongue and groove porch flooring (particular if flat-grained) that has been subjected to wetting. It can also occur in interior wood strip flooring²⁰ or in mortise and tenon joints of windows, doors, and furniture [70].

In wood subjected to compression perpendicular to the grain, the PEL is most commonly recognized as occurring at roughly 1 % strain [71,72].²¹ This value for strain at PEL was evidently the basis for the 1 % allowable compressive strain rule, used by woodcrafters for evaluating the design of mortise and tenon joints [70]. This woodcrafters' rule is that calculated restrained moisture-induced swelling should not exceed 1 %.²² The limit to change in moisture content that results in no more than 1 % strain can be calculated by dividing 1 % (0.01) by the appropriate coefficient (for species and grain direction) in Table 6. For example, the allowable MC changes that limit dimensional change of loblolly pine to 1 % are 5.9 MC percentage points, and 3.8 MC percentage points in the radial and tangential directions, respectively.

Strength

The strength of wood increases as its moisture content decreases from the green condition until it reaches roughly 6 to 4 % moisture content. Wood mechanical property values are typically greatest at about 4 to 6 % moisture content; they are slightly less at the oven-dry condition. The National Design Specification (NDS) for Wood Construction [73] contains a default assumption that structural members are in a dry environment, where member moisture content does not exceed 19 % (for sawn lumber) or 16 % (for interior glulam, structural composite lumber, prefabricated wood I-joists, or wood structural panels). Within the range of moisture contents in the dry region, the influence of moisture content on design values for wood members is not considered by the NDS as being of practical concern; it acknowledges no increase in design values for in-service moisture contents below 19 % MC. The NDS does acknowledge, and provide for, de-rating of design mechanical property values in wet use environments. The wet use adjustment factors are applicable to the treated lumber used in wood foundations, and to wood used in intermittently wet environments, such as exterior decks. Designers may also apply wet use factors to untreated members used in humid interior environments, such as in buildings with indoor swimming pools, (where in-service wood moisture contents may exceed 15 % and may not be precisely known), and to damp crawl spaces, (where in-service moisture contents may seasonally exceed 19 %).

As will be discussed later, if in-service moisture conditions exceed 20 % MC in wood (the EMC for wood products corresponding to roughly 90 % RH), there may be problems

²⁰ Compression set in strip flooring is exacerbated if dirt is allowed to collect in the spaces between strips (which are open widest during the dry periods of seasonal moisture cycles).

²¹ Compression testing of wood perpendicular to the grain has traditionally been in the tangential direction (load applied to a radial face).

²² The widest range of allowable moisture content change is obtained by selecting mating pieces with regard to grain direction (the largest dimension of both the mortise and the tenon should be in the radial direction) and with regard to species and density.

with biological infestation, and concerns relating to dimensional movement, to serviceability issues associated with progressive deflection of members under load, or of integrity of mechanically fastened connections. These other concerns generally overshadow concerns over the influence of moisture condition on immediate load-carrying capability.

Provided that attack by biological agents is avoided, and that significant warp or checking does not occur, wood is generally recognized as being capable of undergoing significant moisture cycling without perceptible damage. In contrast, significant moisture cycling of bonded wood products will stress the adhesive bonds, and this may result in some degradation of mechanical properties. Adhesive type and quantity, as well as fabrication variables influence the degree of degradation. It is generally recognized that products fabricated with boil-proof adhesives and either sawn lumber or wood veneers will, if carefully manufactured, withstand moisture cycling from oven-dry to moisture contents in excess of fiber saturation without perceptible loss in mechanical properties, provided that the changes in moisture content are gradual and thus do not induce large internal stresses via spatial differences in moisture content. Delamination of bonded wood products will (obviously) result in a degradation of their mechanical properties. Internal stresses associated with irreversible thickness swelling of densified wood composition materials are, as indicated previously, a causal factor in degradation of mechanical properties [66]. Over a limited number of wet-dry cycles, the flatwise load carrying capacity in bending of irreversibly swollen wood composition panels may be unaffected due to increase in cross-sectional moment of inertia in bending, but the load carrying capacity will eventually be degraded with repetitive cycling [54,68,74,75].

Creep

Wood members placed under constant structural load undergo progressive deformation (creep). The rate of creep increases with increasing imposed load, that is, as imposed load becomes a greater portion of the member's load carrying capacity. Moisture conditions influence creep deformation; creep in constant damp conditions exceeds that in constant dry conditions, and creep under fluctuating moisture conditions exceeds that under constant damp conditions. The term "mechano-sorption" reflects the recognized influence that moisture content changes have on mechanical behavior of members under load.²³ The direction of change (wet to dry or dry to wet) has been observed to be inconsequential [76,77]; it is the magnitude, rather than the direction of change, that matters. When creep deformation is significant, and the imposed load that caused the creep deformation remains applied, failure will eventually occur [78]. This time-dependent failure, occurring after significant deflection, is termed duration of load or creep-rupture. Elevated temperatures can interact with high moisture levels or with mechano-sorption to exacerbate creep deformation and creep-rupture.

²³ Mechano-sorption is recognized as occurring in members that are either subjected to deformation or are restrained while undergoing sorption or desorption. It plays a role in mitigation of warp of lumber by drying under restraint, in compression set shrinkage, and in loosening of fasteners in members subjected to moisture cycling.



Fig. 10—(a) Sag in the wood roof framing of a stone-wall house built in the 1850s (photo taken in 2005). Line above roof accentuates ridgeline sag. Roof framing was under-sized by modern standards. (b) Sag along the span of rafters in a house built in 1940 (photo taken in 2005). Reference stick touches the roof near peak and at eave. Arrowheads point to deflection of approximately 65 mm at mid span.

Despite the potential for creep and creep-rupture in wood structures, wood design codes in North America do not show much concern over these phenomena. Although noticeable sag is common in older structures (Fig. 10; [78]), in-service failure by creep-rupture is uncommon. The National Design Specification [73] does not address creep-rupture. The (unstated) assumption is that if the guidance of the NDS is followed (relating to adequate structural performance without consideration of creep-rupture) that imposed stresses will be sufficiently low that creep-rupture will not occur. The NDS does, in certain circumstances, however, recognize creep deflection as an issue, with the issue relating to serviceability (as opposed to structural integrity). Consideration of creep by the NDS is confined to a deflection allowance for members in bending; it specifies that a higher amount of anticipated creep deflection be calculated for wood beam members installed in the green condition and maintained in a dry environment. Failure to adequately account for the larger deflection of window or door headers installed green sometimes results in excessive header deflection and accompanying problems with fenestration units installed in such openings. The NDS does not address the effect of seasonal fluctuation in moisture conditions on creep. If substantial seasonal moisture cycling occurs, creep deformation as great as would occur in green material drying under load (the situation addressed by the NDS) may occur.

The creep and creep-rupture behaviors of wood composition materials are conceptually similar to those of wood or of glued wood products fabricated from veneer [79,80]. Wood composition materials are however somewhat more prone to creep and creep rupture [79,81] than wood or than bonded wood products fabricated from lumber or veneers. The creep behavior of OSB has been reasonably well researched [82–84]; the *APA Engineered Wood Handbook* [17] specifies a substantially larger creep adjustment factor for OSB exposed to elevated moisture conditions in service than for OSB that remains in a continually dry environment.

Fastener Performance

The structural integrity of wood buildings depends on the integrity of connections between members. Where catastrophic structural failures of wood buildings occur (most commonly as the result of extreme wind or earthquake), failure of mechanical connections usually plays a critical role. Fasteners used in building structures are usually made of carbon steel. Carbon steel fasteners may be treated to resist corrosion (galvanized, or coated with phosphate, organic or ceramic coatings), or may be untreated (commonly sold as “bright”). In exposures where wet conditions can be anticipated (e.g.: treated wood foundations, exterior exposure), corrosion resistance is particularly important. In wet exposures where maintenance of connection integrity is crucial, use of fasteners with dual treatment (galvanized with organic coating) or of fasteners made from nonmagnetic stainless steel may be specified by trade association construction guides. Wood used in wet environments is usually pressure-treated with preservative chemicals, some of which accelerate fastener corrosion. A literature review [85] indicates that the issue of corrosion of fasteners in pressure-treated wood has been widely investigated, but is not fully understood. In situ corrosion resistance is important in selection of fasteners for treated wood, [86,86a], especially where in-service MC may exceed 20 %.

In-service moisture content level and moisture cycling are recognized as influencing the strength of mechanical connections in untreated wood. The NDS [73] specifies load adjustment factors for mechanical connections based on wood moisture content at time of joint fabrication and on in-service moisture content. Where fasteners are installed in dry wood (defined as moisture content of 19 % or lower) and the wood remains dry, no adjustment in connection load carrying capacity is deemed necessary (adjustment factors are 1.0). This applies to any type of connector, in either lateral load transfer²⁴ or in withdrawal resistance.²⁵ Adjustment factors ranging from 0.9 to 0.25 are specified for load-carrying capacity of mechanical connections when in-service conditions either exceed 19 % moisture content, or where there is change from wet to dry conditions or dry to wet conditions. The greatest adjustment (factor of 0.25) applies to withdrawal resistance of nails where there is a wet to dry or dry to wet change between moisture content at time of driving and moisture content in service. All other adjustment factors are relatively modest, ranging from 0.9 to 0.7, depending on fastener type, loading mode, and moisture history. The adjustment factors for load-carrying capacity of mechanical connections in the NDS do not appear to address significant repetitive moisture cycling, nor do they account for significant corrosion of fasteners.

Complete failure of wood joints, associated with corrosion of steel fasteners, has been observed within six years in damp wood under moderately acidic conditions at elevated temperature [87]. Baker [88] reported that nearly complete weakening of nailed connections, resulting from steel fastener corrosion, frequently occurs in weathered house or barn siding. In weakened joints with significantly corroded fasteners, joint weakening results from degradation of the

²⁴ Load transfer perpendicular to the fastener axis.

²⁵ Force needed to remove (pull) the fastener axially from the wood member.

fastener itself, and also from chemically-induced deterioration of the wood in contact with the corroding fastener [85,88–91]. Quantification of fastener corrosion rate of nails in wood at moisture contents below fiber saturation has been investigated fairly recently by Cole et al. [92] and by Imamura and Kiguchi [93].

Cole et al. [92] found corrosion rate to depend on wood moisture content, in a rather complex manner, and that the relationship between corrosion rate and wood moisture content varied with wood type and to generally be different for bright than for galvanized steel nails. They proposed the following generalized description for the relationship between corrosion rate and wood moisture content.

- Minimal or no corrosion occurs at moisture contents below a threshold MC value, with threshold values ranging from roughly 10 to 14 % MC depending on wood and fastener type.
- A plateau in corrosion rate (usually) occurs at some wood moisture content below fiber saturation, with no marginal increase in corrosion as wood MC increases beyond the maximum rate value. Untreated woods show a plateau in corrosion rate of embedded fasteners, with “maximum rate” MC value varying from roughly 16 to 24 % MC. The behavior of wood pressure-treated with waterborne preservatives can differ from that of untreated wood; in such wood, a plateau in corrosion rate may not occur.
- Between the threshold value and maximum rate value, fastener corrosion rate correlates with wood moisture content.

Cole et al. [92] apparently did not observe iron-induced wood degradation around fasteners; the duration of their tests was 120 days, a time period that evidently was insufficient to result in noticeable degradation.

Imamura and Kiguchi [93] performed longer-term tests than Cole et al. [92]. They found that corrosion of bright steel nails embedded in hemlock at room temperature for four years was significantly influenced by relative humidity (and in turn equilibrium moisture content). In a parallel investigation, they observed that lateral resistance of nailed joints was significantly influenced by the degree of nail deterioration. Joints with nails that had lost around 11 % of their mass (5 % of shank diameter) to corrosion had roughly 40 % of the strength of joints with nails that were scarcely rusted. Finally, in a forensic investigation, they observed nail condition and surrounding wood condition in sheathing boards behind cement plaster stucco-cladding on houses that were roughly three decades old. In the vicinity of cracks in the stucco cladding, they observed very significant nail corrosion (25 % or greater loss in shank diameter), and noticeable iron-induced deterioration of wood surrounding deteriorated nails. Time/temperature/moisture histories at these locations were unknown, but moisture contents in these locations at time of cladding removal ranged from 18 to 24 %. They concluded that moisture conditions in excess of 20 % would cause 5 % loss in nail shank diameter in four years, and could plausibly lead to 25 % or greater loss in shank diameter over three decades, and finally that joint deterioration associated with such a loss of shank diameter (and accompanying wood deterioration) might significantly compromise the shear resistance of exterior building walls.

Moisture and Biological Attack

Although moisture conditions (including fluctuations) affect the physical and mechanical properties of wood, wood products, and constructions, it is the role of moisture in the biological attack of wood and wood products that is regularly viewed as being most significant. There are two main groups of organisms that attack or alter wood in buildings: microbes and insects. In the case of microbes, moisture relations within the wood are critical to the prevention of attack, the type of microbes that may grow, and the damage that may be done. For insects, the question of moisture is of varying importance depending on the type of insect infesting the wood.

Moisture and Microbes

The susceptibility of wood to microbial attack is a function of the moisture content and duration of the wetting. For bacteria, stains, and wood decay, the FSP of the wood must be exceeded for a significant duration (generally weeks or months), and to reach this point, liquid water must be regularly available to the wood. For molds, the FSP need not be reached, and moisture contents sufficiently high to permit the growth of mold can be reached by high relative humidity, over shorter time periods.

Molds

Molds are fungi that grow on moist surfaces, scavenging their nutrition from either their substrate (the wood) or the dust and other particles that accumulate on the substrate. They typically produce dark brown, purplish, or black growths that spread over a surface. Because mold growth is essentially a surface phenomenon, it is influenced by surface moisture conditions, which may differ from substrate bulk moisture content. Mold propagation does not require surface moisture conditions in excess of fiber saturation. Mold growth can occur when humidity level in the air immediately adjacent to the wood surface (termed “surface equilibrium RH”) exceeds roughly 80 %, and growth occurs rapidly when surface RH values exceed roughly 90 % [94,95]. A surface equilibrium RH value of 80 % corresponds with a wood surface moisture content of approximately 16 % at room temperature (Table 1). To prevent mold growth, a 75 % surface RH value at room temperature appears to be a reasonable daily-average not-to-exceed value. It appears however that this target surface RH value should not be considered a never-to-exceed value. Viitanen and Salonvaara [95] indicate that unfinished softwood surfaces that are otherwise maintained at 75 % surface RH can withstand as much as two hours per day of exposure to a 95 % surface RH without developing mold growth. If the dry-period RH value is increased above 75 % or the duration of the wet period is lengthened beyond two hours per day, noticeable mold growth can occur over a roughly half-year period.

Molds are primarily an aesthetic problem, and often can be wiped away or removed with gentle abrasion. They generally do not penetrate deeply into the wood, and do not cause appreciable damage to the cell walls, instead living on free sugars, starches, and other metabolites (generally found in cell lumina, particularly in sapwood). Although molds do not cause structural failure of wood, they can give off un-

pleasant odors or produce large numbers of spores which may become an indoor air quality concern.

Bacteria

Bacterial contamination of wood can occur where the moisture content of the wood remains substantially in excess of the FSP for extended periods. Wood-dwelling bacteria generally have the ability to live anaerobically. The oxygen-deficient environment of very wet wood is most conducive for bacterial growth as it inhibits growth of other microbes with which the bacteria would otherwise have to compete. Very wet conditions rarely occur in wood or wood products in buildings; therefore risk of bacterial infestation in service is hardly, if ever, recognized. Concern over bacterial colonization of wood is instead related to wood harvested from infested trees and to colonization that may occur during pond storage of logs, or both. Wood-dwelling bacteria generally do not cause a reduction in the mechanical properties of wood. Utilization concerns are related to strongly malodorous compounds produced during anaerobic respiration, or to challenges faced by commercial drying operations in drying wood of exceptionally high moisture content.

Stains

Microbial staining of wood is caused by fungi that penetrate the wood, often colonizing the sapwood of trees within a short time after felling as the sapwood begins to dry out, but the wood is still above FSP. They live on the free sugars, starches, and other cellular contents of the sapwood, but do not harm the structural integrity of the cell walls. For this reason, stain fungi are not considered wood decay fungi. Their growth can, however, be problematic to the wood industry, because they produce aesthetically objectionable blue, green, black, or purple stains inside the wood that cannot be removed by sanding or surfacing. Stained wood is also considered unsuitable for use as siding or exterior millwork as stain infestation often results in greatly increased permeability, which in turn results in increased water absorptivity.

Wood Decay

Wood decay, or rot, is caused by a group of fungi that derive nutrition primarily from the components of wood cell walls. Consumption of cell wall material results in structural degradation. It is estimated that 10 % of the wood harvested each year goes to replace decayed wood in existing structures [96]. Cell wall material, in particular the lignin component, is fairly resistant to biochemical breakdown. Wood decay fungi have thus developed relatively specialized biochemical processes to digest cell wall material. These processes require free water; in other words, a moisture content in excess of fiber saturation. In addition, the MC must remain in excess of fiber saturation for a substantial period of time; rapid cycling of MC is not conducive to fungal decay propagation. Increasing the drying rate of wetted wood can be helpful in preventing decay establishment [97]. There can, however, be limitations on the utility of this strategy; as indicated in previous discussions, rapid and significant fluctuation, or both, in moisture content may engender nonbiological problems with wood products.

There are three main types of wood decay; soft rot, white rot, and brown rot. Soft rot fungi grow in wood that remains

substantially wetter than fiber saturation for long periods of time, such as inside pilings just above the water line, in posts set in damp earth, and in other more or less constantly wet locations. Soft rot fungi are most closely related to the mold fungi, though their effect on the structural properties of wood, unlike the molds, can be severe. Soft rot is rarely seen inside buildings in North America; further discussion of wood decay in this chapter is thus limited to that caused by white rot and brown rot fungi.

For decay to propagate, five major factors must be present: there must be a wood decay fungus, there must be wood, there must be a regular source of water, the temperature must be appropriate, and there must be oxygen. If any of these are missing, wood will not decay. For the most part, only the moisture content of the wood can be regulated by people; oxygen is always present in buildings, decay fungi are ubiquitous as spores in the air, and, of course, wood is present. In the exterior envelopes of buildings, the temperature during winter may be too low for decay propagation, and in parts of unshaded roof structures during summer, the temperature may even reach a level that is lethal to decay fungi. For significant periods of the time, however, in most locations within buildings, the temperature is within a range that decay fungi will not only tolerate, but also find reasonably conducive for propagation.

White rot and brown rot fungi degrade the cell walls of wood in ways that differ significantly from a biochemical standpoint, and the appearance of wood decayed by the two types of fungi also differs. Both, however, can cause significant structural damage to wood. In nature, white rot fungi grow on hardwood logs on the forest floor, and brown rot fungi tend to grow on softwoods. In the laboratory and in buildings, either type of decay can progress in either type of wood, but as buildings in North America are made predominantly from softwood species, brown rot decay is the most common type of decay found in buildings.

The current guideline for confidence in prevention of decay establishment in wood and wood products (specifically those that have no marked decay resistance) is to keep them at a moisture content equivalent to that of wood at 20 % MC. The value has been prescribed in textbooks for decades [98]. Experimental work to support the guideline has been presented by Zabel and Morrell [96]. There is some mechanistic evidence [99] that wood decay may propagate, albeit relatively slowly, under conditions where capillary condensation occurs in the smallest of cell-wall pores (at conditions slightly drier than fiber saturation). More recently, Viitanen [100] reported that decay propagation can occur at 90–92 % RH at a constant ideal temperature; this is the apparent lower RH limit for decay propagation, and propagation at this limit progresses very slow (60 months for detectable weight loss to occur). The 20 % MC guideline, which has been used for decades, obviously could not at its promulgation, reflect the findings of Viitanen [100], but it did reflect acknowledged imprecision in estimate of where fiber saturation occurs, it allowed for spatial variation in moisture content within members, and it provided some margin of safety. Carll and Highley [101] concluded that no published experimental data exist that would contradict the long standing 20 % MC guideline. Where in-service moisture content can be anticipated to exceed 20 % MC, material with

marked decay resistance (either adequately treated with preservative chemical, or heartwood from a durable species) should be selected. Exceptions can be made where moisture conditions in excess of 20 % MC are known to occur only under temperature conditions unfavorable for decay propagation.

Moisture and Insects

Insect pests of wood are generally able to infest wood at much lower moisture contents than can most microbes. This means that wood destroying insects can be a problem even in structures that are maintained at the correct moisture conditions. Despite the ability of wood destroying insects to colonize dry wood, insect infestation is nevertheless more common and generally more severe in wood maintained at moisture levels that correspond with high RH levels (for example, above 18 % MC). In some cases, insects also prefer to infest wood in which decay is taking place, presumably because the wood is easier to chew. There are three main types of insects that infest wood structures in the United States; carpenter ants, boring beetles, and termites.

Carpenter Ants

Carpenter ants are typically large black or brown ants that delve tunnels and galleries in wood in order to produce secure dwellings. They do not ingest wood and they remove any wood debris from their tunnels, resulting in piles of wood dust near their entrances. Despite the fact that they do not eat wood for sustenance, they nonetheless can do significant structural damage, particularly to solid wood products such as dimensional lumber. They prefer to inhabit damp wood, often attacking decaying wood, presumably due to the greater ease of mastication. Due to their preference for moist or decaying wood, elimination of excess moisture is often an effective way to prevent infestation.

Wood-Boring Beetles

There are a variety of wood-boring beetles that can infest wood. Most such beetles are pests to living trees in the natural world, and do not cause problems for wood or wood products once the products are dried. A few of the wood-borers will emerge from dried wood, but do not reinfest dry wood; they instead seek living trees. Of the remaining wood-boring beetles, most will be killed by the kiln-drying process, and some even by air-drying. There are only a few types of borers, specifically the anobiid and lyctid powder-post beetles, that will grow in woods with a moisture content lower than about 20 %. The former do damage very slowly and will not thrive at moisture contents less than 15 %; they typically are not a major economic problem. Lyctid powder-post beetles only infest large-pored hardwoods like ash and oak, and thus are unlikely to infest structural members of buildings, which are typically softwood species.

Termites

The most destructive of the wood-damaging insects in the United States are the termites. There are three general classes of termites in the United States, and they are, in rising order of economic importance, the dry-wood termites, the subterranean termites, and the Formosan termite. In each case, termites dwell in large colonies of thousands to millions of individual insects, and consume wood as their

food.²⁶ They use their excrement as an adhesive to bind soil particles to form tunnel passageways. Dry-wood termites are only found in the southern-most reaches of the United States, but as their name implies, they require little water and thus cannot be controlled by keeping wood at low moisture content. Fumigation and exclusion are the only practical controls.

Subterranean termites are a significant problem across much of the United States, although the rate of infestation is currently believed to be lower than it was in the past. Much of the reduction in termite infestation of buildings appears to be due to improved building practices and site preparation. This includes better foundation backfill practices (keeping wood scrap out of backfill material), use of pressure-treated mudsills, better understanding of the role of soil moisture, and better understanding of the propensity of termites to access wood structures through hidden passageways. Subterranean termites almost exclusively infest structures by building tunnels up from their underground colonies. In nature they eat the woody detritus on the forest floor, and do not attack living trees. Subterranean termite colonies require a regular source of water, which need not come from the wood itself, and so improving drainage around homes to keep the soil near the foundation relatively dry can limit infestation risk. Maintaining a moderately large distance between the soil line and the lowest wood of a structure (300–450 mm) can help prevent termites from easily reaching wood via their tunnels, and increases the likelihood that tunnels, if constructed, will be noticed by concerned parties. Apart from the tunnels that they build, subterranean termites do not leave conspicuous evidence that they are at work in a building, preferring to eat away the interior of a piece of wood and leave a thin veneer of uneaten wood between their tunnels and the air. Subterranean termites prefer moist or decaying wood, but are capable of eating dry wood that is free of decay if the colony has a source of regular moisture. For this reason, moisture exclusion can limit infestation risk, although it does not preclude the possibility of attack.

The Formosan termite is an introduced species (not native to North America) with substantial destructive potential. Formosan termites can infest and destroy living trees as well as wood and wood products. It has been estimated that the annual cost of wood and tree destruction by the Formosan termite exceeds one billion dollars annually in the United States. Whereas subterranean termites only form colonies in the ground, Formosan termites can form colonies isolated from ground contact as well as underground colonies. Exclusion of the termites from the structure is an important tool in preventing infestation, as is moisture control. Although the Formosan termite colonies can form colonies isolated from the ground, they must have regular access to water to thrive. Therefore control of moisture in the building can be particularly helpful in limiting the risk of colony formation within a building. As is the case with subterranean termites, moisture control also limits the risk of Formosan termite infestation via the soil, although it does not preclude the possibility of attack.

²⁶ Termites depend on a complicated interaction of micro-organisms (protozoa and bacteria) within their gut to utilize wood for sustenance.

Summary

The effect of moisture on wood and wood product properties and behaviors has its origin in the chemical composition and biological structure of wood. Wood products can react differently than solid wood to moisture and to changes in moisture; the extent to which wood products respond differently than solid wood is related to the degree of physical or chemical alteration of the product relative to the parent wood material.

Bonded wood products came into use in building construction, for the most part, after the Second World War, and their widespread adoption generally coincided with development and industrial availability of synthetic polymeric adhesives. Bonded wood products have evolved over time with regard to the adhesives and wood constituents used, and with regard to processing techniques and intended end uses. Some bonded wood products are suitable for use on building exterior walls; some have shown decades of acceptable performance in this end use when protected with a suitable exterior finish system. A few bonded wood products (for example, pressure-treated plywood) can even be used in wet environments. Most bonded wood products, however, including sheathing panels, I-joists, and structural composite lumber adhered with waterproof adhesives, are neither intended nor suitable for exterior exposure or for wet service, and are thus expected to be protected from wetting in service.

Moisture content (MC) in excess of 20 % is a major predictor of performance problems with wood and wood products, influencing their susceptibility to fungal and insect infestation and the susceptibility of fasteners embedded in them to corrosion. High MC and repetitive, large fluctuations in MC are also implicated in creep deflection. To prevent these deleterious effects and to provide for the long service life of solid wood in use, an MC of 20 % or less has therefore long been recommended. This level is approximately the equilibrium MC value of wood at 90 % relative humidity and room temperature. It corresponds with approximately 19 % MC in construction plywood and 17 % MC in oriented strand board. Maintaining wood and wood products below these target MCs will prevent the establishment and growth of decay fungi and will preclude the possibility of objectionable creep deflection in adequately sized members. It will also greatly reduce the likelihood or extent of fastener corrosion and of insect infestation. Maintaining wood and wood products below these target levels, although useful for limiting risk of biological infestation, for limiting long-term deflection of load-bearing members, and for helping assure long-term integrity of fastened connections, cannot be expected to prevent all moisture-related moisture problems in all end uses.

Normal seasonal fluctuations in ambient temperature and relative humidity (RH) give rise to changes in MC of wood in service. Serviceability issues associated with dimensional movement of wood or wood-based components may be better served by limits on in-service moisture content more restrictive than the 20 % MC rule, both in terms of the maximum average MC and range across which MC is allowed to vary. Judgment of what constitutes unacceptable dimensional movement varies with the application. Dimen-

sional change equations are provided in this chapter [Eqs (1) and (2)], along with applicable coefficients (Tables 6, 8, and 9). These equations should allow the reader to set their own restrictions for acceptable in-service MC fluctuation based on application-specific criteria for acceptable dimensional movement. Alternatively, a rough rule for acceptable in-service MC fluctuation in finish carpentry can be extracted from Table 5 of this chapter; the rule is for fluctuations to be restricted to no more than 2–3 % above or below the average annual MC for the location of service. This rule will in many cases roughly correspond with allowable moisture fluctuation as calculated by the 1 % allowable dimensional change rule, used by wood craftsmen for prevention of compressive set shrinkage in joinery. This is clearly a much more restrictive criterion than the 20, 19, and 17 % maximum values for wood, construction plywood, and OSB, respectively, outlined in the preceding paragraph. It is almost certainly an excessively restrictive criterion for application to framing or sheathing of light frame buildings.

Wood has been used for millennia in construction; there are structurally sound buildings constructed largely of wood in Scandinavia, China, and Japan that exceed 500 years of age. Invariably, these buildings were designed and constructed such that the wood members were effectively isolated from wetting. The vast majority of residential structures built in North America over the past three centuries were constructed primarily of wood, and most of these have performed reliably. Wood and wood products dried to an appropriate level and maintained within a reasonable range of fluctuating moisture conditions appear capable of performing nearly indefinitely.

Acknowledgments

The authors recognize the varied assistance of individuals of the professional and support staffs of the U.S. Forest Laboratory. These individuals include: JoAnn Benisch, Karen Nelson, Mary Funmaker, David Green, John Hermanson, David Kretschmann, Douglas Rammer, Stephen Schmieding, and Ronald Wolfe.

References

- [1] Panshin, A. and deZeeuw, C., *Textbook of Wood Technology: Fourth Edition*, McGraw-Hill (ISBN 07-048440-6), 1980.
- [2] Tsoumis, G., *Science and Technology of Wood: Structure, Properties, Utilization*, Van Nostrand Reinhold (ISBN 0-442-23985-8), 1991.
- [3] Anderson, A., "The Influence of Extractives on Tree Properties: II Ponderosa Pine," *Jour. Institute of Wood Science*, Vol. 10, 1962, pp. 29–47.
- [4] Kretschmann, D. E., Moody, R. C., Pellerin, R. F., Bendtsen, B. A., Cahill, J. M., McAlister, R. H., and Sharp, D. W., "Effect of Various Proportions of Juvenile Wood on Laminated Veneer Lumber," Research Paper FPL 521, U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, 1993.
- [5] Hann, R., "Longitudinal Shrinkage in Seven Species of Wood," Research Note FPL-0203, USDA Forest Service, Forest Prod. Laboratory, 1969; Harris, J. and Meylan, B., "The Influence of Microfibril Angle on Longitudinal and Tangential Shrinkage of Pinus Radiata," *Holzforschung*, Vol. 19, No. 5, 1965, pp. 144–153.
- [6] Ying, L., Kretschmann, D., and Bendtsen, B., "Longitudinal

- Shrinkage in Fast-grown Loblolly Pine Plantation Wood," *For. Prod. J.*, Vol. 44, No. 1, 1994, pp. 58–62.
- [7] Bao, Z., "Chapter 6: Structural Composite Lumber," *APA Engineered Wood Handbook*, T. Williamson, Ed., McGraw-Hill (ISBN 0-07-136029-8), 2002.
- [8] Baldwin, R., *Plywood Manufacturing Practices*. Miller Freeman Publications Inc. (ISBN 0-87930-030-2), 1975.
- [9] Marra, A., *Technology of Wood Bonding: Principles in Practice*, Van Nostrand Reinhold (ISBN 0-442-00797-3), 1992.
- [10] Geimer, R., Herian, V., and Xu, D., "Influence of Juvenile Wood on Dimensional Stability and Tensile Properties of Flakeboard," *Wood Fiber Sci.*, Vol. 29, No. 2, 1997, pp. 103–120.
- [11] Jokerst, R. and Lutz, J., "Oak-Cottonwood Plywood—Minimum Cure Time," Research Paper FPL 231, U.S. Dept. Agriculture, Forest Service, Forest Products Laboratory, 1974.
- [12] Jokerst, R. and Geimer, R., "Steam-Assisted Hot-Pressing of Construction Plywood," *For. Prod. J.*, Vol. 44, No. 11/12, 1994, pp. 34–36.
- [13] Rinne, V., *The Manufacture of Veneer and Plywood* [textbook in English], Kuopio, Finland 1952.
- [14] Williamson, T., 2002, *APA Engineered Wood Handbook*, T. Williamson, Ed., McGraw-Hill (ISBN 0-07-136029-8), 1967.
- [15] U.S. Department of Commerce, "Voluntary Product Standard PS1-07: Structural Plywood," 2007.
- [16] Maloney, T., *Modern Particleboard and Dry-Process Fiberboard Manufacturing*, Miller Freeman Publications (ISBN 0-87930-063-9), 1977.
- [17] Baker, W., "Chapter 2: Wood Structural Panels," *APA Engineered Wood Handbook*, T. Williamson, Ed., McGraw-Hill (ISBN 0-07-136029-8), 2002.
- [18] Suchsland, O. and Woodson, G., *Fiberboard Manufacturing Practices in the United States*, United States Agriculture Handbook 640, U.S. Dept. of Agriculture, Forest Service, Washington, DC, 1986.
- [19] Lehmann, W., "Improved Particleboard Through Better Resin Efficiency," *For. Prod. J.*, Vol. 15, No. 4, 1965, pp. 155–161.
- [20] Liiri, O., "Pressdruck bei der spanplattenherstellung (Pressure in Particleboard Manufacture)," *Holz als Roh- und Werkstoff*, Vol. 27, No. 10, 1969, pp. 371–378. (Translated in part in 1971 by the New Zealand Forest Service, and presented in the 1974 textbook, *Particleboard: Volume 2*, by A. Moslemi, Southern Illinois Univ. Press (ISBN 0-8093-0656-5).
- [21] Carll, C., "Basic Mechanical Properties of Flakeboards from Ring-Cut Flakes of Eastern Hardwoods," *For. Prod. J.*, Vol. 44, No. 9, 1994, pp. 26–32.
- [22] Kamke, F. and Casey, L., "Fundamentals of Flakeboard Manufacture: Internal-Mat Conditions," *For. Prod. J.*, Vol. 38, No. 6, 1988, pp. 38–44.
- [23] Dai, C. and Wang, S., "Press Control for Optimized Wood Composite Processing and Properties, Part 1: Pressing Variables and Sensors," *Proceedings of a Workshop: Fundamentals of Composite Processing* J. Winandy and F. Kamke, Eds., General Technical Report FPL-GTR-149, U.S. Dept. Agriculture, Forest Service, Forest Products Laboratory, 2004.
- [24] Geimer, R., Mahoney, R., Loehnertz, S., and Meyer, R., "Influence of Processing-Induced Damage on Strength of Flakes and Flakeboards," Research Paper FPL 463, U.S. Dept. Agriculture, Forest Service, Forest Products Laboratory, 1985.
- [25] Wang, S. and Winistorfer, P., "Flake Compression Behavior in a Resinless mat as Related to Dimensional Stability," *Wood Sci. Technol.*, Vol. 35, No. 5, 2001, pp. 379–393.
- [26] Groom, S., "Plywood vs. OSB," *Fine Homebuilding* #169, March 2005.
- [27] Spalt, H., "The Sorption of Water Vapor by Domestic and Tropical Woods," *For. Prod. J.* Vol. 7, No. 10, 1957, pp. 331–335.
- [28] Hedlin, C., "Sorptions Isotherms of Twelve Woods at Subfreezing Temperatures," *For. Prod. J.*, Vol. 17, No. 12, 1967, pp. 43–48.
- [29] Choong, E. and Manwiller, F., "Dimensional and Hygroscopic Properties of Hardwoods from Southern Pine Sites," *Wood Sci.*, Vol. 9, No. 1, 1976, pp. 39–43.
- [30] Ahmet, K., Dai, G., Tomlin, R., Kacsmar, P., and Riddiough, S., "The Equilibrium Moisture Content of Common U.K. Species at Three Conditions of Temperature and Relative Humidity," *For. Prod. J.*, Vol. 50, No. 6, 2000, pp. 64–68.
- [31] Wangaard, F. and Granados, L., "The Effect of Extractives on Water-Vapor Sorption by Wood," *Wood Sci. Technol.*, Vol. 1, 1967, pp. 253–277.
- [32] Choong, E., "Effect of Extractives on Shrinkage and Other Hygroscopic Properties of Southern Pine Woods," *Wood Fiber*, Vol. 1, 1969, pp. 124–133.
- [33] Suchsland, O., "Linear Hygroscopic Expansion of Selected Commercial Particleboards," *For. Prod. J.*, Vol. 22, No. 11, 1972, pp. 28–32.
- [34] Richards, R., Burch, D., and Thomas, W., "Water Vapor Sorption Measurements of Common Building Materials," *ASHRAE Transactions*, Vol. 98, No. 2, 1992.
- [35] Carll, C., and TenWolde, A., "Durability of Hardboard Lap Siding: Determination of Performance Criteria," Research Paper FPL-RP-622. U.S. Dept. Agriculture, Forest Service, Forest Products Laboratory, 2004.
- [36] Koch, P., "Utilization of the Southern Pines, Volume I, The Raw Material," *Agriculture Handbook No. 420*, USDA, Forest Service, Southern Forest Exp't. Sta. Libr. of Congress Card # 79-188-856, 1972.
- [37] Zylkowski, S., "Chapter 1: Introduction to Wood as an Engineering Material," *APA Engineered Wood Handbook*, T. Williamson, Ed., McGraw-Hill (ISBN 0-07-136029-8), 2002.
- [38] Zylkowski, S., "Dimensional Stability of Structural-Use Panels," Report No. R&D86L-43, American Plywood Association, Tacoma, WA, 1986.
- [39] Nordenson, D., "Equilibrium Moisture Content and Effects of Moisture on Flexural Properties of Typical Building Fiberboards and Particleboards," Office report (unpublished), U.S. Dept. of Agriculture, Forest Service, Forest Prod. Laboratory, 1965.
- [40] Myers, G. and McNatt, J., "Fiberboard and Hardboard Research at the Forest Products Laboratory: A 50-Year Summary," General Technical Report FPL-GTR-47, U.S. Dept. Agriculture, Forest Service, Forest Products Laboratory, 1985.
- [41] U.S. Department of Commerce, "PS-20: American Softwood Lumber Standard," 1999.
- [42] Garrahan, P., Meil, J., and Onysko, D., "Moisture in Framing Lumber: Field Measurement, Acceptability and Use Surveys," Submitted to Canada Mortgage and Housing Corporation, Forintek Canada Corp, 1991.
- [43] ASTM Standard D4444, "Standard Test Methods for Use and Calibration of Hand-Held Moisture Meters," *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA, 1992.
- [44] Forest Products Laboratory, "Wood Handbook: Wood as an Engineering Material," General Technical Report FPL-GTR-113, U.S. Dept. Agriculture, Forest Service, Forest Products Laboratory, 1999.
- [45] Carll, C., Knaebe, M., Malinauskas, V., Sotos, P., and TenWolde, A., "Performance of Back-Primed and Factory-Finished Hardboard Lap Siding in Southern Florida," Research Paper FPL-RP-581, U.S. Dept. Agriculture, Forest Service, Forest Products Laboratory, 2000.
- [46] Dost, W., "Shrinking Siding: Estimating Prior Moisture Con-

- tent," *Wood Design Focus*, Vol. 9, No. 4, 1998, pp. 20–23.
- [47] Stiles, L. and Custer, M., "Reduction of Moisture in Wood Joists in Crawl Spaces—A Study of Seventeen Houses in Southern New Jersey," Recommended Practices for Controlling Moisture in Crawl Spaces, *ASHRAE Technical Data Bulletin*, Vol. 10, No. 3, 1994 pp. 30–40.
- [48] Forest Products Laboratory, "Longitudinal Shrinkage of Wood," FPL Report #1093 U.S. Dept. Agriculture, Forest Service, Forest Products Laboratory, 1960.
- [49] Chern, J., "Shrinkage of Redwood Siding," Office report (unpublished), U.S. Dept. of Agriculture, Forest Service, Forest Products Laboratory, 1980.
- [50] Gorman, T., "Juvenile Wood as a Source of Seasonal Arching in Trusses," *For. Prod. J.*, Vol. 35, No. 11/12, 1985, pp. 35–40.
- [51] Percival, D., "Separation Between Ceiling/Floor and Partition Walls," *Wood Design Focus*, Summer, 1991.
- [52] ASTM Standard D1037, "Standard Test Methods for Evaluating Properties of Wood-Base Fiber and Particle Panel Materials," *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA, 1996; Talbott, J., Maloney, T., Huffaker, E., Hoyle, R., and Meyer, R., "Linear Expansion Design Theory for Com-Ply Panels," Research Paper SE-224, USDA Forest Service, Southeast Forest Experiment. Sta., 1981.
- [53] Wu, Q. and Suchsland, O., "Linear Expansion and Its Relationship to Moisture Content Change for Commercial Oriented Strandboards," *For. Prod. J.*, Vol. 46, No. 11/12, 1996, pp. 79–83.
- [54] Alexopoulos, J. and Szabo, T., "Performance of Waferboard: Load Duration, Dimensional Stability and Biodeterioration," *Proceedings of a Workshop on the Durability of Structural Panels*, General Technical Report SO-53. U.S. Dept. of Agriculture, Forest Service, Forest, Southern Forest Experiment Sta, 1984.
- [55] Lehmann, W., "Moisture-Stability Relationships in Wood-Base Composition Boards," *For. Prod. J.*, Vol. 22, No. 7, 1972, pp. 53–59.
- [56] Luxford, R., "Properties of Insulating Fiberboard Sheathing," FPL Report #2032, U.S. Dept. Agriculture, Forest Service, Forest Prod. Laboratory, 1955.
- [57] ASTM Standard C208, "Standard Specification for Cellulosic Fiber Insulating Board," *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA, 1995.
- [58] American National Standard Institute (ANSI), American National Standard for Particleboard: ANSI A208.1–1999. Published by Composite Panel Assn. Gaithersburg, MD (www.pbmdf.com), 1999.
- [59] Biblis, E., "Engineering Properties of Commercial Hardboard Siding. Part 1. Embossed Panels," *For. Prod. J.*, Vol. 39, No. 9, 1989, pp. 9–13.
- [60] Biblis, E., "Engineering Properties of Commercial Hardboard Lap Siding. Part 2. Smooth Boards," *For. Prod. J.*, Vol. 41, No. 3, 1991, pp. 45–49.
- [61] American Hardboard Assn. (AHA), American National Standard for Hardboard Siding: ANSI/AHA A135.6-1998, Palatine, IL, 1998.
- [62] Lang, E. and Loferski, J., "In-Plane Hygroscopic Expansion of Plywood and Oriented Strandboard," *For. Prod. J.*, Vol. 45, No. 4, 1995, pp. 67–71.
- [63] Wu, Q. and Suchsland, O., "Effect of Moisture on the Flexural Properties of Commercial Oriented Strandboards," *Wood Fiber Sci.*, Vol. 29, No. 1, 1997, pp. 47–57.
- [64] McNatt, J., "How Cyclic Humidity Affects Static Bending and Dimensional Properties of Some Wood-Base Panel Products," *Proceedings of a Workshop on the Durability of Structural Panels*, General Technical Report SO-53, U.S. Dept. of Agriculture, Forest Service, Forest, Southern Forest Experiment Sta., 1984.
- [65] Wu, Q. and Piao, C., "Thickness Swelling and Its Relationship to Internal Bond Strength Loss of Commercial Oriented Strandboard," *For. Prod. J.*, Vol. 49, No. 7/8, 1999, pp. 50–55.
- [66] Linville, J. and Wolcott, M., "Controlling Thickness Swell in Oriented Strand Composites," *Proceedings, 35th International Particleboard/Composite Materials Symposium*, Washington State Univ., Pullman, WA, 2001.
- [67] Nofal, M. and Kumaran, K., "Moisture's Effects on OSB," *Professional Roofing*, April 2000, pp. 28–30.
- [68] River, B., "Outdoor Aging of Wood-Based Panels and Correlation with Laboratory Aging," *For. Prod. J.*, Vol. 44, No. 11/12, 1994, pp. 55–65.
- [69] Quarles, "How Durable is Structural Sheathing?" *Proceedings: 35th International Particleboard/Composite Materials Symposium*, Washington State Univ., Pullman, WA, 2001.
- [70] Hoadley, R. B., *Understanding Wood: A Craftsman's Guide to Wood Technology*, Taunton Press (ISBN 0-918804-05-1), 1980.
- [71] Kollman, F. and Côté, W., *Principles of Wood Science and Technology: Vol. I Solid Wood*, Springer-Verlag. Libr. or Congress Card # 67-29614, 1968.
- [72] Markwardt, L. and Wilson, T., "Strength and Related Properties of Woods Grown in the United States," Technical bulletin 479, U.S. Dept. Agriculture, Washington, DC, 1935.
- [73] American Forest and Paper Association, National Design Specification for Wood Construction: ANSI/AF&PA NDS-2001, 2001.
- [74] Lehmann, W., "Durability of Composition Board Products," *Proceedings, 11th International Particleboard/Composite Materials Symposium*, Washington State Univ., Pullman, WA, 1977.
- [75] Sekino, N. and Suzuki, S., "Durability of Wood-Based Panels Subjected to Ten-Year Outdoor Exposure in Japan," *Proceedings: The 6th Pacific Rim Bio-Based Composites Symposium*, Oregon State Univ., Corvallis, OR, 2002.
- [76] Grossman, P., "Requirements for a Model that Exhibits Mechano-Sorptive Behavior," *Wood Sci. Technol.*, Vol. 10, 1976, pp. 163–168.
- [77] Bengtsson, C., "Short-Term Mechano-Sorptive Creep of Well Defined Spruce Timber," *Holz als Roh-und Werkstoff*, Vol. 59, 2001 pp. 117–128.
- [78] Gehards, C., "Bending Creep and Load Duration of Douglas-fir 2 by 4s Under Constant Load for up to 12-Plus Years," *Wood Fiber Sci.*, Vol. 32, No. 4, 2000, pp. 489–501.
- [79] Dinwoodie, J., Robson, D., Paxton, B., and Higgins, J., "Creep in Chipboard Part 8: The Effect of Steady-State Moisture Content, Temperature and Level of Stressing on the Relative Creep Behavior and Creep Modulus of a Rang of Boards," *Wood Sci. Technol.*, Vol. 25, No. 3, 1991a, pp. 225–238.
- [80] Dinwoodie, J., Paxton, B., Higgins, J., and Robson, D., "Creep in Chipboard Part 10: The Effect of Variable Climate on the Creep Behavior of a Range of Chipboards and One Waferboard," *Wood Sci. Technol.*, Vol. 26, No. 1, 1991b, pp. 39–51.
- [81] McNatt, J. and Laufenberg, T., "Creep and Creep-Rupture of Plywood and Oriented Strandboard," *Proceedings The 1991 International Timber Engineering Conference*, Vol. 3, 1991, pp. 3.457–3.464.
- [82] Pu, J., Tang, R., and Cos Davis, W., "Creep Behavior of Commercial Oriented Strandboard Under High Relative Humidity," *For. Prod. J.*, Vol. 42, No. 4, 1992a, pp. 49–54.
- [83] Pu, J., Tang, R., and Price, E., "The Effect of Hot and Humid Environmental Conditions on the Creep Behavior of Commercial Structural Oriented Strandboards," *For. Prod. J.*, Vol. 42, No. 11/12, 1992b, pp. 9–14.
- [84] Pu, J., Tang, R., and Hse, C., "Creep Behavior of Sweetgum OSB: The Effect of Load Level and Relative Humidity," *For.*

- Prod. J.*, Vol. 44, No. 11/12, 1994, pp. 45–50.
- [85] Zelinka, S. and Rammer, D., "Review of Test Methods Used to Determine Corrosion Rate of Metals in Contact with Treated Wood," General Tech. Report FPL-GTR-156, U.S. Dept. Agriculture, Forest Service, Forest Products Laboratory, 2005.
- [86] Malloy, D., "Exposed Subfloors and Galvanized Bolts?: Not Any More," *Build* (ISSN: 0110 4381). Bldg. Research Assn. of New Zealand, Feb./March 2005.
- [86a] Baker, A., "Corrosion of Nails in CCA- and ACA-Treated Wood in Two Environments," *For. Prod. J.*, Vol. 42. No. 9, 1992, pp. 39–41;
- [87] MacLean, H. and Gardner, J., "Deterioration of Wooden Dry Kilns Used for Drying Western Hemlock Lumber," *The Lumberman*, Vol. 78, No. 12, 1951, pp. 88–90.
- [88] Baker, A., "Degradation of Wood by Products of Metal Corrosion," Research paper FPL 229, U.S. Dept. of Agriculture, Forest Service, Forest Products Laboratory, 1974.
- [89] Thompson, W., "Effect of Chemicals, Chemical Atmospheres, and Contact with Metals on Southern Pine Wood: A Review," Research Report #6, Forest Products Utilization Laboratory, Mississippi State Univ., 1969.
- [90] Highley, T., Scheffer, T., and Selbo, M., "Wood Minesweepers are Sound After 15 Years of Service," *For. Prod. J.*, Vol. 21, No. 5, 1971, pp. 40–48.
- [91] Emery, J. and Schroeder, H., "Iron-Catalyzed Oxidation of Wood Carbohydrates," *Wood Sci. Technol.*, Vol. 8, 1974, pp. 123–127.
- [92] Cole, I., Trinidad, G., and Chan, W., "Prediction of the Impact of the Environment on Timber Components: AGIS-Based Approach," *Proceedings, Durability of Building Materials and Components-8*, M. Lacasse and D. Vanier, Eds., National Research Council Canada (ISBN 0-660-17737-4 (Volume 1)), 1999.
- [93] Imamura, H. and Kiguchi, M., "Prediction of Wood Decay in the Exterior Wall of Wooden Houses by the Deterioration of Nails," *Proceedings, Durability of Building Materials and Components-8*, M. Lacasse and D. Vanier, Eds., National Research Council Canada (ISBN 0-660-17737-4 (Volume 1)), 1999.
- [94] Flannigan, B. and Miller, J. D., "Humidity and Fungal Contaminants," *Proceedings of the Moisture Control Workshop: Bugs, Mold & Rot II*, W. Rose and A. TenWolde, Eds., Nat'l Institute of Bldg. Sciences, Washington, DC, 1993.
- [95] Viitanen, H. and Salonvaara, M., "Chapter 4: Failure Criteria," *Moisture Analysis and Condensation Control in Building Envelopes ASTM MNL-40*, H. Trechsel, Ed. (ISBN 0-8031-2089-3), ASTM International, West Conshohocken, PA, 2001.
- [96] Zabel, R. and Morrell, J., *Wood Microbiology*, Academic Press, (ISBN 0-12-775210-2), 1992.
- [97] Gaby, L. and Duff, J., "Moisture Content Changes in Wood Deck and Rail Components," USDA Forest Service Research Paper SE-190, 1978.
- [98] Hunt, G. and Garratt, G., *Wood Preservation*, 1st ed., McGraw-Hill Book Co. L.O.C. #TA422.H85, 1938.
- [99] Griffin, D., "Water Potential and Wood-Decay Fungi," *Annual Reviews Phytopathology*, Vol. 15, 1977, pp. 319–329.
- [100] Viitanen, H., "Modeling the Time Factor in the Development of Brown Rot Decay in Pine and Spruce Sapwood—The Effect of Critical Humidity and Temperature Conditions," *Holz-forschung*, Vol. 51, No. 2, 1997, pp. 99–106.
- [101] Carll, C. and Highley, T., "Decay of Wood and Wood-Based Products Above Ground in Buildings," *J. Test. Eval.*, Vol. 27, No. 2, 1999, pp. 150–158.

Carll, Charles ; Wiedenhoef, Alex. Moisture-related properties of wood and the effects of moisture on wood and wood products. IN: Moisture control in buildings: the key factor in mold preventions / Heinz R. Trechsel and Mark T. Bomberg, editors. 2nd ed. West Conshohocken, PA : ASTM International, c2009. Chapter 4, p.54-79.;2009