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Dimensional Stability of Western Lumber

From WWPA publication Dimensional Stability (TG-3), rev. 1990

Contents

Wood is one of our most important building materials. We live in wood houses, utilize wood furniture and enjoy the beauty and warmth of wood. Many people work with wood for a livelihood or as a hobby because of its unique features, abundance in many areas and the renewability of the forests from which it is derived. Wood is used in many forms throughout the world, however, few people fully understand its properties.

Wood possesses many excellent qualities, but it also has certain peculiarities which must be understood and considered for optimum application. One of these is its hygroscopicity which causes change in some properties due to the moisture absorption and desorption.

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WWPA Lumber Shrinkage Estimator

Right click on the button above or here to begin downloading. If you have Microsoft Excel loaded, the program will open in your browser window.

Features easy-to-use form to estimate shrinkage by selecting the Western species group, starting moisture content, ending moisture content and product size from 1x2 to 24x24. Comparisons can be made between two Western species groups.

Minimum requirements:

- Microsoft® Excel (Windows version 97 or higher)
- 32 MB RAM

The WWPA Lumber Shrinkage Estimator was created by Oregon State University, in cooperation with Western Wood Products Association, Portland, Ore.

Wood, composed mainly of cellulose and lignin, shrinks as it dries and swells as it absorbs moisture. Dimensional changes generally take place from 0% to 30% moisture content (M), based on its oven-dry weight. In a dry atmosphere, wet or "green" wood loses moisture in the form of water vapor. Dry wood, on the other hand, absorbs moisture from a humid atmosphere; the moisture content of wood also may be increased by wetting with liquid water. If wet wood is put into place, it eventually dries to a moisture content in equilibrium with the surrounding air -- the equilibrium moisture content (EMC). This drying is accompanied by shrinkage. If wood has been dried too far below the moisture content reached in use, it absorbs water until the equilibrium moisture content is achieved and swelling results.

When changes in moisture content are great and occur quickly, shrinkage and swelling may cause not only dimensional changes, but also splitting, cracking, or glueline separations in woodwork, furniture and other wood products. Small changes that take place slowly usually cause very small, hardly noticeable dimensional changes. However, slight drying taking place over a fairly long period of time may generate cracks and distortions when wooden parts are severely restrained -- for example, by mechanical fastenings such as staples, screws, nails, and bolts -- so that shrinkage is inhibited. When drying stresses exceed the strength of either the wood itself or an adhesive bonding agent, cracking and glueline separations will also occur, either in the wood itself or in the gluelines.

Drying wood products to the moisture content best suited to the intended use conditions before placing the wood into service will eliminate most problems. Drying, either in kilns or air-drying yards, is often a critical step in manufacturing lumber. Proper drying reduces drying defects. Kiln drying permits the manufacturer to better control the rate of moisture reduction and equilibrate the moisture content of lumber close to, or at, the desired final level.

When lumber is to be surfaced before drying, moisture-content changes must be considered. Boards may be surfaced either in an unseasoned (green) condition or, after partial drying, at a lower moisture content. If lumber is to be surfaced green, the desired equilibrium moisture content should be known. The lumber must be surfaced to a dimension greater than the final size to compensate for the reduction that will occur during subsequent drying. Mills therefore must cut lumber to the so-called equilibrium green size, which will, on the average, yield the desired size at the final equilibrium moisture content.

Reasons for Drying Wood

For both technical and performance reasons, drying or seasoning wood is required when making glued wood products such as laminated beams, plywood, particleboard, furniture and many other products.

(1) Drying to the desired final moisture content minimizes dimensional changes and warping in use. Pieces that might degrade and develop defects during drying can be sorted out at the mill and possibly directed to another use. Such quality control helps to assure performance of products in service and leads to customer satisfaction.

(2) Dry wood provides a better base for paints, finishes and adhesives. Many finishes may not adhere at all to green wood, or the subsequent drying of wood may lead to failures in the paint coat. Adhesives may not bond well on green wood.

(3) Water- or oil-borne preservatives cannot be forced under pressure into wood that has free water in its cells. When a preservative cannot penetrate deeply, full protection against attack by decay fungi or insects cannot be obtained.

(4) Drying improves the resistance to decay. Wood that has been dried and kept below 20% moisture content does not have sufficient moisture to support most decay organisms. Also, organisms already in the wood will be killed when exposed to high kiln-drying temperatures for several hours.

(5) Drying may increase the strength of wood unless defects developing during drying counteract this trend.

(6) Drying reduces the weight of wood, and since truck and railroad shipping rates are based on weight, shipping costs can be reduced.

Structure of Wood

The anatomical structure of wood and the amount and location of moisture

it contains are the main factors influencing size changes in lumber. The cellular structure of wood varies greatly among the tree species growing throughout the world. This publication focuses only on a few conifers (softwood trees) which grow in the western United States and have certain similarities.

Figure 1 shows a cross section of a coniferous tree, from the outside to the inside: bark, light-colored sapwood and the sometimes darker heartwood. Often a small soft core, the pith, can be seen. Magnification by microscope reveals the cellular structure. Coniferous wood contains hollow, tubelike cells, most of which are tiny fibers oriented with their longitudinal axis up and down the tree. In a living tree, these cells are fully saturated and the cell cavities are partially to completely filled with water. A few cells, the wood rays, lie nearly perpendicular to the long axis of tree trunks and form radial lines from pith to bark.

Every year, a living tree adds several new layers of wood cells to the outside of the sapwood, forming an annual ring. Springwood, also called earlywood, is formed during the early part of the growing season. It appears light-colored because cells are generally larger and have thinner walls. The darker outer portion of a ring, called summerwood or latewood, appears darker because cells have thicker walls, forming a much denser and stronger material.

In a living tree, the sapwood contains living cells, which serve mainly in the transfer and storage of food, and dead cells, which serve as channels for the movement of dissolved nutrients and help to support the tree physically. The centrally located heartwood, which consists of dead cells only, has the principal function of mechanical support and also stores extraneous materials. Relative amounts of sapwood and heartwood vary considerably within and between species.

In most species such as in Western Red Cedar, Douglas Fir or Ponderosa Pine, heartwood is distinctly darker than sapwood. However, heartwood of some other species, such as White Firs or Western Hemlock, is not distinctively darker. Generally, heartwood of the first group has become infiltrated with resins, coloring matter and other extraneous materials. In the case of Western Red Cedar, extraneous materials deposited within the cell walls reduce shrinkage and fiber saturation point somewhat below those observed in other species. While heartwood is in general less permeable and dries more slowly than sapwood, it generally also has a lower moisture content than sapwood in a living tree.

Juvenile wood formed adjacent to the pith as shown in Figure 1, shrinks more than the surrounding mature wood. Juvenile wood in a board may contribute to warping.

Compression wood, occurring on the underside of trunks of leaning coniferous trees and branches, is formed in reaction to gravity and assists the tree in straightening up. The annual growth rings in compression wood show a gradual transition from springwood to summerwood, with summerwood bands usually wider than normal. Compression wood shrinks more longitudinally than does normal wood and may therefore cause warping.

Moisture in Wood

Moisture in trees or freshly cut lumber is often referred to as sap. A distinction is made between free water, which is located in cell cavities, and bound water, which is held within cell walls. Sapwood of freshly cut softwood lumber contains more moisture in its cell cavities than does heartwood. Average moisture contents for green

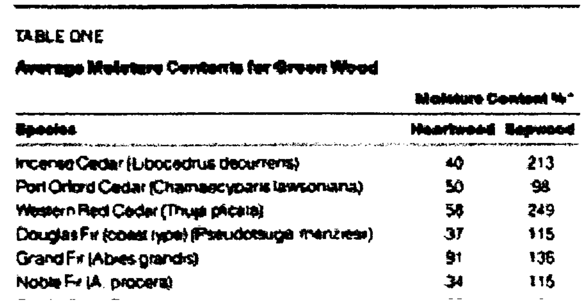


TABLE ONE

Average Moisture Contents for Green Wood

	Moisture Content %*	
Species	**Heartwood**	**Sapwood**
Incense Cedar (Libocedrus decurrens)	40	213
Port Orford Cedar (Chamaecyparis lawsoniana)	50	98
Western Red Cedar (Thuja plicata)	58	249
Douglas Fir (coast type) (Pseudotsuga menziesii)	37	115
Grand Fir (Abies grandis)	91	136
Noble Fir (A. procera)	34	115

wood of Western softwood species
are listed in Table 1. Moisture contents may vary at different heights in trees and with growing conditions such as seasonal weather influences. Butt-logs of many trees may have much higher moisture contents and sometimes higher specific gravities than upper logs. Thus, they may sink in water (sinker logs), while upper logs usually float.

When free water has evaporated from cell cavities, but bound water still saturates cell walls, the fiber saturation point (FSP) has been reached . This condition exists at a moisture content of up to 30%. Moisture loss below FSP causes shrinkage because wood molecules draw closer together as water molecules leave.

Below fiber saturation point, electrical methods for measuring moisture content become important, especially when the standard method of weighing wet and oven-dry samples is impractical or impossible. There are two primary types of electrical moisture meters: one uses the relationship between moisture content and direct-current resistance of wood, while the other uses the relationship between moisture content and dielectric properties. Portable models are especially useful.

Direct-current resistance meters use pin electrodes, driven into the wood for testing. They read accurately from the fiber saturation point down to about 7% moisture content, provided temperature and species correction factors are applied. Radio-frequency, power-loss and capacitance-type meters normally use surface-contact electrodes from which an electric field penetrates about one inch into the wood.

Atmospheric Conditions and Moisture Content

Moisture content of wood is usually expressed as the ratio of the weight of water (Ww) in a piece of wood to the weight of the wood when completely dry (Wo). Such complete dryness is obtained in a standard test on small samples by oven-drying at 215°F (102° C) until constant weight is reached.

The weight of water (Ww) can be calculated by subtracting the weight of the oven dry wood (Wo) from the weight of the wood at a given moisture content level (W%).

$$M(\%) = \left(\frac{W_W}{W_O}\right) 100$$

$$\text{or } M(\%) = \left(\frac{W_{\%} - W_O}{W_O}\right) 100$$

Humidity is commonly expressed as either absolute or relative humidity. Absolute humidity refers to the actual quantity of moisture present in air and may be expressed in grains per cubic foot or grams per cubic meter. The capacity of air for water vapor is directly proportional to the temperature of air. If air containing a large amount of water vapor is cooled, it may reach the dew point at which water vapor condenses from the air. Relative humidity (RH) is the ratio of the actual amount of moisture in air at a certain temperature to the maximum amount it could hold at that temperature.

Atmospheric humidity depends on climatic conditions and varies with changes in weather. In buildings, we often regulate air temperature by heating or air conditioning but only rarely do we directly add moisture to or remove it from the air. However, if absolute humidity remains unchanged, relative humidity will be lowered by heating and increased by cooling.

Equilibrium Moisture Content

Moisture content of wood below the fiber saturation point is a function of both the relative humidity and the temperature of surrounding air (see Table 2). At equilibrium moisture content, wood neither gains nor loses water, because it has reached equilibrium with the vapor pressure of the surrounding atmosphere. Changes in relative humidity and temperature of surrounding air cause both seasonal, long-term and daily, short-term changes in the moisture content of wood. However, long-term changes are gradual as moisture slowly penetrates the wood, while short-term fluctuations influence only the wood surface. Protective coatings such as lacquers or varnishes slow changes even more.

The recommended procedure for interior woodwork is to dry raw material to the moisture content it will have in use before manufacturing it to desired dimensions, and then to keep it as much as possible at that moisture content. However, this may not always be possible because of climatic changes. Therefore, upon arrival at its final destination, wood work should be preconditioned by storing it -- with separators of a constant size evenly spaced between layers -- for a week to 10 days in the room in which it is to be installed, to allow the moisture content to equilibrate with conditions to be maintained over time.

Click here to view maps showing the recommended levels of average moisture content for interior woodwork to be installed in January and July, respectively. Moisture content values recommended for wood used in interior parts of heated buildings range from 4%-13%, with an average of 8% for most of the United States; the dry southwestern and the damp southeastern coastal states are notable exceptions. In air-conditioned buildings, the equilibrium moisture content might be slightly lower by one or two percentage points.

Click here for a chart showing the average equilibrium moisture content of wood exposed to outdoor conditions for each month of the year at major U.S. cities, as determined by the U.S. Forest Products Laboratory.

Shrinkage and Swelling

Wood is anisotropic, i.e. its properties differ according to the direction of measurement. Unless there is abnormal wood, such as juvenile wood or compression wood, contraction is greatest in the tangential direction of the annual growth rings, approximately one-half as much radially across the rings, and minimal (between 0.1% and 0.2%) longitudinally along the grain. Many variables affect dimensional change. Shrinkage values differ not only for different wood species, but also between and within trees of the same species. Shrinkage also may vary slightly depending on the drying conditions: low or high temperatures, rapid or slow drying, or drying with or without restraint.

There is no completely adequate explanation of the anisotropic properties of wood because of the complexity and diversity of wood structure. Research has shown that many mechanisms act simultaneously. Differential dimensional changes are related in part to alternation of summerwood and springwood increments within the annual rings, because springwood and summerwood shrinkage are not alike. Cell lumens (cavities) and cell perimeters of earlywood and latewood do not shrink to the same amount, and the reduction in wall

TABLE THREE

Dimensional Change (%) from Green to the Oven-dry Condition (S_R, S_T)[1]
Dimensional Change Coefficient (C_R, C_T)[2]

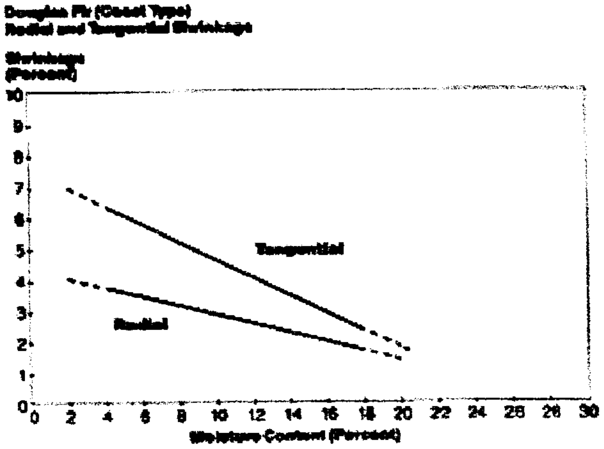
Species (common and botanical names)	**Radial**		**Tangential**	
	S_R	C_R	S_T	C_T
Incense Cedar (Libocedrus decurrens)	3.3	.00112	5.2	.00180
Port Orford Cedar (Chamaecyparis lawsoniana)	4.6	.00158	6.9	.00241
Western Red Cedar (Thuja plicata)	2.4	.00111	5.0	.00234
Douglas Fir (coast type) (Pseudotsuga menziesii)	4.8	.00165	7.6	.00267
Douglas Fir (intermed. type) (P. menziesii)	3.8	.00130	6.9	.00241
Douglas Fir (Rocky Mt. type) (P. menziesii var. glauca)	4.8	.00165	7.5	.00263
Alpine Fir (Abies lasiocarpa)	2.6	.00088	7.4	.00259
Noble Fir (A. procera)	4.3	.00148	8.3	.00293
California Red Fir (A. magnifica)	4.5	.00155	7.9	.00278
Pacific Silver Fir (A. amabilis)	4.4	.00151	9.2	.00327
White Fir (A. concolor)	3.3	.00112	7.0	.00245
Western Hemlock (Tsuga heterophylla)	4.2	.00144	7.8	.00274
Western Larch (Larix occidentalis)	4.5	.00155	9.1	.00323
Lodgepole Pine (Pinus contorta)	4.3	.00148	6.7	.00234
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

thickness differs in these two wood types. Microscopic structure of the compound middle lamella (inner layer) of cell walls influences shrinkage in earlywood cells. In addition, the angle of fibrils in the secondary wall of cells affects dimensional changes. Last, but not least, the ratio of shrinkage in the tangential to the radial direction is influenced by the ratio of the number of cell walls in the tangential and radial plane between summerwood and springwood.

Dimensional change data for wood of the major Western conifers is available from many sources. One must distinguish carefully between values obtained on small clear specimens cut true to the tangential and radial grain, and lumber which may or may not have had true tangential or radial grain. Total shrinkage is from green to oven-dry condition. Dimensional contraction is assumed, for most species, to start between 25% and 30% moisture content, and end in the oven-dry condition, or 0% moisture content. The latter can be achieved only by drying small samples in an oven, a practice that normally cannot be implemented for full-size boards.

Shrinkage values shown in Table 3 are averages obtained on small samples that were cut true to the tangential and radial directions and dried with a minimum of stress (U.S. Forest Products Laboratory, 1987). Figure 4 relates shrinkage to moisture content of Douglas Fir board sections 7/8 in. thick, by 5-1/2 in. wide by 8-1/2 in. long. In this graph, one line shows the shrinkage of flat-grained or plain-sawed board sections (their wide face in a true tangential direction) and the other shows that of edge-grained or quarter-sawn board sections (their wide face cut in a true radial direction) (Peck 1928, and Comstock 1965).

FIGURE FOUR



True linear relationships between contraction or expansion and moisture contents can be established from 4% to 18% moisture content. Below and above this range, straight-line relationships remain good approximations, even though curves become slightly sigmoid (curved like an S).

Lumber with larger cross-sectional dimensions shows slightly less shrinkage because of "set" developing during the drying process. (See Preventing Defects section for more information on case hardening and an explanation of "set"). While sapwood boards sometimes have slightly higher shrinkage values than heartwood boards of the same species, that difference can almost always be neglected.

Shrinkage calculations are fairly simple, with the assumption that shrinkage is directly proportional to the water removed from cell walls. In North America, shrinkage (S) is expressed as a percentage of the green or wet dimensions of a piece in accordance with the following equation:

$$S\,(\%) = \frac{FSP-M}{FSP}\,.\,Smax = \left(1 - \frac{M}{FSP}\right) Smax$$

Where FSP is the fiber saturation point, M the moisture content and Smax is the maximum shrinkage possible.

EXAMPLE:
A 7-1/2 in. (nominally 8 in.)-wide, flat-grained board of coast Douglas Fir, which has a FSP of 28%, is dried from the green condition to a moisture content of 15%. It is desired to approximate the width of this board at the lower moisture content. Table 3 indicates a total or maximal shrinkage in the tangential direction (ST) of 7.6%.

The percent shrinkage(s) can be calculated as:

S = ((28% - 15%)/28%) x 7.6% = 3.5%

The difference in width is then:

Ddif = (7.5 in. x 3.5%)/100% = .26 in

Therefore, drying the board from its green condition to 15% moisture content reduces its width to:

7.50 in. - .26 in. = 7.24 in., or about 7-1/4 in.

At the same time, one can estimate the shrinkage of the board's thickness, (radial shrinkage is 4.8%) as follows:

S = ((28% - 15%)/28%) x 4.8% = 2.23%

With a nominal thickness of 1-1/2 in., the actual dimension is 1-13/32 or 1.41 in. and the shrinkage:

Ddif = (1.41 in. x 2.23%)/100% = 0.03in.

Therefore, drying to 15% moisture content reduces the thickness to:

1.41 in. - .03 in. = 1.38 in., or 1-3/8 in.

This calculation can be simplified by using the formula:

D% = DG (1-S/100)

where D% is the dimension at a certain percent moisture content, DG is the dimension when green, and S% is the shrinkage from the green condition to that at the given percent moisture content:

D15 = 1.41 in. (1 - .03) = 1.37 in.

The amount of shrinkage can also be presented graphically. Figure 4 is the result of measurements on 175 boards of coast-type Douglas Fir (Comstock 1965).

Using Figure 4 and the preceding example, one can obtain shrinkage values of 3.1% for shrinkage in width (tangential direction) and 2.2% in thickness (radial direction) when drying from green to 15% moisture content.

Using these values, one obtains:

width = 7.50 in. (1 - .03) = 7.27 in.
thickness= 1.41 in. (1 - .02) = 1.38 in.

Not all boards are either flat sawn or contain only vertical grain, some may have "mixed" grain. It is therefore important to consider the growth-ring orientation.

The effect of ring angle on shrinkage in width and thickness can be calculated from the equations by MacLean (1945):

$$S_{width} = ST\cos^2 e + SR \sin^2 e$$
$$S_{thickness} = ST\sin^2 e + SR \cos^2 e$$

where e is the angle between the growth rings and the flat face of the board.

This relationship is illustrated in the following table, using shrinkage values from Comstock's research (1965):

Shrinkage percent for Douglas Fir dried from green to 15% moisture content

	Angle of Growth Rings			
Dimension	*0 deg.*	*15 deg.*	*30 deg.*	*45 deg.*
Width	3.10	3.04	2.88	2.65
Thickness	2.20	2.26	2.43	2.65

Using Dimensional Change Coefficients

Wood in service, especially indoors, normally changes its dimensions only slightly with changes in climatic conditions. These changes are smaller than the original shrinkage when drying from the green condition. Estimates of dimensional changes, Ddif, can be made within the moisture content limits of 6% to 14% by using the dimensional change coefficients CR or CT from Table 3 (U.S. Forest Products Laboratory 1974):

$$D_{dif} = DI\ [C(MF-MI)]$$

where DI is the initial dimension, MI and MF the initial and final moisture contents (%), respectively, and C is the dimensional change coefficient. When (MF-MI) is negative, the wood will shrink; when it is positive, the wood will swell.

This method can be exemplified by considering a flat-sawn Douglas Fir board with a width of D14 = 7.22 in., or 7-7/32 in., at 14% moisture content. Using CT as the coefficient (because flat sawn board), the dimensional change when it dries to 10% is:

$$D_{dif} = 7.22 \text{ in. } [.00267\ (10-14)] = -.08 \text{ in.}$$

and the new width is:

$$D_{10} = 7.22 \text{ in. } -.08 \text{ in.} = 7.14 \text{ in.}$$

Preventing Defects Caused by Unequal Dimensional Changes

A basic understanding of shrinkage behavior is helpful in processing lumber. A number of defects may either develop or be prevented from developing during the drying operation. Some defects may become visible as they develop, while others may not be obvious until a later stage of manufacturing, or during use. Kiln operators should use procedures and drying schedules that minimize development of defects leading to lumber degrade.

Checking, either at the ends or on the surfaces of boards, is a defect related to too-rapid drying.

End checking occurs when the ends of boards dry much faster than other major portions. Moisture evaporates more rapidly from the end grain than from the surface of boards exposed to excessive air circulation because of a greater rate of moisture movement along the grain. Rapid drying of the ends causes shrinkage stresses in the last few inches of drier wood. If these stresses exceed the strength of the wood, end checks develop extending inward from the ends. Prevention is possible by reducing the rate of drying at the ends through proper piling, application of moisture-resistant coatings on the end grain, or both.

Surface checking also is caused by too-rapid, and therefore unbalanced, drying which leads to stresses through the thickness of a piece. Slowing the drying rate through better control of kiln- or air-drying conditions is the best preventive measure.

Case hardening is not immediately obvious, but often causes defect development during subsequent manufacturing steps. Case hardening also is caused by drying stresses. During the early stages of drying, the wood fibers on the surface (shell) of a board dry rapidly to below the fiber saturation point and equilibrate with the surrounding atmosphere. Consequently, the shell tends to shrink; however, the contraction is restrained by the nonshrinking core, which originally remains above the fiber saturation point. The fibers in the shell are therefore stressed in tension, while those in the core are compressed. When lumber dries rapidly under these conditions, it develops a surface tension "set" in the shell, and similarly a compression "set" in the core.

During subsequent drying, the moisture content of the core also drops below the fiber saturation point, which causes shrinkage. The drying stresses are reversed, because shrinkage of the core is resisted by the fibers in the shell. The core now is stretched in tension and the shell in compression, leading to the case-hardened condition.

Case hardening is not necessarily a defect; if the piece is not further manufactured, case-hardening stresses often balance and no visible distortion results. However, problems will occur if case-hardened lumber is resawn or surfaced more on one side than on the other. These manufacturing steps unbalance the stresses and usually result in warp, mainly cupping.

Case hardening may be prevented by proper kiln drying, mainly by concluding a dry kiln schedule first with an equalization and then a conditioning period. Technical manuals for kiln operators outline how case-hardening stresses can be detected and relieved by proper drying.

Internal checking (honeycomb) also develops when drying stresses exceed the strength of wood, in this case in the interior of lumber. Development of case hardening and honeycomb are related. Honeycomb develops during the second period of drying, when tensile stresses develop in the core because of restraint to shrinkage by the shell.

Warping results from differential shrinkage of layers of wood, caused by growth-ring orientation or the presence of spiral-grain, cross-grain, reaction or juvenile wood.

Bow is lengthwise curvature of the wide surface of a board, crook is lengthwise curvature of the narrow edge. Twist is the curving of the edges so that the four corners are no longer in one plane. Cupping which probably is the most common defect, results either from inherent differences between radial and tensile shrinkage or from one-sided planing or resawing of case-hardened boards. Cupping is mainly a problem on flat-sawn lumber from small to medium-size trees, because tangential shrinkage is somewhat greater on the outer face, but on the inner face, nearer the pith, more radial shrinkage occurs.

Warp can be reduced or prevented by proper sawing and drying. Sawing to a uniform thickness and avoiding grain deviations and cross grain will help a great deal. Good lumber stacking practices before drying, combined with good kiln scheduling, are also helpful.

Loosened and checked knots are caused by different drying rates and shrinkage in knots and surrounding wood. Encased knots shrink more than the surrounding wood and separate from the other wood fiber, so they may loosen or fall out. Intergrown knots cannot separate and the stresses result in their checking. Maintaining higher equilibrium moisture content conditions during drying and avoiding overdrying will reduce knot defects.

Fuzzy lumber surfaces result from too-high moisture content. Fuzzing of surface fibers occurs during machining and can be reduced by feeding the boards through the planer so as to cut with the grain instead of against it. Drying to a lower moisture content may eliminate the problem altogether.

History of text

Authored by Dr. Helmuth Resch, Dean of Research, State University of New York, College of Environmental Science and Forestry, Syracuse, NY. Preparation of the 1987 second edition was completed while the author was head of the Department of Forest Products, Oregon State University.

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