# The effect of subzero temperatures on FSP of cottonwood

Rubin Shmulsky*
Vladimir Shvets

**Abstract**

This research investigates the thermal expansion and contraction of wood at varying moisture content values. The motivation for the research is to explain why less warp is noted and why lumber quality retention through the processing chain improves during the winter in Northeastern Europe and Northwestern Russia. It was found that subzero temperatures can depress the fiber saturation point (FSP) in wetwood, somewhat analogous to freeze drying during which the reduced atmospheric vapor pressure induces reduced equilibrium moisture contents. When wood is sawn in the frozen state, it is in a pre-shrunk and pre-dried condition. As such, by reasonable logical induction, subsequent thawing and drying have a significantly reduced ability to induce warp in lumber.

Around the world, warp in lumber as a result of differential drying shrinkage is a considerable cause of value loss. Colloquial evidence exists that shows freezing logs prior to sawing can reduce warp in lumber. Among sawyers in Eastern Europe and Northwestern Russia it was noted that lumber warp characteristics improved during the winter months. One theory for this noted improvement is that the coldness-induced shrinkage as related to moisture diffusion pre-shrinks the wood before it is sawn. Because straight boards are sawn from pre-shrunk logs, they are less likely to warp during drying, whether in an air yard, in a kiln, or in service. It does not seem reasonable to assume that thermal expansion/contraction, acting alone, could induce such a response.

Incomplete information exists with respect to the coefficients of thermal expansion ($\alpha$) for wood at varying moisture contents (MCs). For any given type of wood, the $\alpha$ values are reportedly constant in the temperature range of −50° to 50°C (Panshin and deZeeuw 1970). This behavior is limited to ovendry wood (USDA 1999). It is also reported that $\alpha$ values are directly related to specific gravity (SG). Related work by Kubler et al. (1973) covers a wider range of MC. In all cases, researchers show that a) thermal expansion in the radial and tangential axes is greater than that in the longitudinal axis; and b) moisture-induced shrinkage and swelling is far more significant than thermal expansion.

The research of Kubler et al. (1973) showed that below 0°C, $\alpha$ values increased considerably for wetwood. This coldness-induced contraction was later a key issue in applied research on timber bridges in cold climates (Kainz and Ritter 1998, Wacker et al. 1998). There, tension rod stress in pre-stressed bridges dropped as a result of sub-freezing temperatures. Kubler et al. noted that below 0°C moisture diffused out of the cell walls and crystallized as ice in the cell cavities even when free water was present.

In that case, free water in the lumina typically has a depressed freeze point due to the presence of solute as governed by Raoults Law. The occurrence of moisture diffusion from the cell walls to the cell lumina is primarily the result of differential vapor pressure. As the temperature decreases, evidently, the vapor pressure in air decreases faster than that of bound water in wood, thereby causing the water to migrate from the cell wall to the air (in the lumina). Once in the lumina, the water quickly crystallizes because it is pure (without solute) and because the inside surface of the cell wall offers many points of seeding about which the water vapor can condense. This condensation and crystallization is not unlike the formation of precipitation in clouds that contain saturated levels of water vapor at subzero temperatures.

The research contained herein builds upon the early work of Kubler et al. related to moisture diffusion from the cell walls

The authors are, respectively, Associate Professor, Forest Products Dept., Forest and Wildlife Research Center, Mississippi State Univ., Mississippi State, MS (rshmulsky@cfr.msstate.edu); and Research Scientist, Faculty of Mechanical Wood Processing, State Forest Academy, Saint Petersburg, Vyborgskaya Storona, Russia (Vladimir_shvets@mail.ru). This paper was received for publication in July 2003. Article No. 9722.
*Forest Products Society Member.

Forest Prod. J. 56(2):74-77.

at subzero temperatures. It was hypothesized that freezing temperatures effectively reduce the fiber saturation point (FSP) of wood. As such, lumber sawn from frozen logs has a reduced amount of bound water at the time of sawing and thus will experience less shrinkage to its in-service condition and less warp due to associated differential shrinkage. The following assumptions were maintained throughout: a) moisture-induced shrinkage is nearly linear between FSP and ovendry (USDA 1999); b) bound water is non-liquid and does not freeze between 0°C and approximately −20°C (Kubler et al. 1973); c) α coefficients for ovendry wood are constant between −50° and 50°C (Panshin and deZeeuw 1970, USDA 1999); and d) moisture-induced dimensional changes are far greater than those related to thermal expansion (Kollmann and Cote 1968, Kubler et al. 1973, USDA 1999).

## Objective

In the research contained here, an attempt was made to partition the shrinkage that is associated with freezing temperatures into true thermal expansion/contraction and moisture-diffusion related shrinkage.

## Procedure

To investigate coldness-induced changes in the FSP of wood, a single cottonwood tree (*Populus* spp.) was sampled. The inside-bark diameter of the tree was approximately 40 cm. The tree was felled in November 2002 and remained outside in Minneapolis, Minnesota until February 2003. For the 6 weeks prior to sampling, the mean temperature was approximately −10°C and the high temperature remained below 0°C. Matched disks were used in order to facilitate rapid moisture equalization at different relative humidity conditions and to minimize variation in the experiment. Disks were selected instead of sawn lumber, lumber sections, or timbers in order to minimize drying stresses and to facilitate rapid moisture and temperature equalization during the experiment. Also, whole tree disks allowed more wood material to be evaluated than would small sections of wood taken from the tree.

Thirteen disks, each approximately 5 cm thick, were cut from the clear stem. Frozen disks were debarked and a stress-relief sawkerf was cut into each. Disks were labeled and measured in the tangential direction, the radial direction, and about the circumference (**Fig. 1**). **Table 1** lists the conditions under which the disks were stored and measured during the experiment. The following paragraph describes the sequence of conditions that was used for treating the disks. After each step (temperature and moisture condition), disk dimensions and weights were measured for calculation of dimensional change and MC, respectively.

Initial processing and measuring were conducted while the disks were at −10°C. Processing included marking the disks for identification and drilling 3-mm-diameter holes in the disks in four principal locations. The holes were used as positive and repeatable points at which to locate the caliper for length measurements. Disks were also weighed for subsequent MC calculation. Next the temperature of the disks was raised to 4°C for 4 days. The disks were then heated to 20°C for 2 days. Finally, the disks were stored in a freezer at −23°C for 5 days. These four steps were used to determine the temperature-related shrinkage (that is, true thermal contraction plus moisture-related shrinkage) behavior at high MC. During these steps, the disks were loosely wrapped in polyethylene to limit moisture loss. For these measurements taken during the

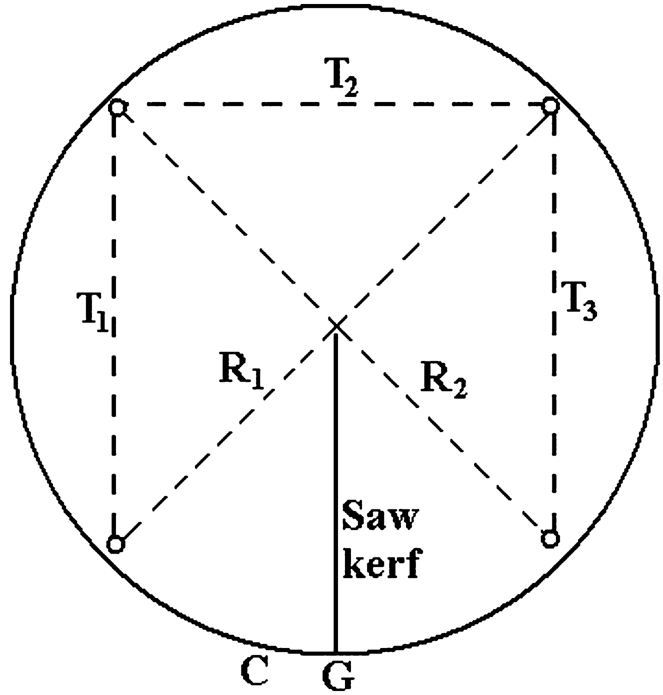


*Figure 1. — Illustration of the three tangential ($T_n$), two radial ($R_n$), circumferential (C), and gap (G) measurement lines per disk.*

*Table 1.—Temperature and moisture conditions.*

| Temperature | Mean MC |
|---|---|
| (°C) | (%) |
| −23 | 115.8 (3.1)[a] |
| −10 | 122.9 (2.1) |
| 4 | 119.8 (1.9) |
| 20 | 118.6 (2.8) |
| 20 | 13.9 (1.4) |
| −23 | 0.3 |
| 20 | 0.2 |
| 101 | 0.0 |

[a]Values in parentheses are standard deviations.

green condition, initial and final average MC values were 123 and 116 percent, respectively. Standard deviations for these MC measurements were 2.1 and 3.2 percent, respectively.

Next the disks were moisture equilibrated at 20°C and 65 percent relative humidity until they reached a constant weight. These conditions correspond to an equilibrium wood MC of approximately 12 percent. At equilibrium, average disk MC was 13.9 percent, MC standard deviation (SD) was 1.4 percent.

The disks were then ovendried and measured at 101°C. The disks were then wrapped in polyethylene, cooled to 20°C, and measured. Finally, the ovendry disks were wrapped in polyethylene, stored at −23°C for 3 days, and measured for the final time.

## Analysis

Moisture-induced dimensional changes at 20°C were used to determine the approximate FSP of the wood. From the three independent MC values (0%, 13.9%, and green) and the mea-

*Table 2.—Calculated FSP and shrinkage values by measurement plane at room temperature.*

| Measurement plane | Average total percent shrinkage | Unit shrinkage | Average calculated percent FSP |
|---|---|---|---|
| | (%) | (% per %ΔMC) | (%) |
| Tangential | 7.5 (1.1)[a] | 0.267 | 28.0 (1.5)[a] |
| Radial | 5.4 (0.44) | 0.206 | 26.0 (3.3) |
| Circumferential | 5.9 (0.55) | 0.176 | 33.7 (2.9) |
| Volumetric | 11.5 | 0.347 | 33.1 |

[a]Values in parentheses are standard deviations.

sured dimensions, the respective tangential, radial, and circumferential shrinkage coefficients were calculated (**Table 2**). The calculated volumetric shrinkage was based on the area of the entire disk. Unit shrinkages (percent shrinkage per percent ΔMC) are also presented in **Table 2**. The midrange MC (i.e., 13.9%) was needed for calculation of the FSP. The total shrinkage values were then divided by the unit shrinkage coefficients to determine the approximate FSP. Because four different measures were recorded, four FSP values were generated. The four calculated FSP values based on tangential, radial, circumferential, and volumetric measures are presented in **Table 2**.

For ovendry wood in the −23° to 101°C temperature range, the tangential, radial, circumferential, and volumetric α values were calculated and are presented in **Table 3**. Regression analysis was used to show the relationship of shrinkage (dependent variable) to temperature (independent variable). This analysis showed that the ovendry α values were linear throughout this temperature range. These α coefficients compare reasonably well with the tangential and radial values for cottonwood published by Kollmann and Cote (1968): $\alpha_t$ 32.6 × $10^{-6}$ and $\alpha_r$ 23.2 × $10^{-6}$ per °C.

As expected for the green wood, sub-freezing temperatures caused excessive shrinkage, that is, thermally induced shrinkage well above and beyond that normally attributed to wood. For this wood in the 0° to −23°C temperature range, the tangential, radial, circumferential, and volumetric α values were calculated and are presented in **Table 4**. These α values were from 10 to 46 times higher than the corresponding values for ovendry wood. Regression analysis showed that these relationships were also linear in this temperature range, similar to those for ovendry wood.

Next, the total observed shrinkage in the green lumber was partitioned into true thermal expansion/contraction, then that was related to moisture diffusion. The difference between the ovendry and green α values was attributed to coldness-induced moisture diffusion out of the cell walls. **Figure 2** uses the observed volumetric shrinkage values to illustrate how these two shrinkage components are related. **Table 5** shows the coldness-induced shrinkage coefficients that are attributed only to moisture diffusion. These shrinkage factors were multiplied by the green wood dimensions and by the absolute difference in temperature below freezing (i.e., |23°C|) to determine the coldness-induced dimensional change related to moisture diffusion at −23°C. The dimensional change was then divided by the green dimension to determine the percent shrinkage caused by moisture diffusion. **Table 5** illustrates these shrinkage percentages.

*Table 3.—Thermal expansion/contraction (α) factors, per degree Celsius for ovendry wood where termperature is the independent variable and shrinkage is the dependent variable*

| Measurement plane | α (−23 to 100 °C) | $r^2$ |
|---|---|---|
| Tangential | 46.3 × $10^{-6}$ | 1.00 |
| Radial | 12.2 × $10^{-6}$ | 0.60 |
| Circumferential | 14.2 × $10^{-6}$ | 0.98 |
| Volumetric | 26.3 × $10^{-6}$ | 0.99 |

*Table 4.—Thermal expansion/contraction (α) factors, per degree Celsius for green wood where temperature is the independent variable and shrinkage is the dependent variable.*

| Measurement plane | α (−23° to 0°C) | $r^2$ |
|---|---|---|
| Tangential | 499 × $10^{-6}$ | 1.00 |
| Radial | 391 × $10^{-6}$ | 0.98 |
| Circumferential | 440 × $10^{-6}$ | 0.80 |
| Volumetric | 1210 × $10^{-6}$ | 0.91 |

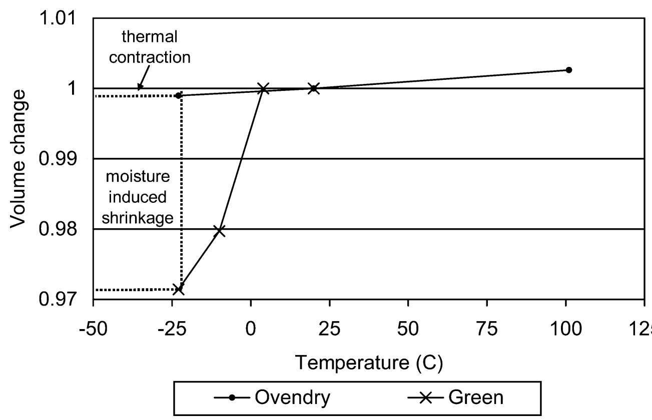


*Figure 2. — Graphical presentation of volumetric shrinkage for ovendry and wetwood by temperature. Volume data points are standardized such that 4°C equals unity.*

*Table 5.—Coldness-induced shrinkage factors per degree Celsius caused by moisture diffusion, based on $\alpha_{green}$ minus $\alpha_{ovendry}$ and total coldness-induced shrinkage coefficients as related to moisture diffusion.*

| Measurement plane | α (−23° to 0°C) | Coldness-induced shrinkage |
|---|---|---|
| | | (%) |
| Tangential | 453 × $10^{-6}$ | 1.04 |
| Radial | 379 × $10^{-6}$ | 0.87 |
| Circumferential | 426 × $10^{-6}$ | 0.98 |
| Volumetric | 1180 × $10^{-6}$ | 2.72 |

Finally, the coldness-induced shrinkage, caused by moisture diffusion, was divided by the total shrinkage values for the four measurement planes. These results illustrate the reduction of bound water in the cell walls caused by the cold temperatures (**Table 6**). As percentages, they are equivalent to the FSP depression caused by the cold temperatures.

## Discussion

The four calculated FSP points show reasonably good agreement among the measurement axes. FSP values ranged

*Table 6.—Percent of total shrinkage caused by coldness-induced moisture diffusion and calculated FSP values at −23°C.*

| Measurement plane | Percent of total shrinkage | FSP at −23°C |
|---|---|---|
| | ----------------(%)---------------- | |
| Tangential | 13.9 | 24.1 |
| Radial | 16.3 | 21.7 |
| Circumferential | 16.5 | 28.2 |
| Volumetric | 23.6 | 25.3 |

from 26.0 to 33.7 percent. The tangential, radial, and volumetric shrinkage values, 7.5, 5.4, and 11.5 percent, respectively, agreed reasonably well with the respective published values from the USDA (1999), i.e., 7.1, 3.0, and 10.5 percent.

The coldness-induces shrinkage of wetwood, greater than 115 percent MC, was at least an order of magnitude higher than that for ovendry wood. This difference strongly suggests that in wetwood as the temperature decreases below 0°C, moisture migration from the cell walls to the cell lumina occurs and manifests itself as moisture-related shrinkage. In essence, at subzero temperatures the water vapor pressure in cell lumina must be lower than that of bound water in the cell walls. This observed difference in shrinkage behavior between wetwood and drywood supports the hypothesis and past research findings that bound water migrated out of the cell walls at subzero temperatures, despite the fact that ample bulk water was present in the cell lumina.

From this experiment, the proportional reduction in the maximum amount of bound water that cell walls can hold at freezing temperatures was determined. This change was noted at MC levels well above 100 percent. Thus, in essence, the FSP of wetwood is depressed at subzero temperatures. This being the case, there is strong reasoning to support the notion that warp reduction in lumber can be achieved by sawing logs at subzero temperatures. One of the strongest factors that influences warp in lumber is uneven and differential shrinkage. This research illustrates the impact that sub-freezing temperatures have on wood shrinkage. Therefore, this factor is a likely contributor to the noted improvement in quality for lumber sawn from frozen logs.

## Literature cited


Kainz, J.A. and M.A. Ritter. 1998. Effect of cold temperatures on stress-laminated timber bridge decks. *In*: Proc. 5th World Conf. on Timber Engineering. J. Natterer and J.L. Sandoz, eds. Swiss Federal Institute of Technology, Lausanne, Switzerland.

Kollmann, F.F.P. and W.A. Cote, Jr. 1968. Principles of Wood Science and Technology. Springer-Verlag, New York.

Kubler, H., L. Liang, and L.S. Chang. 1973. Thermal expansion of moist wood. Wood and Fiber 5(3):257-267.

Panshin, A.J. and C. deZeeuw. 1970. Textbook of Wood Technology. Vol. I, 3rd ed. McGraw-Hill, New York.

USDA Forest Service, Forest Products Laboratory (USDA). 1999. Wood Handbook: Wood as an Engineering Material. Forest Prod. Soc., Madison WI.

Wacker, J.P., R. Seavey, and R.W. Erickson. 1998. Cold temperature effects on stress-laminated timber bridges. *In*: National Conf. on Wood Transportation Structures. M.A. Ritter et al., eds. FPL-GTR 94. USDA Forest Serv., Forest Prod. Lab., Madison, WI.