Impact of Hygrothermal Gradients on Juvenile Wood

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ABSTRACT

The longitudinal thermal and hygrocoefficients of expansion properties of solid wood cause it to deform spatially when it is subjected to hygrothermal gradients that are perpendicular to the longitudinal or wood fiber direction. This phenomenon has been evidenced with structural members located in the thermal envelope of residential buildings in cold climates. An ever-increasing volume of dimensional lumber is juvenile wood (wood near the pith of the tree), which has a larger longitudinal hygrocoefficient of expansion than mature wood; this will lead to an increase in the frequency and severity of spatial deformation of wood due to hygrothermal gradients.

This paper describes research that examines the behavior of solid wood, both juvenile and mature, when it is subjected to hygrothermal gradients. Specific gravity, S2 microfibril angles, and longitudinal hygrocoefficients of expansion are determined through the depth of the wood test samples to evaluate the role they play in the deformation that takes place.

INTRODUCTION

Wood is commonly used in thermal envelopes of buildings as a structural element or as a component of openings such as windows and doors. In cold climates, where the vapor retarder is located on the warm side of the wall, the vapor pressure across the space filled with a porous insulation is fairly uniform and tends toward the vapor pressure that is found outside. Therefore, during the winter, a stud contained in the thermal envelope will develop a large thermal gradient across its width but will be surrounded by a uniform vapor pressure, which gives rise to a large relative humidity gradient in the wall cavity. These conditions lead to the development of moisture content (MC) gradients or hygrogradients through the width of wood structural elements, such as studs.

There have been numerous reports of exterior walls bowing outward during the winter in cold climates. In the kitchen, this has led to a seasonal gap appearing between the kitchen counter backsplash and the exterior wall. Builders in Minnesota have reported eight-foot walls bowing out 3/4-inch (19 mm) every winter, and window manufacturer's have experienced field problems with deformation of wood casement windows so that they become inoperable each spring.

The moisture content gradients that develop have not caused pronounced problems in the past because most wood came from unmanaged forests where the ratio of juvenile wood to mature wood was very low. However, today's wood from managed forests contains a greater percentage of juvenile wood because of the shorter rotations (Smith and Briggs 1986; Youngs and Erickson 1984; Barrett and Kellogg 1986). Because juvenile wood has a higher longitudinal hygrocoefficient of expansion than mature wood, there are more frequent and pronounced cases of deformation or crook developing in thermal envelopes.

Much of the research done on juvenile wood has focused on its specific gravity and strength in comparison to mature wood (Senft et al. 1986; Bendtsen and Senft 1986; Bendtsen 1978; Pellerin et al. 1989; Pearson et al. 1988). Juvenile wood research has also examined S2 microfibril angle and longitudinal hygrocoefficients of expansion (Keith and Chauret 1988; Smith and Briggs 1986; Meylan 1968).

Figure 1 (Haygreen and Bowyer 1989) shows the layering of a mature cell wall and identifies the S2 layer of the secondary wall, which is comparatively thick and dominates the dimensional behavior of the cell as it gains or loses adsorbed water. The S2 layer consists of bundles of cellulose molecules (microfibrils) that are laid down with a

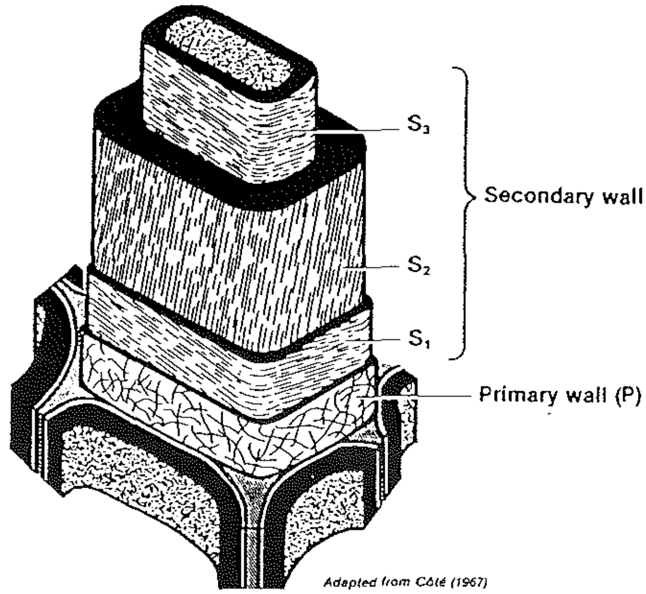

Figure 1 *Layering of a mature cell wall.*

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small angle to the long axis of the cell. Because these microfibrils are almost parallel to the long axis of the tree, the longitudinal hygrocoefficients of expansion are usually very small. But juvenile wood, which constitutes the first 15 to 20 years of growth (depending on species) from the pith, lays down S2 microfibrils with a pronounced angle to the long axis of the cell. Therefore, juvenile wood has higher longitudinal hygrocoefficients of expansion than the mature wood that is formed after 15 to 20 years' growth from the pith (Meylan 1968, 1972). The transition of properties and anatomical features from juvenile to mature wood is gradual over the time span involved.

This study examined the response of solid wood, both mature and juvenile, to hygrothermal gradients as found in the thermal envelopes of buildings located in cold climates.

EXPERIMENTAL DESIGN

Species of Wood and Sample Preparation

The wood species selected for the research was lodgepole pine (Pinus contorta) that came from western Canada. This species of wood commonly provides the studs used for residential construction in the north central part of the United States.

Ten 2-in. (38 mm) by 6-in. (140 mm) by 104 ⅝-in. (2,658 mm) precision end-trimmed studs were selected at a local builders' supply center. They were quartersawn (growth rings were perpendicular to the wide face) and contained the pith.

At the laboratory, chalk lines were snapped end-to-end on the wide face of each stud to obtain two smaller pieces. One piece contained juvenile wood with the pith located on one face, and the other consisted of mature wood. The age span in each of these pieces was recorded.

Each juvenile and the other mature wood piece obtained from a stud was ripped to produce a quartersawn ⅜-in. (9.5 mm) by 1½-in. (38 mm) by 104 ⅝-in. (2,658 mm) strip. All the strips produced from the initial ten studs were visually examined for defects, and the strips from studs 2, 3, 7, and 9 were selected for the experiment. These numbers are used throughout this paper to identify material from the respective studs. A stud number followed by a J or an M indicates that the material is either juvenile or mature, respectively. For example, 9M means mature wood from stud number 9.

Each full-length strip was crosscut to yield two strips, one of which was 48 in. (1,219 mm) long. This 48-in. (1219-mm) strip contained the clearest, highest-quality wood and was used to measure crook. The remaining length was crosscut into five pieces, as shown in Figure 2. One piece, 4 in. (101.6 mm) long, was used to determine the temperature profile from the warm to the cold edge of the crook samples during the experiment. The temperatures were determined using type-T thermocouples (which were calibrated in an ice bath) that were inserted into the 1½-in. (38-mm) face of the piece at the center of successive ¼-in. (6.4-mm) increments of depth. These incremental depths are hereafter referred to as sections, and, since each piece was 1½-in. (38-mm) deep, it contained six sections.

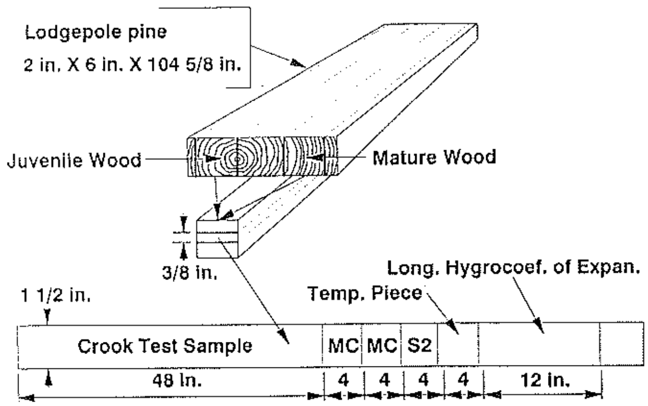

Figure 2 Breakdown of experimental material.

Because it was known from preliminary work that the moisture content would increase the most near the cold face, the crook sample from juvenile wood was placed in the thermal panel with the pith edge facing the freezer. The mature wood was placed in the thermal panel with the edge nearest the pith facing the warm environment. These orientations were intended to maximize the differential in crook development for the two sample types.

Two pieces 4 in. (102-mm) long were inserted in the thermal panel to determine the moisture content gradient when the crook had stabilized—one for each of the two freezer temperatures. When removed, each piece was ripped into six strips measuring 4 in. (101.6 mm) by ⅜ in. (9.5 mm) by approximately ¼ in. (6.4 mm). Each strip was weighed immediately after ripping, placed in an oven at 220°F (104°C) for at least 24 hours, and then reweighed to get moisture contents that were calculated based on the oven dry weight.

The fourth piece of 4-in. (102-mm) length was used to evaluate the S2 microfibril angle for each ¼-in. (6.4-mm) increment of depth through the test sample.

The fifth piece, 1 foot (305 mm) long, was used to measure the longitudinal hygrocoefficients of expansion through the depth of the test sample.

Experimental Setup

Figure 3 is a cross section of the experimental setup. The test samples used to measure deformation (crook) were placed in slots contained in a thermal panel made of extruded expanded polystyrene that was 1½ in. (38 mm) thick. The warm air circulated above the thermal panel was conditioned to 72°F (22°C) and 40% RH, while the freezer air was first maintained at 16°F (−9°C) and 85% RH and then subsequently at −18°F (−28°C) and 90% RH.

Also shown in the figure is a spun-bonded polyolefin membrane that was placed on the cold side of the thermal

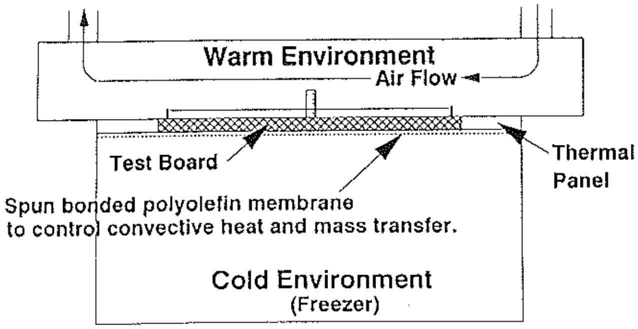

Figure 3 *Experimental setup for evaluating the response of juvenile and mature wood to hygrothermal gradients.*

panel to control convective heat and mass transfer. A fan "pulled" the conditioned air through the warm environment, thus reducing the potential of convective mass transfer from the warm side to the cold side of the panel and condensation on the wood samples.

Each of the four test samples in the thermal panel was 48 in. (1,219 mm) long, 1½ in. (38 mm) wide, and ⅜ in. (9.5 mm) thick and was contained in its own individual slot. The four samples came from two parent boards, each of which provided two test samples. One was predominantly juvenile wood and the other was predominantly mature wood (see Figure 2). A total of four parent boards provided eight experimental samples.

A screw with the head removed and the shank split and spread was inserted 1 inch (25.4 mm) in from the ends of each test sample and extended upward into the warm environment. A mono-filament line was tightly stretched and secured between the corresponding halves of the split shanks. Thus there were two parallel lines running from one end of the test sample to the other. A plastic ruler was secured vertically between the parallel lines to the top face of the sample at mid-length. The installation is illustrated in Figure 3. The double lines eliminated parallax and ensured an accurate reading of the vertical displacements of each sample.

Samples for monitoring moisture content were also contained in slots that were machined into the thermal panel. These moisture content samples were removed periodically from the thermal panel and weighed to the nearest 0.001 grams. When they attained constant weight, it was assumed that the hygrogradient had attained a steady state. Once steady state was attained with the cold environment at 16°F (−9°C), the temperature was dropped to −18°F (−28°C) and deformation was remeasured until the hygrogradient had reached its new steady state.

Measurement of S2 Microfibril Angle

The angle of the microfibrils in the S2 layer of the secondary wall was measured using a polarizing light microscope following the procedure described in an article by Leney (1981).

The procedure involves microtoming wood samples in the longitudinal-radial plane so that, after maceration, fibers are split. This allows for passing polarized light through a single radial wall of the wood fiber and thus ascertaining the S2 microfibril angle.

For boards 7 and 8, 24 microfibril angle readings were averaged to obtain an angle for each ¼-in. (6.4-mm) depth through the test samples. For boards 2 and 3, 50 microfibril angle readings were averaged to obtain an angle for each ¼-in. (6.4-mm) depth. The reason for the increase in readings was that boards 7 and 8 were done first and a large standard deviation was found, suggesting that more readings should be taken. However, the 50 readings also had a large standard deviation. It was concluded that the lumping together of fibers from both early wood and late wood from several years of growth caused the large standard deviation.

Longitudinal Hygrocoefficient of Expansion

Longitudinal hygrocoefficients of expansion were determined for each ¼-in. (6.4-mm) depth of the 1-foot-long samples that were matched along the grain to the crook samples. Each piece was cut longitudinally to produce six equal sticks measuring ⅜ in. (9.5 mm) by ¼ in. (6.4 mm) by 12 in. (305 mm) that were oven dried, weighed, and then measured for length to the nearest 0.001-in. (0.025-mm). Following this, a series of saturated salt solutions at room temperature were used to progressively increase their moisture content. When the equilibrium moisture content (weight) had been reached for each salt solution, the weight and length of the sticks were again determined. Finally, the sticks were equilibrated to constant weight in the saturated atmosphere of distilled water maintained at room temperature. These data were used to develop an equation to predict longitudinal swelling as a function of moisture content, i.e., the longitudinal hygrocoefficient of expansion. Due to hysteresis, the dimensional change during desorption will be different.

Statistical Analysis

The following model was used to statistically analyze the crook data:

$$Y = \mu + \alpha_i + \beta_j + \tau_k + \alpha\beta_{ij} + \alpha\tau_{ik} + \beta\tau_{jk} + \alpha\beta\tau_{ijk},$$

where

Y = crook,
μ = mean,
α = tree (i=1,2,3,4),
β = wood type (juvenile/mature: j=1,2), and
τ = hygrothermal gradients (k =1,2).

RESULTS

S2 Microfibril Angle

Table 1 contains the data on S2 microfibril angles. For each board number, the highest angle occurs in growth rings nearest the pith. Section 1 from the juvenile wood of board 2 has the highest average angle of 34.6°, which is an average for the first five years of growth from the pith. For juvenile test boards, the lowest angle of 3.3° is found in sections 5 and 6 of 7J. This actually could be mature wood, as it is found in the transition zone between juvenile and mature wood. The age span of these two sections is 14 to 21 years. The juvenile wood of this particular board has unusually low microfibril angles even right next to the pith, where the second through fourth years of growth have an average angle of 9.8°.

Mature wood test samples range from a minimum microfibril angle of 3.0° for section 3 of board 7M to a maximum angle of 15.1° for section 4 of board 3M.

It can be seen from the data in Table 1 that the microfibril angle does indeed remain low and constant after the approximate age of 15 years as found by others.

TABLE 1
Specific Gravity, S2 Microfibril Angle, and Swelling and Age Properties of Each Section Through the Depth of the Test Boards

Brd. #	Section	Age Range	Specific Gravity[1]	S2 Angle[2]	% Swelling[3]	Brd. #	Section	Age Range	Specific Gravity[1]	S2 Angle[2]	% Swelling[3]
2J	1	1-5	.37	34.6	.33	7J	1	2-4	.36	9.8	.20
	2	4-9	.37	26.4	.27		2	4-6	.37	5.6	.21
	3	8-13	.38	16.8	.24		3	7-10	.36	5.1	.20
	4	12-16	.40	20.9	.24		4	10-13	.40	4.5	.18
	5	16-22	.41	11.5	.23		5	14-17	.39	3.3	.17
	6	21-29	.40	9.3	.19		6	17-21	.48	3.3	.15
2M	1	20-24	.41	13.2	.18	7M	1	8-14	.36	3.8	.18
	2	23-28	.40	10.9	.18		2	13-20	.39	3.5	.18
	3	27-33	.40	9.32	.17		3	18-29	.39	3.0	.19
	4	31-37	.41	10.8	.16		4	28-33	.40	7.5	.22
	5	35-43	.43	7.82	.16		5	32-28	.42	8.1	.18
	6	41-47	.43	7.96	.17		6	37-44	.42	5.1	.18
3J	1	1-7	.41	21.4	.28	9J	1	1-3	.37	15.8	.31
	2	4-9	.43	13.6	.24		2	2-5	.38	19.5	.30
	3	8-13	.43	12.1	.23		3	4-6	.36	15.5	.28
	4	12-17	.42	7.9	.23		4	5-7	.38	16.5	.26
	5	17-22	.43	6.4	.21		5	7-9	.39	10.3	.24
	6	22-29	.45	5.5	.19		6	8-11	.39	11	.22
3M	1	21-23	.49	14.1	.23	9M	1	12-15	.38	5.7	.21
	2	23-26	.48	13.6	.21		2	15-18	.40	6.7	.19
	3	26-30	.46	12.7	.18		3	18-21	.43	9.6	.15
	4	30-35	.46	15.1	.18		4	21-26	.45	8.6	.14
	5	35-39	.50	10.6	.15		5	25-37	.48	10.7	.13
	6	40-44	.47	11.6	.14		6	37-52	.47	6.8	.14

[1]Specific gravity based on oven dry weight and green volume.
[2]S2 Microfibril angle is the average of 24 readings for boards 7J, 7M, 9J and 9M, and 50 readings for boards 2J, 2M, 3J and 3M.
[3]% swelling based on dimensional change from 0% MC to the fiber saturation point (30% MC) and oven dry length.

Longitudinal Hygrocoefficient of Expansion

In Table 1, the general trend for all the boards is that the swelling from 0% moisture content to the fiber saturation point (30% moisture content) is highest near the pith and decreases as the wood becomes more mature. Section 1 of board 2J, which has the highest S2 microfibril angle, also has the highest percent swelling of 0.33. Section 5 from board 9M had the lowest percent swelling (0.13).

Figures 4 and 5 show the exponential relationship between percent moisture content and percent longitudinal dimensional change, based on oven-dried length.

Moisture Content Gradients

In Figure 6 it is seen that when the cold environment was at 16°F (−9°C), the average moisture content for section 5 of boards 2 and 3 was the highest at 10.9%, based on oven-dried weight. In Figure 7, sections 4 and 5 from boards 7 and 9 both had a moisture content of 12.2%. This is about a 1% moisture content increase for boards 2 and 3 and a 2% increase for boards 7 and 9 compared to the respective initial moisture contents.

The maximum moisture content increased dramatically when the cold-environment temperature was lowered to −18°F (−28°C). In Figure 6, section 5 of boards 2 and 3 increased to an average moisture content of 14.4%. Section 5 of boards 7 and 9 in Figure 7 increased to a moisture content of 16.4%. Thus section 5 increased 4.5% in moisture content for boards 2 and 3 and 6.5% for boards 7 and 9 compared to their respective initial moisture contents.

Figure 7 shows that at a cold-environment temperature of 16°F (−9°C), the largest difference of 2.1% moisture content was found in boards 7 and 9 between sections 1 and 4, while at a temperature of −18°F (−28°C), the greatest difference was 6.7%. In Figure 6 the greatest differences in average section moisture contents were 1.0% and 4.0% for temperatures 16°F (−9°C) and −18°F (−28°C), respectively.

Crook Due to Hygrothermal Gradient

The thermocouple readings indicate that the temperature gradients were established in less than one hour, and, seen in Figures 8 through 11, the effect of the thermal gradient upon crook was almost immediate. The longitudinal thermal contraction of the cold edge of the board caused crooking of the boards toward the warm environment. This upward crooking (i.e., crook became smaller) was most clearly evident when the cold-side temperature was lowered from 16°F (−9°C) to −18°F (−28°C).

The rapid effect of the thermal gradient upon crook was followed by a more time-dependent effect of the hygrogradient upon crook.

The establishment of a steady-state hygrogradient took about 500 hours, as determined by the moisture content gradient pieces in the thermal envelope that were weighed every few days to monitor weight change. Meanwhile, it appears from Figures 8 through 11 that the developing hygrogradients had their major impact on crook within 100 to 200 hours when the cold environment was 16°F (−9°C) and within about 500 to 600 hours after the cold-environment temperature was dropped to −18°F (−28°C).

It can be seen from the figures that the hygrogradients developed in this experiment have more impact on crook

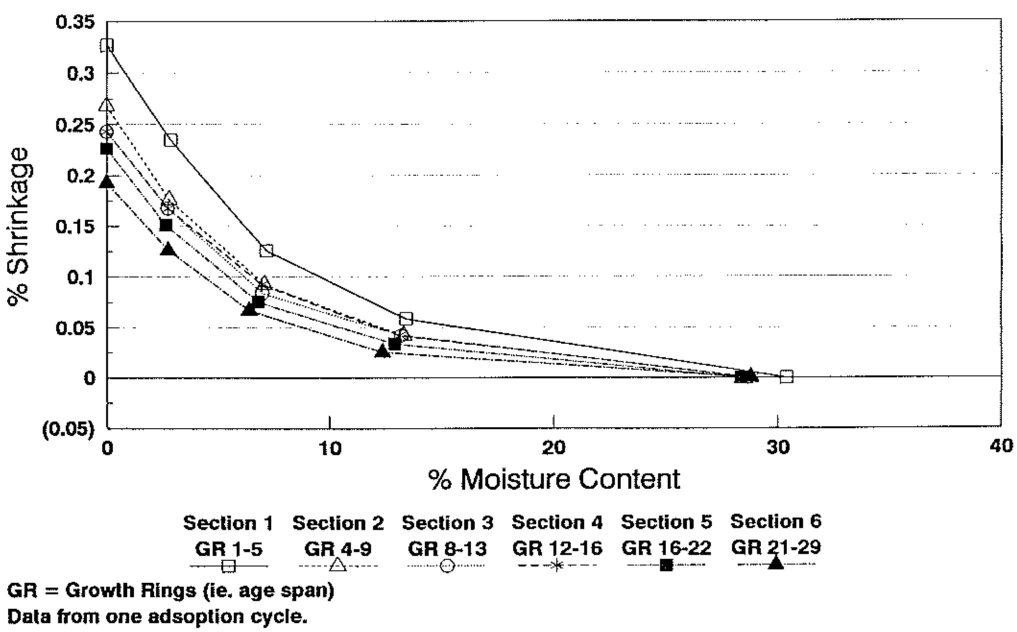

Figure 4 *Longitudinal shrinkage vs. moisture content for juvenile wood of board 2.*

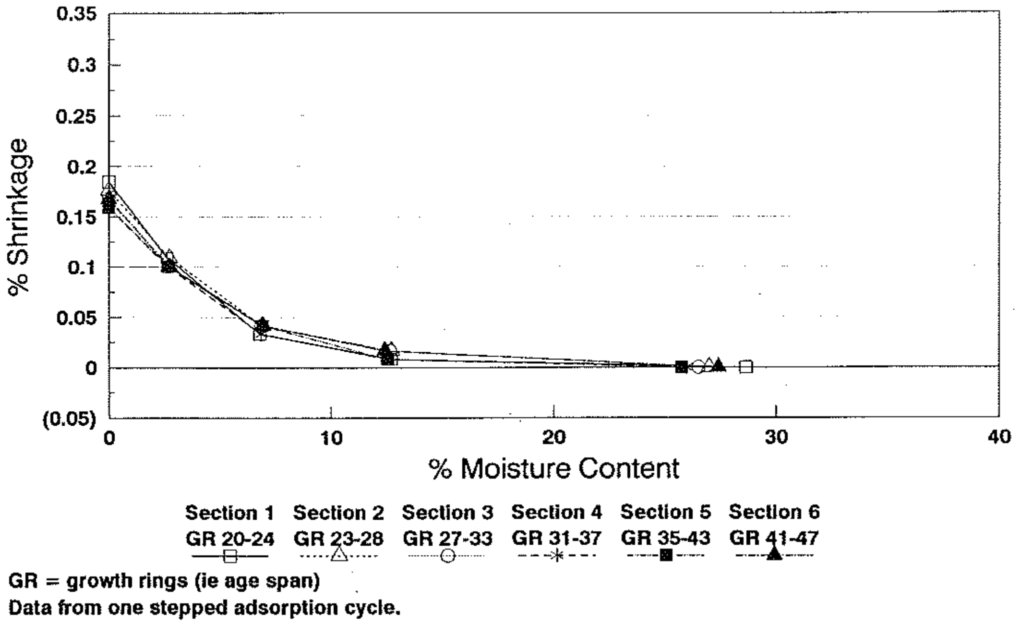

Figure 5 *Longitudinal shrinkage vs. moisture content for mature wood of board 2.*

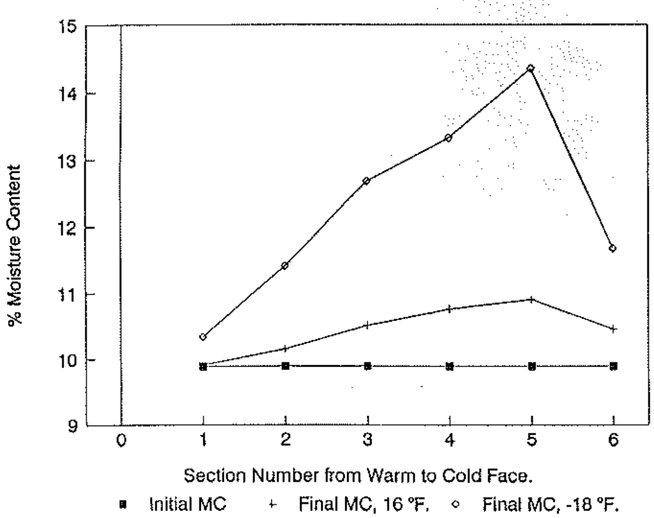

Figure 6 *Final moisture content gradients for boards 2 and 3.*

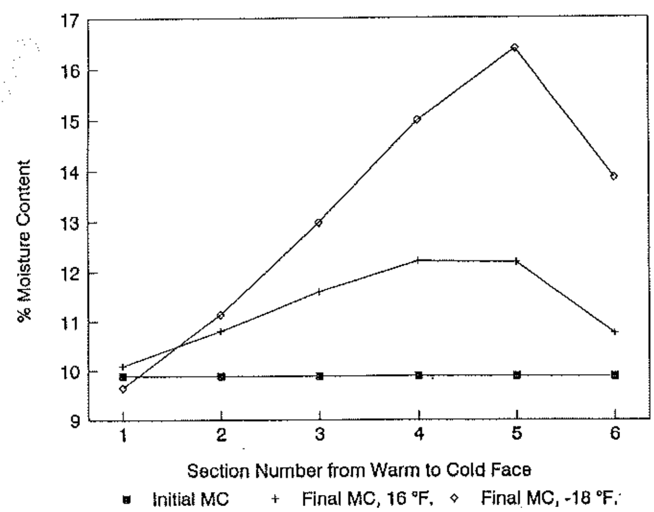

Figure 7 *Final moisture content gradients for boards 7 and 9.*

than the thermal gradients. For example, in Figure 8, the thermal gradient near time 0 caused 2J to crook from 0 to −0.03 in. for a total change of 0.03 in. (.76 mm). Then, as the hygrogradient established itself (from just after 0 hours to just before 500 hours), the board deformed from −0.03 in. to 0.04 in., for a total change of 0.07 in. (1.78 mm).

Figures 8 through 11 show the development of crook for juvenile and mature wood over time as they equilibrated to each of the hygrothermal gradients to which they were subjected. It is evident that for all conditions and all boards, with the exception of board 2 at a cold environment of 16°F (−9°C), the samples containing juvenile wood crooked more than the samples containing mature wood.

In Figure 9, board 3 demonstrates the difference between juvenile wood and mature wood most dramatically. When the cold environment was at a temperature of 16°F (−9°C), the juvenile wood crooked more than two times as much as the mature wood. Under the conditions of −18°F (−28°C), the juvenile sample crooked more than four times as much as the mature wood.

In Figure 10, the mature wood from board 7 crooked more than any other of the mature wood samples and yet had the lowest average distribution of S2 microfibril angles through its sections (see Table 1). Its largest average angle was 8.1° and was found in section 5. It is possible that this may be attributed to the existence of spiral grain but was not examined.

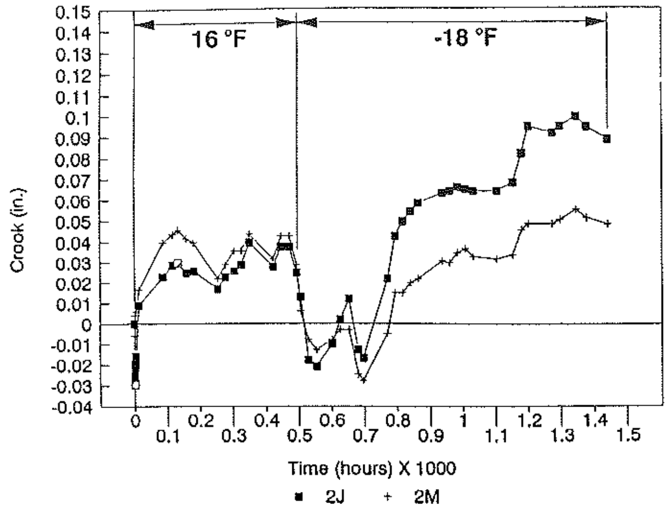

Figure 8 *Crook of juvenile and mature wood from board 2.*

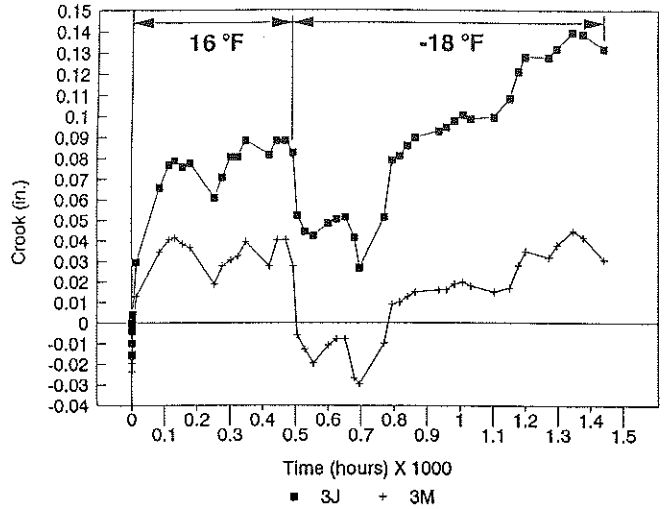

Figure 9 *Crook of juvenile and mature wood from board 3.*

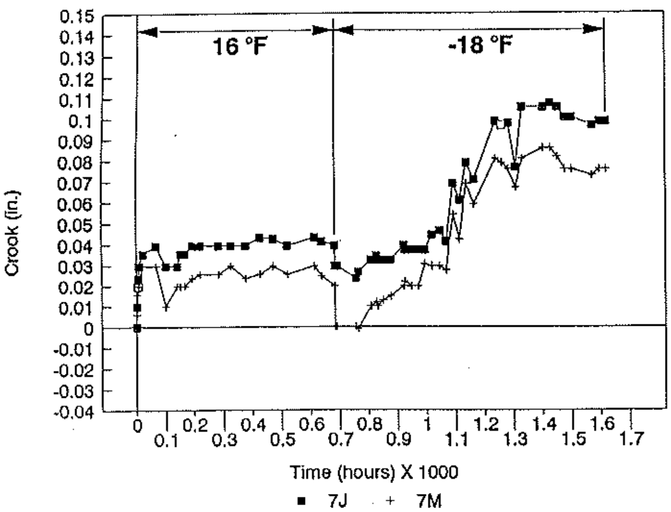

Figure 10 *Crook of juvenile and mature wood from board 7.*

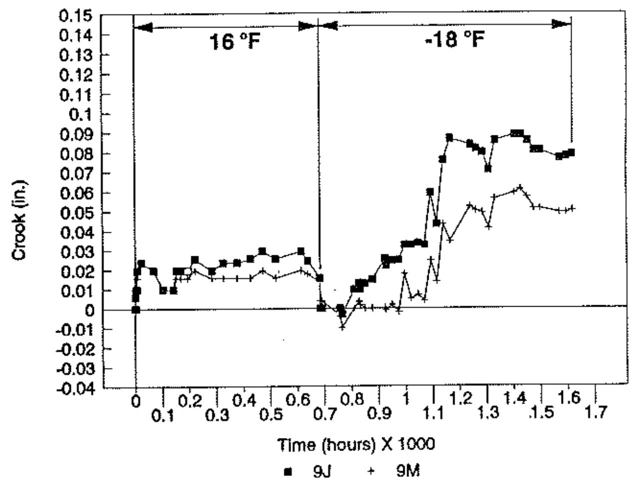

Figure 11 *Crook of juvenile and mature wood from board 9.*

The mature wood sample from board 3 shown in Figure 9, which has the highest average distribution of S2 microfibril angles of all the mature wood samples, did not increase in crook when the temperature in the cold environment was dropped to −18°F (−28°C) as did all other boards both mature and juvenile.

Statistical Analysis

The analysis of variance in Table 2 shows that there is statistical significance to juvenile wood deforming more than mature wood for the material and the hygrothermal gradients used in this experiment. In addition, the increase in deformation, or crook, as the temperature gradient increased is also statistically significant for these conditions.

DISCUSSION

It is evident from this experiment that hygrothermal gradients cause both juvenile and mature wood to crook. The moisture content gradient that developed from the cold to warm face causes differential swelling/shrinking in the piece of wood, which leads to its deformation, or crook. The higher longitudinal hygrocoefficients of expansion found in juvenile wood cause it to crook more than mature wood for the same given hygrothermal gradients.

These experimental results support field reports of exterior walls bowing outward during the winter months. Moreover, the cyclical deformation that window manufacturers have experienced with wood casement windows during the winter could be due in part to the presence of hygrothermal gradients.

TABLE 2
Analysis of Variance for Crook of Juvenile and Mature Wood Subjected to Two Hygrothermal Gradients

Source	DF	SS	MS	F	P
Tree (α)	3	1.7188E-03	5.7294E-04	4.2	0.1345
Hygrothermal Gradients (τ)	1	6.9514E-03	6.9514E-03	50.99	0.0057
Wood (β)	1	4.4256E-03	4.4256E-03	47.51	0.0063
$\alpha * \beta$	3	2.6704E-03	8.9014E-04	9.56	0.0481
$\beta * \tau$	1	8.8061E-03	8.8061E-04	9.45	0.0544
Error	6	6.8840E-04	1.1473E-04		
TOTAL	15	1.7335E-02			
GRAND AVG.	1	4.7535E-02			

The juvenile wood of board 3 crooked 0.14 in. (3.6 mm) in a 46-in. (1,168.4-mm) span. Assuming a similar moisture content gradient and radius of curvature in a stud (92 ⅝ in. [2,353 mm] long), the amount of crook would be 0.28 in. (7.1 mm).

In fact, the crook of a stud in an exterior wall would be worse than this for the following reasons. The moisture content gradient for 3J was 10.4% (section 1) to 14.4% (section 5) (see Figure 6). If exterior conditions were −10°F (−23°C) and 70% relative humidity and interior conditions were 70°F (21°C) and 40% relative humidity, hygrothermal gradients can be estimated using steady-state techniques for a residential exterior wall described in the *ASHRAE Handbook* (ASHRAE 1985). A wall composed of drywall, vapor/air retarder (i.e., no convective mass transfer), R-19 (3.34 [$m^2 \cdot °C$]/W) fiberglass insulation, 1 in. (25.4 mm) polystyrene sheathing and lap siding will create a cavity environment that will lead to a 10% moisture content difference between the warm face and cold face of a 2-in. by 6-in. (38-mm by 140-mm) stud. The moisture content of the warm face will be around 3% while that of the cold face will be around 13%. This moisture content gradient lies in the region where the hygrocoefficient of expansion is large compared to the experimental gradient, which is near 12% moisture content, above which there is very little longitudinal change (see Figures 4 and 5).

In addition, the polystyrene thermal panel forced moisture diffusion to take place from the warm to the cold face of the wood test samples. In Figure 6 it can be seen that section 6 had a lower moisture content than section 5. The effect of a lower moisture content in section 6 is to reduce or restrain section 5 from expanding and thus reducing the overall deformation or crook. In an exterior wall stud, the diffusion will primarily be perpendicular to the wide face, and the moisture content gradient should be linear from the warm to the cold face with the section on the cold face having the highest moisture content. This means that the reduction in deformation or crook that took place due to section 6 in the experiment will not occur in the studs of exterior walls.

Because the crook of the wood test boards increased as the temperature gradient increased, it can be assumed that as climates subject thermal envelopes to larger temperature gradients, keeping all other things constant, one can expect greater amounts of bowing in exterior walls.

One way to deal with the problem is to reduce the thermal gradient to which the stud is subjected in the exterior wall. This can be done by the use of curtain wall construction, which would locate the stud inside all or most of the thermal resistance of the exterior wall. This would also permit the vapor retarder and the air barrier to be placed between the insulation and the stud, where they would be protected from abuse, and allow the stud cavity to be used as a plumbing and electrical chase. In addition, residential construction could reduce the width of the stud as the depth for insulation would no longer be needed.

Another approach to dealing with the problem would be to develop trees that produce juvenile wood with low longitudinal hygrocoefficients of expansion or to take an integrated management approach to forestry, which designates certain forests to provide the mature wood needed for wood products used in the thermal envelopes of buildings (Barrett and Kellogg 1986).

CONCLUSIONS

1. The test samples from four 2-in. by 6-in. (38-mm by 140-mm) dimensional lumber studs (lodgepole pine) used in this experiment show that both juvenile wood and mature wood crook when subjected to hygrothermal gradients.
2. Juvenile wood crooked more than mature wood for the two hygrothermal gradients used in this experiment. In

one instance, juvenile wood crooked more than four times as much as mature wood from the same tree.

3. An increase in the hygrothermal gradients across the depth of the wood test samples used in this experiment led to an increase in the amount of crook or deformation.

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