EFFECT OF LOW RELATIVE HUMIDITY ON PROPERTIES OF STRUCTURAL LUMBER PRODUCTS

David W. Green†
Supervisory Research General Engineer

and

James W. Evans
Supervisory Mathematical Statistician
USDA Forest Service
Forest Products Laboratory[1]
Madison, WI 53726-2398

(Received July 2002)

ABSTRACT

Wood used in industrial settings, and in some arid parts of the United States, may be subjected to very low relative humidity (RH). Analytical models available for predicting the effect of moisture content (MC) on the properties of solid-sawn lumber imply significant strength loss at very low MC. However, these models are generally valid only for MC above about 10%. The objective of this study was to evaluate the flexural and tensile properties of standard 38- by 89-mm (nominal 2- by 4-in.) dimension lumber equilibrated at 15% RH compared with lumber at 65% RH. Testing was done on solid-sawn lumber, laminated veneer lumber (LVL), and laminated strand lumber (LSL). The results of this study indicate that modulus of elasticity (MOE) in transverse vibration was about the same for lumber equilibrated at 15% and 65% RH for solid-sawn lumber and LVL, whereas LSL, at 15% RH was slightly higher in MOE than that at 65% RH. For solid-sawn lumber, the modulus of rupture (MOR) at 15% RH was found to be up to 8% less than that at 65% RH, whereas there was little difference between the two RH levels for LVL and LSL. The ultimate tensile stress of solid-sawn lumber and LVL was found to be about 10% lower at 15% RH, but there was little difference between the two RH exposures for LSL. The models of the American Society for Testing and Materials standard D1990 predicted the average shrinkage of the solid-sawn lumber, but none of the models adequately predicted mechanical properties after equilibration at 15% RH compared with those at 65% RH. Procedures are suggested for estimating allowable properties at 4% MC from currently assigned properties at 15% MC.

Keywords: Lumber, laminated veneer lumber, laminated strand lumber, modulus of rupture, modulus of elasticity, ultimate tensile stress, moisture content.

INTRODUCTION

Moisture content is one of the most important factors that can affect the properties of wood (Forest Products Laboratory 1999). It has historically been assumed that as MC decreases from green to oven-dry, most mechanical properties increase (Gurfinkel 1981). This is not always true for clear wood (Wilson 1932), and in recent years, it has been shown that this may also not be true with some lumber properties (Green and Evans 1989). However, the lumber data are limited to MC above about 8% and provide little guidance on the behavior of lumber at very low MC. In addition, there is only limited information about the effect of MC on the mechanical properties of structural composite lumber.

The MC of wood depends upon the temperature and RH of the surrounding air. If the

---

[1] The Forest Products Laboratory is maintained in cooperation with the University of Wisconsin. This article was written and prepared by U.S. Government employees on official time, and it is therefore in the public domain and not subject to copyright.

The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

† Member of SWST.

Wood and Fiber Science, 35(2), 2003, pp. 247–265

wood stays for long enough at a constant temperature and RH, the MC will reach an equilibrium moisture content (EMC). For most of the United States, the average recommended EMC for wood in exterior exposure is 12% (Forest Products Laboratory 1999; Simpson 1998). However, for wood in exterior exposure in parts of the southwest, the EMC may average only 6% and individual pieces may reach EMC of 4% or less. During the winter in the interior of houses in northern climates, EMC as low as 6% may also be attained (Boise 1959; Harrje et al. 1986). Even in such relatively humid locations as Louisiana, the MC of roof rafters may be near 8% for much of the year (Hopkins 1962). Low MC could contribute to performance problems, such as those associated with seasonal arching of trusses (Gorman 1985). Low MC may also occur in commercial and industrial buildings where spans are significantly longer than those generally found in housing. In these situations, environmental factors may be of greater concern.

The objective of this paper is to compare the properties of solid-sawn and composite lumber products tested in bending and in tension parallel to the grain after equilibration to room temperature at 65% and 15% RH (anticipated 12% and 4% MC for solid-sawn lumber). The paper provides information that can be used to make engineering judgments about the properties of lumber at low MC. The study was limited to standard 38- by 89-mm (nominal 2- by 4-in.) lumber sizes.

BACKGROUND

Clear wood properties

Bending.—Wilson (1932) developed an exponential formula for relating mechanical properties of clear wood to change in MC (Forest Products Laboratory 1999).

$$P = P_{12}(P_{12}/P_g)^{((12-M)/(M\mathrm{p}-12))} \qquad (1)$$

where P is the property to be calculated at moisture content M (%), P_{12} is the same property at 12% MC, P_g is the same property for green wood, and M_p is the MC above which properties do not change with changing MC. M_p varies by species (Forest Product Laboratory 1999) but is approximately 25% for most species.

In comparing this empirical relationship with his data, Wilson notes

> *In making this comparison points representing the sets of specimens tested at the lowest moisture content were omitted because the tendency, observed in some instances, for these points to fall below the inclined lines averaging other points of the same series suggested either that drying to so low a moisture content had resulted in injury to the strength properties or that the assumed straight-line relation between percentage of moisture content and the logarithm of the strength property would not hold for very low moisture-content values.*

Data points for the lowest MC levels were dropped from the analysis, and therefore, the model should not have been applied to MC below about 8%. Historically, however, no specific lower MC limits were recommended for the formula (Forest Products Laboratory 1935).

There have been many studies on the effect of MC on the properties of clear wood specimens (see summaries presented in Gerhards (1982) or Green and Kretschmann (1994)). Generally, the studies indicate an increase in modulus of rupture (MOR) to very low MC but not necessarily increasing in a linear manner. The studies on ultimate tensile strength (UTS) generally indicate a peak in the UTS–MC relationship in the range of 5% to 15% MC. Studies on the relationship between bending MOE and MC usually show an increase to quite low MC, with some deviations at ≤4%. In most reports, either a limited number of properties were studied or the sample sizes were extremely small.

Kretschmann and Green (1996) presented empirical models for clear southern pine for 15 elastic and strength properties at MC ranging from green to 4%. Their study used specimens cut from previously dried commercial lumber and had about 40 specimens per property and MC level. While many properties continued to increase as the wood was dried

TABLE 1. *Maximum value in the property–moisture content (MC) relationship for clear southern pine (Kretschmann and Green 1996).*[a]

Strength	MC peak (%)	Elastic moduli	MC peak (%)
UTS parallel	12.6	MOE tension parallel	Inc.[b]
Tension perp.	10.2	MOE tension perp.	4.3
MOR	Inc.[b]	MOE bending	Inc.[b]
UCS parallel	Inc.[b]	MOE compression parallel	4.3
Compression perp.	Inc.[b]	MOE compression perp.	Inc.[b]
Shear parallel	1.2[c]	Poisson's ratio LT[d]	Inc.[b]
$KI_{C\ TL}$[e]	6.9	Poisson's ratio LR[d]	Inc.[b]
$KII_{C\ TL}$[e]	10.9		

[a] UTS, ultimate tensile stress; MOE, modulus of elasticity; MOR, modulus of rupture; UCS, ultimate compressive stress.

[b] Inc. means continued to increase to projected 0% moisture content.

[c] Below the range of the experimental data.

[d] L, longitudinal, T, tangential; R, radial; the first letter indicates the axis perpendicular to the crack plane, the second indicates the direction of crack propagation.

[e] $KI_{C\ TL}$ is the critical value of the mode I (opening) fracture toughness in the tangential longitudinal plane, and $KII_{C\ TL}$ is the critical value of the mode II (forward shear) fracture toughness in the tangential longitudinal plane (Forest Products Laboratory 1999).

from green to about 4% MC, some properties reached a peak in the property–MC relationship at an intermediate MC (Table 1).

Ultimate tensile stress parallel to the grain.—From tests on 1,600 pieces of clear spruce, Curry (1952) found the peak in the UTS–MC relationship to be between 14% and 18% MC, depending upon density. Other studies are discussed in Gerhards (1982). Kersavage (1973) found that the tensile strength of single Douglas-fir tracheids increased with drying from the green condition to a maximum value at about 12% MC and then decreased with further drying. He postulates a fracture-based mechanism related to the different behavior of the cellulose and hemicellulose during drying. A broader discussion of potential failure mechanisms at different MC levels is given in Kretschmann and Green (1996). Ostman (1985) observed that the UTS–MC relationship had a maximum value at about 12% MC for spruce at 25°C (77°F) and 50°C (122°F). At 90°C (177°F), the peak shifted to about 7% MC. Ostman proposed that the shift in the peak value is related to shifts in the glass transition temperature. The clear southern pine data of Kretschmann and Green (1996) predict a maximum value for UTS at 12.6% MC.

From this discussion, it is clear that while some properties of clear wood increase continuously with drying, even to very low MC, other properties do not. However, for at least 75 years, it has been recognized that these potential increases in clear wood properties may be partially or totally offset in larger members by the weakening effects of drying degrade. For this reason, MC design factors for flexural properties of solid-sawn lumber have historically been based on tests of full-size commercial lumber (Green and Evans 2001a). In the last 25 years, research on the effect of MC on the properties of lumber has increased significantly.

Solid-sawn lumber properties

Bending.—Design factors for lumber with nominal thickness greater than 102 mm (4 in.) were historically allowed no increase in MOR and only a small increase in MOE (Green and Evans 2001a). Increases in MOR and MOE were allowed for lumber ≤102 mm in nominal thickness. In the 1970s, however, interest in basing allowable properties on tests of full-size commercial lumber and misunderstandings about the basis for American Society for Testing and Materials (ASTM 2001) moisture adjustments for properties (Green 1981) led to renewed studies of MC–property relationships (Brynildsen 1977; Hoffmeyer 1978, 1980; Madsen 1975; Madsen et al. 1980). Generally,

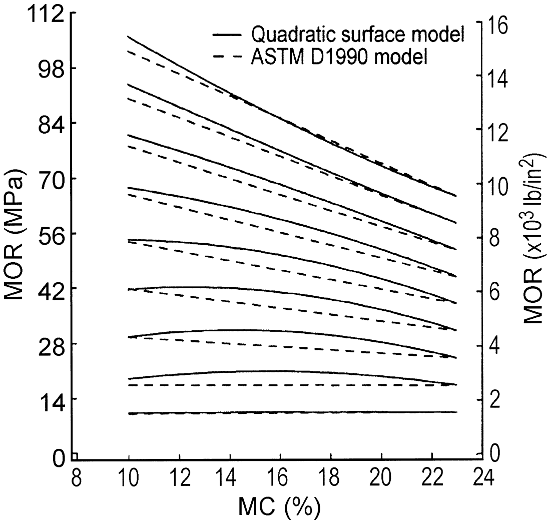

FIG. 1. Modeling the relationship between modulus of rupture (MOR) and moisture content (MC) by the quadratic surface model (Green and Evans 1989) and the model of ASTM D1990 (ASTM 2001).

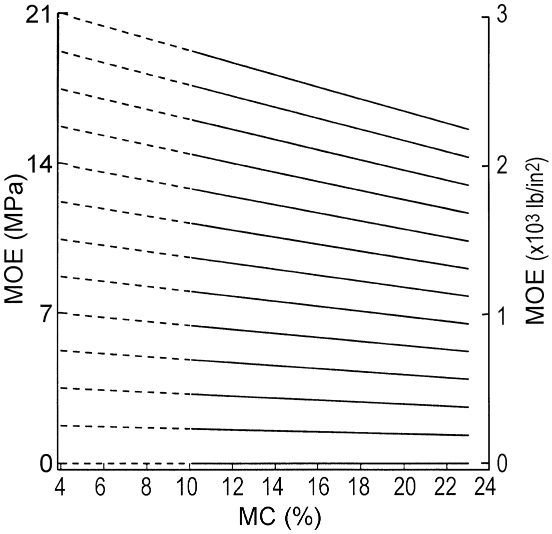

FIG. 2. Modeling the relationship between modulus of elasticity (MOE) and moisture content (MC) by the moisture adjustment model of ASTM D1990 (ASTM 2001).

these studies were limited to MC above 10% to 12%. However, the Madsen studies do contain some data at about 7% to 8% MC. The specimens at the lower MC in Madsen (1975) and the equilibrated specimens at the lower MC of Madsen et al. (1980) tended to have about the same strength as those at 10%.

In the mid-1980s, two studies were conducted in virtually identical fashion, one on southern pine dimension lumber (McLain et al. 1984) and one on Douglas-fir (Aplin et al. 1986). In each study, material was obtained green from one mill for each of three grades (Select Structural, No. 2, and No. 3) and three sizes (38- by 89-, 38- by 140-, and 38- by 184-mm (2 by 4, 2 by 6, and 2 by 8). The lumber in each of the grade–size cells was divided into four equal samples of about 120 specimens using green MOE with each grade as the sorting criteria. Three of the samples were equilibrated to 10%, 15%, and 20% MC, and the fourth sample was kept green. The specimens were tested on edge in third-point bending using a span-to-depth ratio of 17:1. The results from these studies were then used to establish analytical models relating flexural properties to MC. For MOR, the most accurate model was a quadratic surface model (Fig. 1), and for MOE, it was a constant percentage adjustment model (Fig. 2; Green and Evans 1989; Evans et al. 1990). Because of the complexity of the quadratic surface model for MOR, a simplified model was developed and adopted in ASTM D1990 (ASTM 2001) for derivation of allowable bending strength (Fig. 1; Green and Evans 2001a).

Tension parallel to grain.—Historically, in the United States, allowable strength in tension parallel to the grain was estimated from bending strength (Green and Evans 2001a). Thus, increases in tensile strength due to drying would be the same as those for bending strength. Research by Hoffmeyer (1978, 1980) and Madsen and Neilsen (1981) established that changes in UTS with change in MC were not the same as those for MOR, but those studies were limited in the number of MC levels studied or the number of grades tested. In 1990, a study was completed on the effect of MC on the tensile properties of Douglas-fir dimension lumber (Green et al. 1990). In this study, lumber of three grades and two sizes was tested at MC levels of green, 20%, 15%,

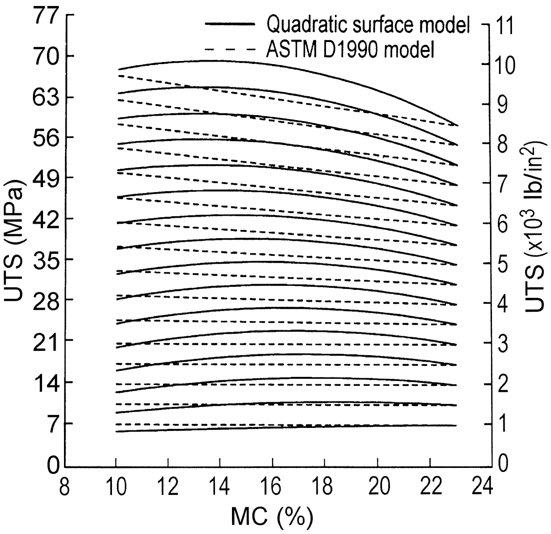

FIG. 3. Modeling the relationship between ultimate tensile stress (UTS) parallel to the grain and moisture content (MC) by the quadratic surface model (Green and Evans 1989) and the model of ASTM D1990 (ASTM 2001).

and 10%. There were approximately 110 specimens per grade, size, and MC category. An empirical quadratic surface model fit to these data clearly indicated that UTS did not always increase, and might decrease, as MC decreased from green to 10% (Fig. 3; Green and Evans 1989; Evans et al. 1990). Although this model implies that further reductions might occur at lower MC, the authors felt that the model should not be used for MC lower than about 10%. As with MOR, the quadratic surface model was judged to be too complex for use in ASTM D1990 (ASTM 2001). A simplified model, judged to be applicable only to the lower end of the strength distribution (Green and Evans 2001a) was therefore developed and incorporated into the standard (Fig. 3).

Eskelsen et al. (1993) explored the effects of drying on the ultimate tensile capacity (product of ultimate tensile stress and cross sectional area) of mechanically graded 2100f Douglas-fir 38- by 140-mm lumber (2 by 6s). They assumed that decreases in UTS of the type predicted from the quadratic surface model (Green and Evans 1989) were correct for carefully dried lumber. However, they hypothesized that the low MCs obtained in the outer zone of the cross-section that result from the severe moisture gradients that occur in lumber dried by commercial schedules may cause a permanent decrease in UTS not recovered when the gradients equalize. Thus, they reasoned that further in-service drying would not produce additional strength loss. In an innovative experiment, they conditioned two matched groups of carefully dried control specimens to approximately 13% MC and one matched group of lumber commercially dried at a maximum dry bulb temperature of 82°C (180°F) to a MC of about 8.5%. There were approximately 170 pieces in each group. At the 5th percentile level, the commercially dried lumber had a tensile strength that was 8% below the average of the merged data for the control specimens. They then predicted the strength of the lumber at 8.5% MC from that of the merged control specimens using the adjustment models of ASTM D2915, D1990 (ASTM 2001), and the quadratic surface model. They confirmed Green and Evans' conclusion that the D2915 model does not adequately predict the effect of MC on the tensile strength of lumber. They found that the quadratic surface model accounted for the effect of further drying for lumber with strength values between the 10th and 60th percentile, but that it was conservative and might not account for the drying effect for values less than or equal to the 5th percentile. Unfortunately, the loss of the actual dimensions of the commercially dried lumber and the failure to achieve a lower target MC, originally intended to be about 6%, clouded somewhat the conclusions from an otherwise excellent study. Thus, the UTS of lumber at very low MC is still an open question.

In a companion study to this paper, computer simulations that employed finite element–brittle fracture mechanisms were used to successfully predict the tensile strength of southern pine lumber equilibrated at 15% relative humidity for dry lumber containing edge knots (Green et al. 2003). The results of that

TABLE 2. *Effect of moisture content on the flexural properties of laminated veneer lumber at two relative humidity (RH) levels (Pu and Tang 1997; Lee et al. 2001).*

Species	Joint type	Ratio of value for 95% RH to that for 65% RH[a]		
		MOE	Etv	Esw
Southern pine	No joint	0.80	0.95	0.89
Yellow-poplar	No joint	0.88	0.95	0.92
	Lap joint	0.81	0.99	1.00
	Scarf joint	0.84	1.03	1.00

[a] Modulus of elasticity (MOE), static value by static test in edgewise orientation; Etv, dynamic value by transverse vibration in flatwise orientation; Esw, dynamic value by stress wave timer in flatwise orientation.

study indicated that for southern pine lumber containing edge knots, clear wood tensile strength parallel to the grain and fracture toughness are the primary influences on lumber tensile strength below 12% MC.

Flexural properties of structural composite lumber

While there is information on how processing and manufacturing variables affect the properties of LVL, there is only a limited amount of information on the effects of MC. Tang and Pu (1997) evaluated the effect of veneer grade and RH for five visual grades of veneer using southern pine rotary-cut veneer bonded with a phenol-formaldehyde adhesive. The LVL was manufactured without glue joints. Testing was conducted in static edgewise bending at 24°C (75°F) and RH of 65% and 95%. The average MC of the five groups of LVL was 11.3% at 65% RH and 18.2% at 95% RH. The MOR was found to decrease by an average of 19% for the five combinations. Pu and Tang (1997) compared MOE of southern pine LVL in edgewise bending to that obtained flatwise by transverse vibration (Etv) and stress wave techniques (Esw) using the same material as discussed in Tang and Pu (1997). Flatwise MOE by the two nondestructive techniques was found to be less sensitive to change in RH than was static edgewise MOE (Table 2).

Recently, Lee et al. (2001) presented information on the MOE of yellow-poplar LVL equilibrated at 23.9°C (75°F) and RH of 65% and 95%. The lumber was fabricated with rotary-peeled veneer and bonded with a phenol-formaldehyde resin adhesive. One group of specimens was manufactured with scarf veneer joints, one with crushed-lap veneer joints, and a control group with no veneer joints. A static edgewise MOE and flatwise MOEs by transverse vibration and stress wave timer were obtained with each piece. The ratio of the static MOE equilibrated at 95% RH to that at 65% RH averaged about 0.84 (Table 2). This is very close to an average ratio of 0.87 that would be predicted for solid-sawn lumber (ASTM D1990). In the flatwise orientation, both dynamic methods for determining MOE gave ratios approaching unity for LVL with joints. The ratio of the edgewise MOR at 95% RH to that at 65% RH for this material is 0.69 for LVL with no joints, 0.66 for LVL with crushed-lap joints, and 0.72 for material with scarf joints (Tang et al. 2000).

Thus, for both southern pine and yellow-poplar LVL, the studies discussed here indicate that flatwise MOE determined by either stress wave or transverse vibration was less sensitive to change in MC than was edgewise MOE determined by static loading.

PROCEDURES

The 38- by 89-mm lumber (2 by 4s) used in this study was obtained from commercial production (Table 3). The solid-sawn lumber was all dried by conventional drying in commercial kilns to a maximum MC of 15%, and the composite lumber products were produced at MC of less than 12%. The solid-sawn Spruce–Pine–Fir (SPF) lumber was obtained from a mill in Vancouver, B.C., Canada, and was a fifty–fifty mixture of 1650f–1.5E and 2100f–1.8E machine-stress-rated (MSR) lumber. The solid-sawn Douglas-fir was 1800F–1.8E and 2400F–2.0E MSR lumber from a mill in western Oregon. The solid-sawn southern pine was taken from existing stocks at the USDA Forest Service, Forest Products Laboratory (FPL), and is a mixture of several MSR grades with assigned MOE values between

TABLE 3. *Experimental design of study on effect of low relative humidity (RH) on properties of 38- by 89-mm lumber (2 by 4s).*

			Tension parallel				Bending			
			15% RH		65% RH		15% RH		65% RH	
Product[a]	Species	Grade	*N*[b]	MC[c]	*N*	MC	*N*	MC	*N*	MC
Solid-sawn	Douglas-fir	1800R-1.8E	30	3.6	30	11.6	30	4.1	29	11.6
		2400R-2.0E	30	3.4	30	11.5	30	4.0	29	11.8
	Southern pine	MSR[d]	52	3.7	52	10.9	52	4.2	52	10.9
	Spruce–Pine–Fir	MSR	—	—	—	—	30	4.4	61	11.2
LVL	Douglas-fir	2.0E	15	3.7	15	9.8	15	4.1	15	8.7
	Southern pine	2.0E	17	3.7	16	10.2	15	4.0	16	9.3
	Yellow-poplar	2.0E	15	3.1	16	9.8	16	3.4	16	8.5
LSL	Aspen	1.3E	15	2.6	15	9.0	15	3.3	15	8.9
	Yellow-poplar	1.5E	14	3.2	14	9.0	14	3.5	14	9.0

[a] LVL, laminated veneer lumber; LSL, laminated strand lumber.
[b] N = number of samples tested.
[c] MC, moisture content.
[d] MSR, machine-stress-rated.

1.6E and 2.0E. Three species of LVL were sampled: Douglas-fir, southern pine, and yellow-poplar. All the LVL was 2.0E grade and was manufactured with approximately 15 plies of 3.2-mm (⅛-in.) rotary-cut veneer and bonded with a phenol-formaldehyde adhesive (Nelson 1997). The veneer was graded by a combination of ultrasonic and visual techniques. The LVL contained crushed-lap joints with at least 127 mm (5 in.) between joints in any given cross section. Two species of LSL were also sampled: aspen (1.3E grade) and yellow-poplar (1.5E). Both species of LSL were manufactured from approximately 305- by 1-mm (12- by 0.04-in.) strands and bonded with an isocyanate-based adhesive (Nelson 1997).

All solid-sawn and composite lumber products were conditioned at 23°C (73°F) and 65% RH, and then an MOE was obtained on each piece by transverse vibration. For each product–species–grade category, the lumber was sorted into four groups of approximately equal numbers of pieces. This was accomplished by ranking the MOE values from high to low and then randomly assigning the first four pieces to a treatment group. The next group of four pieces was then assigned to a treatment group, and the process continued until all pieces were assigned. Each of the four groups was then randomly assigned to one of the four EMC test mode categories. The groups to be tested in bending and tension at 65% and 15% RH were placed in appropriate conditioning chambers to equilibrate prior to testing.

For most of the groups to be tested in bending, an Etv was determined by transverse vibration using a DynaMOE (TP Murphy Trading Co., Riverside, IL), with the specimens in the flatwise orientation and supported at their ends. The MOE of some of the groups were also obtained by longitudinal stress wave techniques and by static edgewise loading. Edgewise MOR was determined on all pieces by ASTM D198 (ASTM 2001) using quarter-point loading and a span-to-depth ratio of 21:1. Quarter-point loading was used because most of the lumber was control specimens from the thermal degradation study (Green and Evans 2001b) and for that study, it was desirable to increase the constant moment region compared with what it would have been for the more traditional third-point loading orientation. The rate of loading was approximately 51 mm (2 in.) per minute. Following testing, oven-dry MC and specific gravity based on oven-dry weight and oven-dry volume were determined from sections taken near the failure region (ASTM D2395 and D4442).

For the specimens to be tested in tension parallel to the grain, an MOE was determined in transverse vibration, with the specimens in the flatwise orientation and supported at their ends. The tensile strength of the specimens was then determined by the procedures of ASTM D198. The clear span between grips for these specimens was 2.4 m (8 ft). Following testing, oven-dry MC and specific gravity based on oven-dry weight and oven-dry volume was determined from sections taken near the failure region (ASTM D2395 and D4442). Unfortunately, the data file containing the measured dimensions of the pieces was inadvertently lost for the solid-sawn lumber and the LSL. For these groups, the Etv values are not reported in this paper. After evaluating several alternatives, it was decided to calculate the UTS values for these groups by dividing the maximum load recorded for each piece by the average dimensions obtained from the bending specimens of the appropriate group for 65% and 15% RH exposures. Since all the lumber for a given product–grade was produced from the same source, the initial dimensions for 65% RH were very similar, and change in dimensions for the bending and data sets would have also been similar. This was confirmed for LVL where actual dimensions were available on the specimens tested in tension.

RESULTS AND DISCUSSION

Change in properties

Physical properties.—Table 3 shows the sample sizes and average MC at time of test for this study. It is apparent that for 65% RH, the composite lumber products tended to come to a lower EMC under the same set of humidity conditions than did the solid-sawn lumber. Because the composite products are subjected to higher heat and pressure during the manufacturing process, it seems reasonable that they might equilibrate at a lower EMC than solid wood. Also, they are probably coming up in MC relative to the 12% EMC conditions while the solid-sawn lumber is coming down in MC from an average that was probably more like 15%. Thus, a hysteresis effect may also play a role in the EMC differences (Avramidis and Enayati 1997). The difference for 15% RH is less apparent, probably because of very low target MC.

Table 4 gives the dimensions at each humidity level and the specific gravity of each group. The specific gravity is based on oven-dry weight and volume, and therefore, differences between RH groups for a given product or grade are just an indication of experimental variability. The National Design Specification for Wood Construction (NDS) (AF&PA 1997) gives the oven-dry–oven-dry specific gravity as 0.49 for Douglas fir–Larch, 0.55 for southern pine, and 0.42 for SPF (but 0.50 if MOE is ≥2.0E). However, the specific gravity of MSR lumber would be expected to increase with increasing grade; thus, the specific gravity values for the solid-sawn lumber are within the expected range. The specific gravity values for the composite lumber products also seem typical for the product and species.

With respect to shrinkage, the solid-sawn lumber shrank about 1.4% in thickness (38-mm dimension) and about 2.0% in width (89-mm dimension) (Table 5). The shrinkage of the LVL was similar to that of the solid-sawn lumber. As might be expected from the orientation of the strands, the LSL shrank about 2.4% in thickness but only about 0.6% in width.

Mechanical properties in bending.—As discussed in the previous section, structural composites may come to a lower EMC in a given set of temperature and RH conditions than does solid-sawn lumber. Although it is traditional in design standards (AF&PA 1997) to compare properties of different species of solid-sawn lumber at the same MC, in this paper, the comparisons are made on the basis of equilibration to a fixed set of environmental conditions (15% and 65% RH at 23°C). This is how research results are traditionally presented and how structural materials would be exposed in end-use environments.

Tables 6 and 7 summarize the results for the lumber tested in bending (mean/standard deviation). Static MOE in edgewise bending was taken on the Douglas-fir and southern pine MSR lumber and the aspen and yellow-poplar

TABLE 4. *Dimensions and specific gravity of 38- by 89-mm lumber (2 by 4s) exposed at 65% and 15% relative humidity (RH).*

				Metric units		Inch-pound units		
Product[a]	Species	Grade	RH (%)	Thickness (mm)	Width (mm)	Thickness (in.)	Width (in.)	Specific gravity[b]
Solid-sawn	Douglas-fir	1800F-1.8E	15	37.49	86.94	1.476	3.423	0.47
			65	38.05	88.87	1.498	3.499	0.46
		2400F-2.0E	15	37.34	86.21	1.470	3.394	0.54
			65	37.90	88.29	1.492	3.476	0.54
	Southern Pine	MSR[c]	15	37.82	87.45	1.489	3.443	0.65
			65	38.56	89.23	1.514	3.513	0.64
	Spruce–Pine–Fir	MSR	15	37.31	87.17	1.469	3.432	0.44
			65	37.69	88.54	1.484	3.486	0.43
LVL	Douglas-fir	2.0E	15	37.29	87.96	1.468	3.463	0.54
			65	37.92	89.20	1.493	3.512	0.52
	Southern pine	2.0E	15	42.57	87.12	1.676	3.430	0.64
			65	43.10	89.20	1.697	3.512	0.62
	Yellow-poplar	2.0E	15	41.53	87.48	1.635	3.444	0.52
			65	42.06	88.80	1.656	3.496	0.50
LSL	Aspen	1.3E	15	37.46	88.67	1.475	3.491	0.59
			65	38.51	89.18	1.516	3.511	0.61
	Yellow-poplar	1.5E	15	36.78	88.65	1.448	3.490	0.69
			65	37.54	89.28	1.478	3.515	0.69

[a] LVL, laminated veneer lumber; LSL, laminated strand lumber.
[b] Based on oven-dry weight and volume.
[c] MSR, machine stress-rated.

LSL but not on the SPF solid-sawn lumber or the LVL. Where static MOEs were taken, none of the solid-sawn or composite lumber products showed a significant change in static edgewise MOE when dried from 65% to 15% RH (Table 8). Because of shrinkage, the ratio of the moment of inertia (EI) products at 15% RH to those at 65% RH is slightly lower than that of MOE. For solid-sawn lumber, the ratio of EI products is about 0.90. This is contrary to the usual assumption, verified at MC of about 10% or greater (Green 1989), that the increase in MOE compensates for shrinkage as lumber dries. For LSL, the ratio of EI products is about 0.96.

For solid-sawn lumber, the ratio for 15% RH to that for 65% RH was slightly higher for MOE by longitudinal stress wave techniques than that observed for static MOE or Etv. For LSL, the ratio of Etv at 15% RH to that at

TABLE 5. *Ratio of mean dimensions for 38- by 89-mm lumber (2 by 4s) equilibrated at 15% relative humidity to those at 65% relative humidity.*

Product[a]	Species	Grade	Thickness	Width
Solid-sawn	Douglas-fir	1800F-1.8E	0.985	0.978
		2400F-2.0E	0.985	0.976
	Southern pine	MSR[b]	0.983	0.980
	Spruce–Pine–Fir	MSR	0.999	0.985
LVL	Douglas-fir	2.0E	0.983	0.986
	Southern pine	2.0E	0.988	0.977
	Yellow-poplar	2.0E	0.987	0.985
LSL	Aspen	1.3E	0.973	0.994
	Yellow-poplar	1.3E	0.980	0.993

[a] LVL, laminated veneer lumber; LSL, laminated strand lumber.
[b] MSR, machine-stress-rated.

TABLE 6. *Effect of low relative humidity (RH) on the elastic properties of 38- by 89-mm lumber (2 by 4s).*[a]

				Metric units[b]				Inch-pound units[b]			
Product	Species	Grade	RH (%)	MOE (GPa)	Etv (GPa)	Esw (GPa)	EI ($\times 10^3$ kg·m^2)	MOE (lb/in^2)	Etv (lb/in^2)	Esw (lb/in^2)	EI ($\times 10^6$ lb·in^2)
Solid-sawn	Douglas-fir	1800F-1.8E	15	15.0/2.4	13.5/1.7	14.6/1.8	3.13/0.5	2.17/0.35	1.96/0.25	2.12/0.26	10.71/1.68
			65	15.3/2.5	13.7/1.8	14.3/2.0	3.47/0.6	2.22/0.36	1.97/0.26	2.07/0.29	11.85/1.90
		2400F-2.0E	15	19.0/2.4	17.0/1.8	18.4/1.9	3.84/0.4	2.75/0.35	2.47/0.26	2.67/0.27	13.13/1.46
			65	19.3/2.4	17.4/2.0	18.4/2.2	4.28/0.5	2.80/0.35	2.52/0.29	2.64/0.32	14.62/1.77
	Southern Pine	MSR	15	18.9/4.4	17.3/3.7	18.3/3.9	4.06/1.0	2.74/0.64	2.51/0.54	2.65/0.56	13.89/3.36
			65	19.0/3.8	16.8/3.4	17.2/3.4	4.39/0.9	2.75/0.55	2.43/0.49	2.50/0.50	15.02/2.94
	Spruce–Pine–Fir	MSR	15	—	11.2/1.1	—	—	—	1.62/0.16	—	—
			65	—	11.9/1.6	—	—	—	1.72/0.23	—	—
LVL	Douglas-fir	2.0E	15	—	16.4/0.8	—	—	—	2.38/0.12	—	—
			65	—	16.6/0.9	—	—	—	2.41/0.13	—	—
	Southern pine	2.0E	15	—	17.9/1.3	—	—	—	2.59/0.19	—	—
			65	—	18.9/1.7	—	—	—	2.74/0.25	—	—
	Yellow-poplar	2.0E	15	—	14.3/1.2	—	—	—	2.07/0.18	—	—
			65	—	14.8/0.8	—	—	—	2.14/0.12	—	—
LSL	Aspen	1.3E	15	11.0/0.9	12.4/0.8	11.9/0.7	2.44/0.2	1.60/0.13	1.80/0.12	1.72/0.10	8.35/0.67
			65	10.9/0.7	11.1/0.6	11.2/0.7	2.53/0.2	1.58/0.10	1.61/0.09	1.63/0.10	8.65/0.55
	Yellow-poplar	1.5E	15	12.1/1.0	12.3/1.0	12.8/1.0	2.63/0.2	1.76/0.14	1.78/0.15	1.85/0.15	9.00/0.69
			65	12.0/1.0	11.6/0.8	12.2/0.6	2.73/0.3	1.74/0.15	1.68/0.11	1.77/0.09	9.33/0.86

[a] MOE, modulus of elasticity obtained edgewise by static load; Etv, MOE obtained flatwise by transverse vibration; Esw, MOE obtained by stress wave techniques: EI, moment of inertia; MSR, machine-stress-rated; LVL, laminated veneer lumber, LSL, laminated strand lumber.

[b] First number is mean value, second number is standard deviation.

TABLE 7. *Effect of low relative humidity (RH) on the strength of 38- by 89-mm lumber (2 by 4s).*[a]

				Metric units[b]				Inch-pound units[b]			
Product	Species	Grade	RH (%)	MOR (MPa)	RS (N·m)	UTS (MPa)	TA (N)	MOR ($\times 10^3$ lb/in^2)	RS ($\times 10^3$ lb·in)	UTS ($\times 10^3$ lb/in^2)	TA (lb)
Solid-sawn	Douglas-fir	1800F-1.8E	15	47.9/16.9	2.26/0.8	32.2/11.4	104.98/37.3	6.95/2.45	20.02/6.98	4.67/1.66	23.60/8.38
			65	45.9/12.7	2.30/0.6	34.6/10.1	116.99/35.3	6.65/1.84	20.34/5.66	5.02/1.47	26.30/7.70
		2400F-2.0E	15	70.5/20.1	3.25/0.9	47.6/10.9	153.11/35.0	10.23/2.91	28.80/7.95	6.90/1.58	34.42/7.87
			65	69.2/19.1	3.40/0.9	49.9/14.7	166.85/49.1	10.04/2.77	30.10/8.09	7.23/2.13	37.51/11.03
	Southern pine	MSR	15	78.7/27.9	3.79/1.3	49.4/19.5	163.21/64.6	11.42/4.04	33.56/11.88	7.16/2.83	36.69/14.53
			65	83.8/25.0	4.27/1.3	54.2/18.3	185.9/64.0	12.15/3.63	37.78/11.16	7.86/2.66	41.80/14.17
	Spruce–Pine–Fir	MSR	15	50.7/13.4	2.39/0.6	—	—	7.35/1.95	21.17/5.64	—	—
			65	55.0/15.9	2.70/0.8	—	—	7.97/2.31	23.89/6.65	—	—
LVL	Douglas-fir	2.0E	15	63.0/6.6	3.03/0.3	40.3/3.2	133.94/11.3	9.13/0.96	26.78/2.86	5.85/0.47	30.11/2.53
			65	61.8/7.9	3.11/0.4	45.1/5.4	149.19/18.3	8.96/1.15	27.49/3.61	6.54/0.78	33.54/4.11
	Southern pine	2.0E	15	76.0/8.8	4.09/0.5	51.6/5.7	191.76/21.8	11.02/1.27	36.24/4.47	7.48/0.83	43.11/4.90
			65	78.5/7.8	4.49/0.5	54.3/7.3	203.02/26.6	11.39/1.13	39.78/4.32	7.87/1.06	45.64/5.98
	Yellow-poplar	2.0E	15	76.1/7.0	4.0/0.4	50.7/7.6	187.85/28.5	11.04/1.02	35.71/3.76	7.35/1.10	42.23/6.41
			65	73.6/5.2	4.07/0.3	53.9/8.2	198.3/32.21	10.68/0.76	36.05/3.13	7.82/1.19	44.58/7.24
LSL	Aspen	1.3E	15	45.4/4.5	2.23/0.2	28.8/3.7	95.41/12.4	6.59/0.65	19.76/1.95	4.17/0.54	21.45/2.79
			65	47.0/2.8	2.40/0.1	29.4/5.1	100.93/17.4	6.81/0.41	21.22/1.31	4.26/0.74	22.69/3.92
	Yellow-poplar	1.5E	15	50.5/6.1	2.44/0.3	35.0/5.9	114.32/19.3	7.33/0.89	21.56/2.68	5.08/0.86	25.70/4.33
			65	51.8/7.0	2.58/0.4	34.8/4.3	116.72/14.5	7.51/1.02	22.86/3.17	5.05/0.63	26.24/3.26

[a] MOR, modulus of rupture; RS, load-carrying capacity in bending, UTS, ultimate tensile stress; TA, load-carrying capacity in tension parallel to the grain; MSR, machine-stress-rated; LVL, laminated veneer lumber, LSL, laminated strand lumber.

[b] First number is mean value, second number is standard deviation.

TABLE 8. *Ratio of mean properties for 38- by 89-mm lumber (2 by 4s) equilibrated at 15% relative humidity to those at 65% relative humidity.*[a]

Product	Species	Grade	MOE	Etv	Esw	MOR	UTS	EI	RS	TA
Solid-sawn	Douglas-fir	1800F-1.8E	0.98	0.99	1.02	1.05	0.93	0.90	0.98	0.90
		2400F-2.0E	0.98	0.98	1.01	1.02	0.95	0.90	0.96	0.92
	Southern pine	MSR	1.00	1.03	1.06	0.94	0.91	0.93	0.89	0.88
	Spruce–Pine–Fir	MSR	—	0.94	—	0.92	—	—	0.89	—
LVL	Douglas-fir	2.0E	—	0.99	—	1.02	0.89	—	0.97	0.90
	Southern pine	2.0E	—	0.95	—	0.97	0.95	—	0.91	0.94
	Yellow-poplar	2.0E	—	0.97	—	1.03	0.94	—	0.99	0.95
LSL	Aspen	1.3E	1.01	1.12	1.06	0.97	0.98	0.97	0.93	0.95
	Yellow-poplar	1.5E	1.01	1.06	1.05	0.98	1.01	0.96	0.94	0.98

[a] MOE, modulus of elasticity obtained edgewise by static load; Etv, MOE obtained flatwise by transverse vibration; Esw, MOE obtained by stress wave techniques; MOR, modulus of rupture; UTS, ultimate tensile stress; EI, moment of inertia; RS, load-carrying capacity in bending; TA, load-carrying capacity in tension parallel to the grain; MSR, machine-stress-rated; LVL, laminated veneer lumber; LSL, laminated strand lumber.

65% RH is larger than that observed for static MOE. Because static edgewise MOE was not taken many years ago when the MOE of the LVL at 65% RH was measured, it is not possible to address the findings of Tang and Pu (1997) that flatwise dynamic MOE of LVL is less sensitive to change in MC than is static edgewise MOE. Neither the solid-sawn lumber nor the LVL showed much change in Etv with change in RH. The Etv value for the LSL increased with drying. For solid-sawn lumber and LSL, the Esw value for 15% RH is always higher than that for 65% RH, and the ratio for Esw is slightly higher than static MOE. The Esw value is obtained lengthwise on each piece, and therefore Esw is not as sensitive to shrinkage as Etv.

For solid-sawn lumber, Douglas-fir shows a slight increase in MOR when equilibrated at 15% RH compared with 65% RH (Table 8). Southern pine and SPF MSR show decreases of 6% and 8%, respectively. The change in MOR for the composite lumber products was about the same for the two RH levels. When shrinkage is taken into account, the load-carrying capacity in bending (RS) of the solid-sawn lumber decreased up to 11% for 15% RH compared with that for 65% RH. For LVL, the decrease was up to 9%, and for LSL, it was up to 7%.

For solid-sawn lumber, Table 9 shows how properties change at selected levels of the strength distribution. These comparisons are based on nonparametric estimates of the percentile values (ASTM D2915). As would be expected based on ratios from two data sets with sample sizes as low as 30 pieces, the ratios are highly variable. This is especially true in the tails of the distribution (Johnson et al. 2002). Given the mean trends for MOR shown in Table 8 and the variation at various percentile levels for the lower half of the distribution shown in Table 9, we believe that a reduction in MOR of about 10% (ratio of 0.9) would be appropriate for the species tested when estimating strength at 15% RH from data tested after conditioning to 65% RH. Although there is still considerable variation in the ratio of MOR for 15% compared with 65% RH for the composite products, it is less variable than that for the solid-sawn lumber. For both LVL and LSL, MOR generally seems to show little difference between results at the two humidity levels.

Mechanical properties in tension parallel to grain.—Table 7 summarizes the strength for the 38- by 89-mm lumber (2 by 4s) tested in tension. For solid-sawn Douglas-fir and southern pine, the mean UTS value decreased 5% to 9% for 15% RH compared with the value for 65% RH (Table 8). For LVL, the reduction is 5% to 11%, and for LSL, the ratio is approximately 1. The change in load-carrying capacity in tension parallel to the grain (TA) is about the same as, or slightly less than, that of UTS. Table 9 gives the ratio of UTS at 15%

TABLE 9. *Ratio of properties of 38- by 89-mm lumber (2 by 4s) equilibrated at 15% relative humidity to those at 65% relative humidity for lumber at various levels of the strength distribution.*[a]

			Percentile level				
Species	Grade	Property	5	10	25	50	75
Douglas-fir	1800F	MOR	0.95	0.99	0.95	0.99	0.99
	2400F		0.66	0.96	1.00	1.05	1.13
Southern pine	MSR		1.10	0.75	0.91	0.93	0.88
Spruce–Pine–Fir	MSR		0.89	0.91	0.93	0.91	0.91
Douglas-fir	1800F	UTS	0.85	0.88	0.99	0.93	1.00
	2400F		0.99	1.02	0.95	1.02	0.92
Southern pine	MSR		0.75	1.02	0.85	0.90	0.95
Douglas-fir	LVL	MOR	—	1.04	1.04	1.01	1.02
Southern pine			—	0.91	1.00	0.99	0.97
Yellow-poplar			—	0.99	1.01	1.01	1.11
Aspen	LSL		—	0.91	0.96	0.96	1.00
Yellow-poplar			—	1.03	0.98	1.00	0.93
Douglas-fir	LVL	UTS	—	1.00	0.97	0.91	0.89
Southern pine			—	0.97	0.97	0.94	0.90
Yellow-poplar			—	0.89	0.96	0.96	0.91
Aspen	LSL		—	1.16	0.94	0.96	0.95
Yellow-poplar			—	0.90	0.93	1.05	1.06

[a] MOR, modulus of rupture; UTS, ultimate tensile stress; MSR, machine-stress-rated; LVL, laminated veneer lumber; LSL, laminated strand lumber.

RH to that at 65% at selected percentile levels. Overall, the data confirm that the UTS value, when equilibrated to 15% RH, can be up to 10% lower than that at 65% RH for LVL while changing little for LSL.

Evaluation of predictive models for solid-sawn lumber

As noted in the background section, most studies that have been done to predict the effect of MC on the mechanical properties, or dimensional shrinkage, of solid-sawn lumber have been based on solid-sawn lumber with MC between green and about 10%. While it is not recommended that such models be applied outside the range of MC for which the model is based, this is not an uncommon practice. Therefore, it is instructive to determine how well these models apply to lumber at low MC. Because of the small numbers of samples found in most of these data sets, estimates in the tails of the distributions may be highly variable and provide a less reliable indication of model performance than estimates in the middle of the property distribution. Therefore, our comparisons will be based on prediction of mean values for solid-sawn lumber. Models are not available for predicting the effect of MC on the properties of composite lumber products.

Shrinkage.—ASTM D1990 presents equations for adjusting lumber dimensions for change in MC. The equation that is applicable to most species was developed from data on coast-type Douglas-fir and was not verified for MC below about 10% (Green 1989). The equation would be expected to be applicable to average trends from a large quantity of lumber but not necessarily to individual pieces.

$$d_2 = d_1\left[\frac{(1 - ((\mathrm{a} - \mathrm{b}M_2)/100))}{(1 - ((\mathrm{a} - \mathrm{b}M_1)/100))}\right] \qquad (2)$$

where d_1 is the dimension at moisture content M_1 (in.); d_2 is the dimension at moisture content M_2 (in.); M_1 is the initial MC (%); M_2 is the desired MC (%); a is 6.031 for width and 5.062 for thickness; b is 0.215 for width and 0.181 for thickness.

Equation 2 was used to predict the dimension of solid-sawn lumber equilibrated at 15% RH given the dimensions and MC shown in Tables 3 and 4. For Douglas-fir, the two MSR

TABLE 10. *Prediction of dimensions of solid-sawn lumber equilibrated at 15% relative humidity from properties at 65% relative humidity.*[a]

Product	Grade	Basis	MC	Metric units		Inch-pound units	
				Thickness (mm)	Width (mm)	Thickness (in.)	Width (in.)
Douglas-fir	MSR	Exp.	11.7	37.97	88.57	1.495	3.487
		Exp	4.0	37.41	86.59	1.473	3.409
		Pred.	4.0	37.44	87.05	1.474	3.427
Southern pine	MSR	Exp.	10.9	38.46	89.23	1.514	3.513
		Exp	4.2	37.82	87.45	1.489	3.443
		Pred.	4.2	37.97	87.88	1.495	3.460
Spruce–Pine–Fir	MSR	Exp.	11.2	37.69	88.54	1.484	3.486
		Exp	4.4	37.31	87.17	1.469	3.432
		Pred.	4.4	37.21	87.12	1.465	3.430

[a] MSR, machine-stress-rated; MC, moisture content.

grades were combined. As can be seen in Table 10, excellent agreement was obtained between actual and predicted dimensions. While it might be expected that shrinkage might follow a linear relationship to quite low MC levels, it is doubtful that the procedure would be linear for lumber with MC above about 19% (Forest Products Laboratory 1999; Green 1989).

Mechanical properties.—Two procedures were used to predict the MOR of solid-sawn lumber for 15% RH from the data for 65% RH (Tables 3, 6, and 7). The first procedure is that given in ASTM D1990, and the other is the quadratic surface model of Green and Evans (1989). Each of the models was used to adjust the average MOR value from the MC measured after equilibration at 65% RH to the MC measured at 15% RH. These predicted MOR values were then compared with the measured values for 15% RH (Table 11a and b). For example, for 1800F-1.8E Douglas-fir, the D1990 model predicted an MOR for 15% RH of 53.6 MPa (7,770 lb/in^2). This prediction is 11.8% higher than the measured value of 47.9 MPa (6,950 lb/in^2). As can be seen from Table 11a and b, the D1990 model predicted a higher MOR value than was actually observed by amounts that range from 12% to 26%. This is because the D1990 model increases linearly with decreasing MC below the green value (Fig. 1). The quadratic surface model predicted MOR values that were generally higher than those measured for 15% RH, but for 1800F Douglas-fir, the prediction was too low.

For MOE, the ASTM D1990 model predicted a value for 15% RH that was 10% to 14% too high (Table 11a and b). The D1990 model, based on 7,532 test specimens, should be accurate down to about 10% MC. Therefore, it seems likely that MOE decreases slightly somewhere between 10% and 4% MC. For UTS, the D1990 model consistently predicted a value that was higher than the measured value by 12% to 17%. The quadratic surface model consistently predicted a UTS lower than the measured value. For southern pine, the prediction was only lower by about 5%, but for Douglas-fir, the prediction was up to 20% too low.

Development of potential adjustment factors for solid-sawn lumber

From this discussion, it is apparent that, generally, the existing models for solid-sawn lumber did a poor job of predicting the mechanical properties of lumber equilibrated at 15% RH (approximately 4% MC). So what judgment might be applied in estimating properties at these low humidities? Allowable properties in the NDS (AF&PA 1997) are given at an average MC of 15% (19% maximum MC). From the plots of properties with MC (Figs. 1–3), it appears that the 15% MC value

TABLE 11A. *Prediction of mechanical properties of solid-sawn lumber equilibrated at 15% relative humidity from those at 65% relative humidity (metric units).*[a]

Property	Species	Grade	MC (%)	Actual and predicted values			Error (%)[b]	
				Actual	D1990	QSM	D1990	QSM
MOR	Douglas-fir	1800F-1.8E	4.1	47.92	53.57	40.61	+11.8	−15.3
(MPa)		2400F-2.0E	4.2	70.54	83.77	77.43	+18.8	+9.8
	Southern pine	MSR	4.0	78.74	99.22	98.74	+26.0	+25.4
	Spruce–Pine–Fir	MSR	4.4	50.68	63.99	53.92	+26.3	+6.4
MOE	Douglas-fir	1800F-1.8E	4.1	14.96	17.03	—	+13.8	—
(GPa)		2400F-2.0E	4.2	18.96	21.58	—	+13.8	—
	Southern pine	MSR	4.0	18.89	20.82	—	+10.2	—
	Spruce–Pine–Fir[c]	MSR	4.4	11.17[b]	13.03	—	+16.7	—
UTS	Douglas-fir	1800F-1.8E	3.6	32.20	36.13	25.65	+12.2	−20.3
(MPa)		2400F-2.0E	3.4	47.58	53.16	42.20	+11.7	−11.3
	Southern pine	MSR	4.1	49.37	57.57	47.16	+16.6	−4.5

[a] MC, moisture content; QSM, quadratic surface model; MOR, modulus of rupture; MOE, modulus of elasticity obtained edgewise by static load; UTS, ultimate tensile stress; MSR, machine-stress-rated.

[b] 100 ((predicted − actual)/actual).

[c] Etv value used here because static MOE not measured for this data set.

might provide a conservative estimate of the value at 4% MC. To evaluate this hypothesis, the properties at 65% RH were adjusted from the MC achieved at this exposure to a MC of 15%. The predicted value at 15% MC was compared with the measured properties for the 15% RH (Table 12).

For MOR, the ASTM D1990 model predicts properties at 15% MC that are 1% to 12% lower than the values measured at approximately 4% MC (ratios of 0.99 to 0.88) (Table 12). For MOE, the value at 15% MC is 0% to 6% lower than the measured value at 4% MC (ratios of 1.0 to 0.94). For UTS, the 15% value is 2% to 6% above the measured value for 15% RH. When the quadratic surface model is used to adjust measured properties for 65% RH to 15% MC, MOR values are 9% lower to 3% higher than the values measured at 15% RH. For UTS, use of the quadratic surface model results in values for 15% MC that are 5% to 11% higher than the measured values for 15% RH.

With respect to our objective of developing

TABLE 11B. *Prediction of mechanical properties of solid-sawn lumber equilibrated at 15% relative humidity from those at 65% relative humidity (inch-pound units).*[a]

Property	Species	Grade	MC (%)	Acutal and predicted values			Error (%)[b]	
				Actual	D1990	QSM	D1990	QSM
MOR	Douglas-fir	1800F-1.8E	4.1	6.95	7.77	5.89	+11.8	−15.3
($\times 10^3$ lb/in^2)		2400F-2.0E	4.2	10.23	12.15	11.23	+18.8	+9.8
	Southern pine	MSR	4.0	11.42	14.39	14.32	+26.0	+25.4
	Spruce–Pine–Fir	MSR	4.4	7.35	9.28	7.82	+26.3	+6.4
MOE	Douglas-fir	1800F-1.8E	4.1	2.17	2.47	—	+13.8	—
($\times 10^6$ lb/in^2)		2400F-2.0E	4.2	2.75	3.13	—	+13.8	—
	Southern pine	MSR	4.0	2.74	3.02	—	+10.2	—
	Spruce–Pine–Fir[c]	MSR	4.4	1.62[b]	1.89	—	+16.7	—
UTS	Douglas-fir	1800F-1.8E	3.6	4.67	5.24	3.72	+12.2	−20.3
($\times 10^3$ lb/in^2)		2400F-2.0E	3.4	6.90	7.71	6.12	+11.7	−11.3
	Southern pine	MSR	4.1	7.16	8.35	6.84	+16.6	−4.5

[a] MC, moisture content; QSM, quadratic surface model; MOR, modulus of rupture; MOE, modulus of elasticity obtained edgewise by static load; UTS, ultimate tensile stress; MSR, machine-stress-rated.

[b] 100 ((predicted − actual)/actual).

[c] Etv value used here because static MOE not measured for this data set.

TABLE 12. *Ratio of predicted property for solid-sawn lumber for 15% moisture content to the measured property for 15% relative humidity.*[a]

Species	Grade	Ratio MOR	Ratio MOE	Ratio UTS
		D1990		
Douglas-fir	1800F-1.8E	0.88	0.97	1.06
	2400F-2.0E	0.90	0.97	1.02
Southern pine	MSR	0.94	0.94	1.06
Spruce–Pine–Fir	MSR	0.99	1.00	—
		QSM		
Douglas-fir	1800F-1.8E	0.97	—	1.11
	2400F-2.0E	0.91	—	1.05
Southern pine	MSR	0.94	—	1.10
Spruce–Pine–Fir	MSR	1.03	—	—

[a] MOR, modulus of rupture; MOE, modulus of elasticity obtained edgewise by static load; UTS, ultimate tensile stress; MSR, machine-stress-rated; QSM, quadratic surface model.

factors that might be used for estimating properties at about 4% MC, the ASTM D1990 models appear to yield slightly more conservative property ratios than does the quadratic surface model. Further, the D1990 models are the ones used to develop the allowable properties for dimension lumber that are given in the NDS (AF&PA 1997). Thus, the D1990 models will be used to estimate potential adjustment factors. The results for MOR and MOE in Table 12 using the D1990 model suggest that the allowable properties given in the NDS at 15% MC might be used as a conservative estimate of those at 4% MC if proper allowance is made for shrinkage. For UTS, the D1990 model would yield estimates that are slightly higher than those measured at about 4% MC. To produce a conservative estimate for UTS, the allowable tensile strength (Ft) value in the NDS would have to be multiplied by a factor of about 0.95, plus shrinkage would have to taken into account.

Using Eq. (2) to adjust from 15% MC to 4% MC predicted slightly more than a 2.0% loss in thickness (smaller dimension) and a 2.4% loss in width (larger dimension) for lumber to be used with an edgewise loading. These changes in dimension would reduce the EI in edgewise loading by about 10% and RS in edgewise loading by about 7%. The reduction in TA due to shrinkage would be about 4.6%, and an additional reduction of about 5% would be needed to account for the possibility that the allowable tensile strength parallel to the grain (Ft) value at 15% MC might be nonconservative compared with the value at 4% MC. Maintenance of equal stiffness or load capacity at 4% MC might be obtained by the use of these factors (1.1 for EI, 1.07 for RS, and 1.1 for TA).

There could be a number of approaches for using the factors to account for potential reductions of properties at 4% MC. One option would be to use oversize lumber. However, to achieve a 10% increase in EI would require dry lumber at approximately the dimensions of rough green lumber. Such lumber would not be commonly available on the market. A second option would be to go to the next larger size of lumber for a given grade. This would produce a much larger increase in capacity than the minimum required. A third option might be to purchase a higher grade of lumber. For example, suppose that the project required No. 2 grade southern pine 38- by 89-mm lumber (2 by 4s), the properties of which are shown in Table 13 at an average MC of 15% (19% maximum MC). To maintain a constant EI between 15% and 4% MC would require the purchase of lumber with an MOE of 12.1 GPa (1.76 million lb/in^2) at 15% MC. The next highest grade with an MOE at least this high would be No. 1 Dense (MOE = 12.4 GPa (1.8 million lb/in^2)). In similar fashion, maintenance of a constant RS in edgewise loading could be met with either No.2 Dense or No.1 southern pine. The Ft value would require No.1 Dense lumber.

The research presented in this paper shows that reductions in lumber properties might occur when individual pieces of lumber are equilibrated to very low MC. Whether any changes should be initiated based on this research is a decision for individual engineers and the engineering community. As discussed, this was a study of limited scope initiated to provide some guidance in an area where little information currently exists. Further, structural

TABLE 13A. *Illustration of one method for estimating allowable properties at 4% moisture content (MC) using allowable properties at 15% average MC and standard dressed dry dimension (metric units).*[a]

	MOE	F_b	Ft
Property at 15% MC[b]	11.0 GPa	10.34 MPa	5.69 MPa
To maintain constat	EI	RS	TA
Multiply by factor	1.1	1.07	1.1
Estimated property at 4% MC	12.14 GPa	11.07 MPa	6.26 MPa
Grade to get estimated property at 4% MC	No. 1 Dense	No. 2 Dense or No. 1	No. 1

[a] MOE, modulus of elasticity obtained edgewise by static load; F_b, allowable bending strength; Ft, allowable tensile strength parallel to grain; EI, moment of inertia; RS, load carrying capacity in bending; TA, load-carrying capacity in tension parallel to the grain.

[b] No. 2 grade southern pine 38- by 89-mm (2 by 4) dimension lumber at 15% average MC. MOE and F_b are for edgewise loading in bending. Allowable properties from AF&PA (1997).

performance is a function of many factors, only one of which is material performance.

CONCLUSIONS

From the results of this study, we conclude:

1. For solid-sawn lumber and LSL, the MOE in static, edgewise bending for lumber equilibrated at 15% RH was about the same as that for 65% RH. Data are not available for LVL.
2. For solid-sawn lumber and LVL, the MOE by transverse vibration was about the same for 15% and 65% RH. The Etv value for LSL for 15% RH appeared to be slightly higher than that for 65% RH.
3. For MOR of solid-sawn lumber, the ratio of the value for 15% RH to that for 65% RH varies slightly with species with values from 5% higher to 8% lower at 15% RH compared with 65% RH. There was little difference in MOR for LVL and LSL at the two humidity levels.
4. The UTS of solid-sawn lumber and LVL was up to 11% lower for 15% than for 65% RH, whereas there was little difference for LSL.
5. The shrinkage models of ASTM D1990 did an excellent job of predicting the average change in dimensions of solid-sawn lumber for RH changes between 65% and 15%. The models are not applicable to composite lumber.
6. In general, neither the quadratic surface model nor the models of ASTM D1990 did a good job of predicting the properties of solid-sawn lumber equilibrated at 15% RH given the properties for 65% RH. None of these models is applicable to composite structural lumber.
7. For solid-sawn lumber, the data suggest that allowable bending strength and MOE at about 4% MC could be estimated using the assigned properties at 15% MC if adjustments are made for the anticipated shrinkage. For tensile strength parallel to the grain, in addition to shrinkage, it would be necessary to take an additional reduction

TABLE 13B. *Illustration of one method for estimating allowable properties at 4% moisture content (MC) using allowable properties at 15% average MC and standard dressed dry dimension (inch-pound units).*[a]

	MOE	F_b	Ft
Property at 15% MC[b]	1.6×10^6 lb/in^2	1,500 lb/in^2	825 lb/in^2
To maintain constant	EI	RS	TA
Multiply by factor	1.1	1.07	1.1
Estimated property at 4% MC	1.76×10^6 lb/in^2	1,605 lb/in^2	908 lb/in^2
Grade to get estimated property at 4% MC	No. 1 Dense	No. 2 Dense or No. 1	No. 1

[a] MOE, modulus of elasticity obtained edgewise by static load; F_b allowable bending strength; Ft, allowable tensile strength parallel to grain; EI, moment of inertia; RS, load-carrying capacity in bending; TA, load-carrying capacity in tension parallel to the grain.

[b] No. 2 grade southern pine 38- by 89-mm (2 by 4) dimension lumber at 15% average MC. MOE and F_b are for edgewise loading in bending. Allowable properties from AF&PA (1997).

in the allowable property at 15% MC by multiplying by a factor of about 0.90 to estimate the properties at 4% MC.

ACKNOWLEDGMENTS

The authors acknowledge the support of Trus Joist, a Weyerhaeuser Business, and the Weyerhaeuser Corporation for supplying some of the lumber used in this study. The authors also acknowledge the efforts of Bob Munson and Cherilyn Hatfield of the FPL staff for their contributions in testing and data analysis.

REFERENCES

AF&PA. 1997. National design specification for wood construction (NDS). American Forest & Paper Association, Washington, DC.

APLIN, E. N., D. W. GREEN, J. W. EVANS, AND J. D. BARRETT. 1986. The effects of moisture content on the flexural properties of Douglas Fir dimension lumber. Res. Pap. FPL-RP-475. USDA Forest Serv., Forest Prod. Lab., Madison, WI. (http://www.fpl.fs.fed.us/documnts/fplrp/fplrp475.pdf)

ASTM. 2001. Annual book of standards. Volume 04.10, Wood. American Society for Testing and Materials, West Conshohocken, PA.

D198-99. Standard test methods of static tests of lumber in structural sizes.

D1990-00. Standard practice for establishing allowable properties for visually graded lumber from in-grade tests of full-size specimens.

D2395-93. Standard test methods for specific gravity of wood and wood-based materials.

D2915-98. Standard practice for evaluating allowable properties for grades of structural lumber.

D4442-92. Standard test methods for direct moisture content measurement of wood and wood-based materials.

AVRAMIDIS, L. C., AND A. A. ENAYATI. 1997. Moisture sorption and movement in Parallam and Timberstrand. Holz Roh Werkst. 55(6):365–369.

BOISE, P. J. 1959. Wood moisture content in homes. Forest Prod. J. 9(11):427–430.

BRYNILDSEN, O. A. 1977. Moisture effect in bending strength and stiffness of European spruce. Proc. CIB W18/IUFRO S5, 02-03 Working Group. London, UK.

CURRY, W. T. 1952. The effect of moisture content on the tensile strength of Sitka spruce. Aircraft Engineering 24:279.

ESKELSEN, V., W. L. GALLIGAN, B. E. SHELLEY, AND J. PETERSON. 1993. Exploring the effects of further drying on the tensile capacity of kiln-dried lumber. Forest Prod. J. 43(1):25–32.

EVANS, J. W., J. K. EVANS, AND D. W. GREEN. 1990. Computer programs for adjusting the mechanical properties of 2-inch dimension lumber for changes in moisture content. Gen. Tech. Rep. FPL-GTR-63. USDA Forest Serv., Forest Prod. Lab., Madison, WI. (http://www.fpl.fs.fed.us/documnts/fplgtr/fplgtr63.pdf)

FOREST PRODUCTS LABORATORY. 1935. Wood handbook: Basic information on wood as a material of construction with data for its use in design and specifications. USDA, Forest Serv., Forest Prod. Lab., Madison, WI.

———. 1999. Wood handbook—Wood as an engineering material. Gen. Tech. Rep. FPL-GTR-113. USDA, Forest Serv., Forest Prod. Lab., Madison, WI. 463 pp. (http://www.fpl.fs.fed.us/documnts/fplgtr/fplgtr113/fplgtr113.htm)

GERHARDS, C. C. 1982. Effect of moisture content and temperature on the mechanical properties of wood: An analysis of immediate effects. Wood Fiber Sci. 14(1): 4–36.

GORMAN, T. M. 1985. Juvenile wood as a cause of seasonal arching in trusses. Forest Prod. J. 35(11/12):35–40.

GREEN, D. W. 1981. Adjusting the static strength of lumber for changes in moisture content. Pages 86–105 *in* Proc., How the Environment Affects Lumber Design: Assessments and Recommendations. May 28–30, 1980. Unnumbered Report. USDA, Forest Prod. Lab., Madison, WI.

———. 1989. Moisture content and the shrinkage of lumber. Res. Pap. FPL-RP-489. USDA, Forest Serv., Forest Prod. Lab., Madison, WI. (http://www.fpl.fs.fed.us/documnts/fplrp/fplrp489.pdf)

GREEN, D. W., AND J. W. EVANS. 1989. Moisture content and the mechanical properties of dimension lumber: Decisions for the future. Pages 44–55 *in* Proc. Workshop on the In-Grade Testing of Structural Lumber, April 25–26, 1988. Madison, WI. Proceedings No. 47363, Forest Products Research Society, Madison, WI.

———, AND ———. 2001a. Evolution of standardized procedures for adjusting lumber properties for change in moisture content. Gen. Tech. Rep. FPL-GTR-127. USDA, Forest Serv., Forest Prod. Lab., Madison, WI. (http://www.fpl.fs.fed.us/documnts/fplgtr/fplgtr127.pdf)

———, AND ———. 2001b. Flexural properties of structural lumber products after long-term exposure to 150°F and 75% relative humidity. Pages 3–15 *in* Proc. 35th International Particleboard/Composite Materials Symposium April 3–5, 2001, Pullman, WA. Forest Products Society, Madison, WI.

———, AND D. E. KRETSCHMANN. 1994. Moisture content and the properties of clear southern pine. Res. Pap. FPL-RP-531. USDA, Forest Serv., Forest Prod. Lab., Madison, WI. (http://www.fpl.fs.fed.us/documnts/fplrp/fplrp531.pdf)

———, R. F. PELLERIN, J. W. EVANS, AND D. E. KRETSCHMANN. 1990. Moisture content and the tensile strength of Douglas-fir dimension lumber. FPL-RP-497. USDA Forest Serv., Forest Prod. Lab., Madison, WI. (http://www.fpl.fs.fed.us/documnts/fplrp/fplrp497.pdf)

———, S. M. Cramer, B. Suryoatmono, and D. E. Kretschmann. 2003. On fracture-related causes for reduction in tensile strength of southern pine lumber at low moisture content. Wood Fiber Sci. 35(1):90–101.

Gurfinkel, G. 1981. Wood engineering, 2nd ed. Kendall/Hunt Publishing Company, Dubuque, IA.

Harrje, D. T., G. S. Dutt, R. G. Gibson, D. I. Jacobson, and S. Hans. 1986. Field measurements of seasonal wood moisture variations in residential attics. Pages 620–633 *in* Proc., Thermal Performance of the Exterior Envelopes of Buildings. December 2–5, Clearwater Beach, FL. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, GA.

Hoffmeyer, P. 1978. Moisture content–strength relationship for spruce lumber subjected to bending, compression, and tension along the grain. Pages 70–91 *in* Proc. IUFRO Wood Engineering Group meeting. August 1978, Vancouver, BC.

———. 1980. The moisture–mechanical property relationship as dependent on wood quality. Pages 60–71 *in* Proc. IUFO All-Division V Conference, Oxford, England.

Hopkins, W. C. 1962. Moisture content of house framing. Forest Prod. J. 12(8):363–366.

Johnson, R. A., J. W. Evans, and D. W. Green. 2003. Confidence intervals for ratios of percentiles from two Weibull populations. Res. Pap. FPL-RP-606. USDA, Forest Serv., Forest Prod. Lab., Madison, WI (in press).

Kersavage, P. C. 1973. Moisture content effect on tensile properties of individual Douglas-fir latewood tracheids. Wood Fiber. 5(2):105–117.

Kretschmann, D. E., and D. W. Green. 1996. Modeling moisture content–mechanical property relationships for clear southern pine. Wood Fiber Sci. 28(3):320–337.

Lee, J. N., R. C. Tang, and J. Kaiserlik. 2001. Nondestructive evaluation of modulus of elasticity of yellow-poplar LVL: Effect of veneer-joint design and relative humidity. Wood Fiber Sci. 33(4):510–521.

Madsen, B. 1975. Moisture content–strength relationships for lumber subjected to bending. Can. J. Civil Eng. 2(4): 466–473.

———, and P. C. Neilsen. 1981. Investigation of test parameters in parallel-to-grain tension. Report No. 24. Department of Civil Engineering, University of British Columbia, Vancouver, BC.

———, W. Janzen, and J. Zwaagstra. 1980. Moisture effects in lumber. Report No. 27. Department of Civil Engineering, University of British Columbia, Vancouver, BC.

McLain, T. E., A. L. DeBonis, D. W. Green, F. J. Wilson, and C. L. Link. 1984. The influence of moisture content on the flexural properties of southern pine dimension lumber. Res. Pap. FPL-RP-447. USDA, Forest Serv., Forest Prod. Lab., Madison, WI. (http://www.fpl.fs.fed.us/documnts/fplrp/fplrp447.pdf)

Nelson, S. 1997. Structural composite lumber. Pages 147–172 *in* S. Smulski, editor in chief. Engineered wood products: A guide for specifiers, designers and users. PFS Research Corporation, Madison, WI.

Ostman, B. A-L. 1985. Wood tensile strength at temperatures and moisture contents simulating fire conditions. Wood Sci. Technol. 19(2):103–116.

Pu, J. H., and R. C. Tang. 1997. Nondestructive evaluation of modulus of elasticity of southern pine LVL: Effect of veneer grade and relative humidity. Wood Fiber Sci. 29(3):249–263.

Simpson, W. T. 1998. Equilibrium moisture content of wood in outdoor locations in the United States and world wide. Res. Note FPL-RN-0268. USDA, Forest Serv., Forest Prod. Lab., Madison, WI.

Tang, R. C., and J. H. Pu. 1997. Edgewise bending properties of laminated veneer lumber: Effect of veneer grade and relative humidity. Forest Prod. J. 47(5):64–70.

———, J. N. Lee, and J. Kaiserlik. 2000. Bending properties of yellow-poplar laminated veneer lumber subjected to 1-year open-shed exposure. Pages 3.3.3-1 to 3.3.3-7 *in* Proc., World Conference on Timber Engineering 2000. July 31–August 2, 2000, Whistler, BC. University of British Columbia, Vancouver, BC.

Wilson, T. R. C. 1932. Strength–moisture relations for wood. Technical Bulletin No. 32. U.S. Department of Agriculture, Washington, DC.