EFFECT OF GROWTH RING ORIENTATION AND PLACEMENT OF EARLYWOOD AND LATEWOOD ON MOE AND MOR OF VERY-SMALL CLEAR DOUGLAS-FIR BEAMS

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ABSTRACT

ASTM standard sizes for bending tests (either 50×50 mm or 25×25 mm in cross-section) are not always suitable for research purposes that characterize smaller sections of wood. Moreover, the ASTM standards specify loading the sample on the longitudinal-tangential surface. If specimens are small enough, then the effects of both growth-ring orientation and whether earlywood or latewood is on the upper and lower surfaces could affect values of modulus of elasticity (MOE) and modulus of rupture (MOR). The objectives of this study were to assess the effects of growth-ring orientation and latewood/earlywood location on bending properties of Douglas-fir specimens ($10 \times 10 \times 150$ mm). MOE did not differ with ring orientation, and MOR was about 5% higher when specimens were loaded on the radial rather than the tangential surface (MOE-LT vs. MOE-LR, respectively). The choice of growth-ring orientation did not affect the relative ranking of trees with respect to MOR or MOE. As expected, the variation of MOR and MOE was lower if the loads were applied to the longitudinal-radial surface than the longitudinal-tangential surface. Thus, rather than following the ASTM standard, within-tree variation measured on very small bending specimens can be minimized if loads are applied to the longitudinal-radial surface. When specimens were loaded on the longitudinal-tangential surfaces, there was an effect on both MOE-LR and MOR-LR of whether the top and/or bottom surfaces were earlywood or latewood. The wood type had a large effect on both MOE-LR and MOR-LR when it was the compression surface rather than the tension surface. This result suggests that variance in MOE and MOR measurements in very small specimens can be reduced by tracking whether the top and bottom surfaces are earlywood or latewood.

Keywords: Size effect, growth-ring orientation, MOE, MOR, Douglas-fir, bending, orthotropic material, small bending specimens.

INTRODUCTION

In our study of the effect of a recent disease outbreak on wood properties, we needed to perform mechanical tests on small samples that contained only the wood that had been produced since the onset of disease (Johnson et al. 2005). The small samples (10- × 10-mm cross-sections) provided an opportunity to study the effects on modulus of elasticity (MOE) and modulus of rupture (MOR) of a) sample orientation (application of the load to the longitudinal-tangential vs. the longitudinal-radial faces), and b) earlywood and latewood positions on the beams with the load applied to the longitudinal-radial face. The North American Standard for evaluating bending strength and stiffness of wood is given by ASTM standard D 143 (ASTM 2003). The recommended sample dimensions for bending specimens are 50 by 50 mm in cross-section and 760 mm long. The standard also provides for a secondary size, 25 by 25 by 410 mm. However, both of these sizes were too large for the research problem at hand.

Various reports have shown that the modulus of elasticity (MOE) and modulus of rupture (MOR) values obtained from bending tests of small clear specimens are well correlated to larger dimension samples from the same material (e.g., Bohannan 1966). However, it is not expected that the values for large and small samples should be the same. For MOE, species with large differences in wood properties across the growth ring should be sensitive to decreases in specimen size, especially as the specimen size approaches a radial dimension that is similar in scale to several growth rings. For MOR, small samples typically have higher MOR than larger samples. This size effect results because the probability that a strength-reducing characteristic will occur in a sample increases as the sample's volume increases (reviewed in Bohannan 1966; Bodig and Jayne 1982).

ASTM Standard D 143 specifies that small clear specimens of either dimension shall be tested with the load applied to the longitudinal-tangential surface (LT) and with the pith side in compression. Beams in this orientation are referred to as LR beams because the longitudinal-radial (LR) plane is the active bending plane and controls MOE-LR and MOR-LR (Fig. 1). Conversely, several European standards recommend testing with the load applied to the longitudinal-radial surface (LR; Adamopoulos 2002). When the bending test is conducted with the load applied to the LR surface, the active bending plane is the longitudinal-tangential (LT) plane, so the beams are referred to as LT beams and the values calculated are MOE-LT and MOR-LT (Fig. 1).

The difference between the protocols has several implications considering the anatomical structure of wood. The MOE of the radial and tangential orientations in wood are significantly different as determined by tension and compression tests. (Brunell 1945, Schniewind 1959; Panshin and deZeeuw 1980; Beery et al. 1983; Burgert et al. 1999, 2001). These papers have shown that ray cells are responsible for the differences in strength and stiffness in the tangential-radial and radial-tangential orientations. In contrast to pure tension and compression tests, the results of bending tests are dominated by the longitudinal stiffness, and stiffness differences across the grain are secondary. Studies in the ring-porous hardwood *Robinia pseudoacacia* L. (Adamopoulos 2002) and in southern pines (Biblis 1971) found no significant differences in MOE and MOR of LR vs. LT beams. Both studies used beams of larger cross-
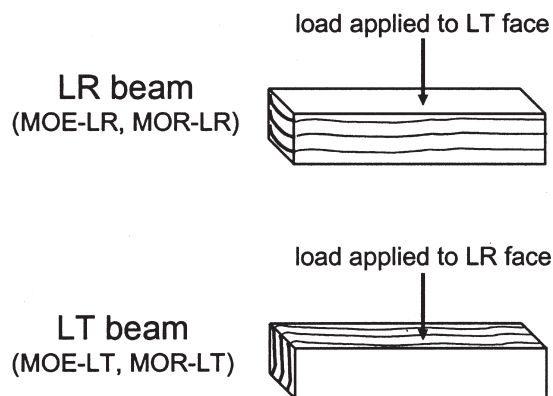

FIG. 1. Schematic diagram of longitudinal-radial (LR) and longitudinal-tangential (LT) beams showing the face to which the load is applied and the terminology for the MOEs and MORs that are calculated.

sectional area (20×20 mm and 25 to 35 by 25 to 35 mm) than the samples examined here. Growth-ring widths were not reported for either study. Forsaith (1933, as cited in Biblis 1971) tested matchstick-sized southern pine specimens. He found larger effects of earlywood or latewood locations in specimens (in LR beams) than the effects of loading on the LT vs. the LR plane. These data and theory both suggest that in small specimens (approaching the width of several individual growth rings) there should be 1) more variance in MOE-LR and MOR-LR than in MOE-LT and MOR-LT; and 2) there should be an effect of the location of earlywood and latewood (on the top and/or bottom faces of the bending sample), with latewood on the surfaces increasing MOE-LR and MOR-LR, and earlywood on the surfaces decreasing these values.

In southern pine, MOR was about 10% higher in LT than LR beams (Biblis 1971). The author gave no interpretation for why wood structure caused this result.

The current study undertook bending tests on small specimens (10×10 mm in cross-section) of Douglas-fir (*Pseudotsuga menziesii*). The objectives were:

To evaluate the effects of ring orientation on MOE and MOR as determined by loading on the longitudinal-radial vs. the longitudinal-tangential face;

To assess patterns of variation in MOE and MOR within and among trees with respect to ring orientation;

To examine whether position of the earlywood and latewood affects MOE-LR or MOR-LR;

To explore the relationship between ring width and the difference in MOE and MOR with respect to ring orientation;

To determine whether the ring orientation affects the relative ranking of individual trees with respect to MOE and MOR.

METHODS

Two samples of Douglas-fir trees were selected for the study. The first sample was used to examine the effect of growth-ring orientation on MOE and MOR by comparing LR to LT beams. It consisted of 35 trees, eight beams per tree. Each tree was selected from a different even-aged stand in the Oregon Coast Range or western slope of the Oregon Cascades. Tree age at breast height ranged from 19 to 49 years.

A second sample of trees (18 of which were in common with the first sample) was used to assess the effects of earlywood and latewood position in beams loaded on the LT face on MOE-LR and MOR-LR. The samples came from stands used to examine the impact of Swiss needle cast on wood quality (Johnson et al. 2005). There were 18 stands, 10–12 trees per stand, for a total of 200 trees. Again, there were eight beams per tree. Sixteen of the stands were from the Oregon Coast Range and two were from the western slopes of the Oregon Cascades. Tree age at breast height ranged from 17 to 32 years.

For all trees in both samples, a 300-mm-long section of stem was taken beginning at 1400 mm above the ground (breast height). Eight beams, 10×10 mm in cross-section and 300 mm long, were cut from each stem section. The beams were from the outermost growth rings and were evenly distributed around the stem's circumference. Depending on growth rate of the tree, the specimens contained one to ten annual rings. Ring orientations were such that the specimens could be tested as either true LR or true LT beams.

From the sample of 35 trees, four of the eight beams from each tree were tested as LR beams (n = 140) while the other four samples from each tree were tested as LT beams (n = 140). For the set of 200 trees, all of the beams were tested as LR beams except for the 18 trees that were common to the first sample. For LR beams, we recorded whether the top and bottom surfaces were made of earlywood, latewood, or a mixture (transition wood).

The specimens were conditioned to 12% moisture content. The bending tests were conducted with a 150-mm span. The specimens were center-loaded, and the displacement-controlled load rate was 5 mm/min.

Differences due to the growth-ring orientation for MOE and MOR were tested using the statistical model:

$$\text{MOE} \quad (\text{or MOR}) = \text{Tree}_i + \text{Load}_j + \\ \text{Tree} \times \text{Load}_{ij} + \text{Error} \tag{1}$$

where Tree_i is the random effect of the ith tree, Load_j is the fixed effect of loading on either the tangential or radial surface, $\text{Tree} \times \text{Load}_{ij}$ is the random interaction of tree and loading surface, and Error is the variation of beams within a tree and loading surface. Tests for statistical differences were performed with the MIXED procedure of SAS (Littell et al. 1996).

The effect of wood type (earlywood, latewood, or transition wood) on the top and bottom surfaces of the LR beams was analyzed using a statistical model where the interaction of surfaces was left out of the model because it was not significant:

$$\text{MOE} = \text{Tree}_i + \text{Top surface} + \\ \text{Bottom surface} + \text{Error} \tag{2}$$

where Tree_i is the random effect of the ith tree, Top surface is the fixed effect of having either earlywood, latewood, or a combination (transition wood) on the top of the beam, Bottom surface is the fixed effect of either earlywood, latewood, or a combination (transition wood) on the bottom of the beam, and Error is the variation within a tree of beams with the same type surface on top and bottom.

RESULTS AND DISCUSSION

For each of the 217 trees studied, we took the mean of all beams per tree. We found that individual trees differed significantly in their MOE (range of 7,256 to 17,288 N/mm², p<0.0001) and MOR (range: 68.6 to 141.4 N/mm²). The tree-to-tree variation is expected in biological materials.

There were no statistically significant differences between mean values of MOE-LT and MOE-LR (Table 1). This result was consistent with the findings on samples that were about two times deeper and wider in a both a ring-porous species (Adamopoulos 2002) and in southern pines (Biblis 1971).

The MOR-LT was significantly greater than MOR-LR (p < 0.0012; Table 1), which is in agreement with Biblis (1971). The difference be-

TABLE 1. *MOE and MOR of small clear beams loaded in different growth-ring orientations: means, variance components, percent of total variation (in italics), and the repeatability (n=136 beams for both LR beams and LT beams). Bold pairs indicate statistically significant differences at p = 0.05.*

| Property | Mean | Variance components | | Repeatability |
		Among trees	Within trees	
MOE-LR N/mm2	12,104	4,307,374 (69%)	1,902,987 (31%)	0.901
MOE-LT N/mm2	12,191	5,103,839 (79%)	1,388,934 (21%)	0.936
MOR-LR N/mm2	**106.8**	262.7 (71%)	**107.4** (29%)	0.907
MOR-LT N/mm2	**112.4**	395.8 (86%)	**67.3** (14%)	0.959

tween MOR-LT and MOR-LR varied with ring width. In trees for which the mean ring width was less than 3.6 mm (about 1/8 in.), MOR-LT was always greater than MOR-LR (Fig. 2). For rings wider than 3.6 mm, there was no consistency: some trees had higher MOR-LT, and other trees had higher MOR-LR.

There appeared to be more variation associated with the LR-beams than the LT-beams (Table 1). The within-tree variation for MOE-LR was larger than for MOE-LT (1,902,987, vs. 1,388,394, p=0.0416). Similarly the within-tree variation for MOR-LR tended to be larger than for MOR-LT (107.4 vs 67.3, p=0.1170) (Table 1).
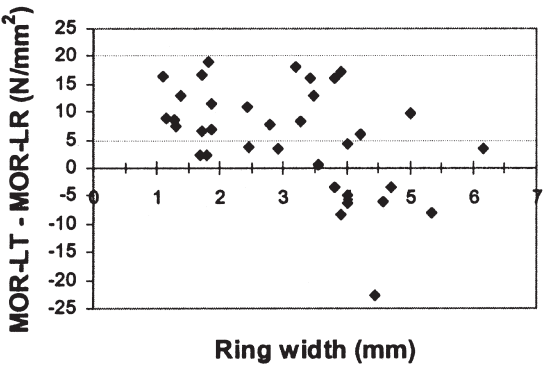

FIG. 2. Difference between mean MOR-LT and MOR-LR for each tree as a function of the mean growth-ring width in the 10- by 10-mm test specimens. Each point is the mean of eight beams.

The ranking of trees for MOE and MOR was consistent regardless of the orientation of the growth rings. Strong correlations were found between MOE-LT and MOE-LR (r=0.87) as well as between MOR-LT and MOR-LR (r=0.89) (Fig. 3). Because there is inherent spatial variation for MOE and MOR within each tree, one would not expect the correlation of sample means to be 1.0, even if both sets of samples were broken in the same direction. The estimated correlation of two samples of four-beam means being broken on the same face can be calculated theoretically with the estimate of repeatability (r_I):

$$r_I = \sigma^2_{among} / (\sigma^2_{among} + (\sigma^2_{within}/n)) \qquad (3)$$

where σ^2_{among} is the among-tree variance component, σ^2_{within} is the within-tree variance component, and n is the number of samples within a tree (four in this study).

Given the repeatabilities for the four combinations of MOE and MOR and ring orientation (Table 1), the maximum correlation that could be expected from the four-sample means was between 0.90 and 0.96. Our actual correlations of 0.87 for MOE and 0.89 for MOR (Fig. 3) were very close to these maxima, suggesting that the correlation between LT and LR was near-perfect.

The wood type on both the top and bottom of the LR beams had a statistically significant effect on MOE-LR and MOR-LR, although the effect of the wood type in the bottom position on the MOE-LR was marginal (Table 2). Both MOE-LR
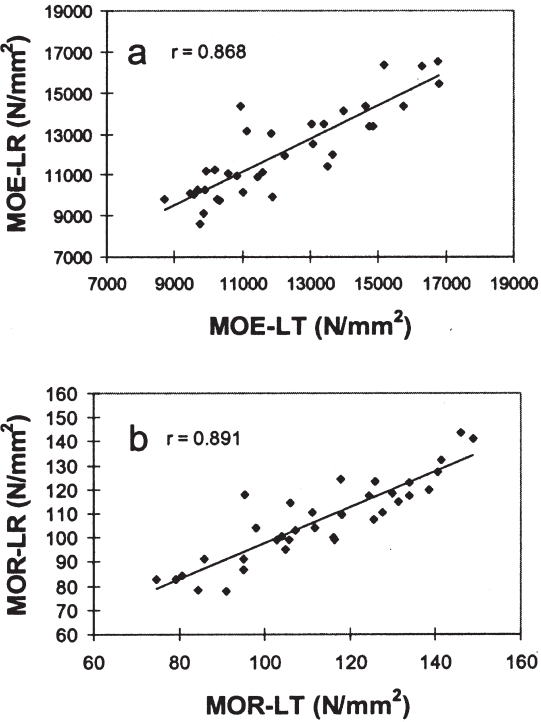

Fig. 3. Correlation of MOE-LT to MOE-LR and MOR-LT to MOR-LR; each point represents a tree, and the x- and y-values are the means of four samples each.

and MOR-LR are affected more by the wood type on the top face (compression) than the wood type on the bottom face (tension). This can be seen in the comparisons of F-values (F=70.65 vs. 2.68 for MOE-LR and F = 45.35 vs. 25.24 for MOR-

TABLE 2. *Least square mean values for MOE-LR and MOR-LR as a function of wood type (EW = earlywood, TW = transition wood, LW = latewood) on the top and bottom surfaces relative to the loading point. Also reported are F-values and probability levels for testing for differences between the wood types. Standard errors ranged from 136 to 164 for MOE-LR and 1.000 to 1.185 for MOR-LR.*

Property/location	Least square means			Statistics	
	EW	TW	LW	F value	P value
MOE-LR (N/mm²)					
Top layer	11,983	12,518	13,259	70.65	<0.0001
(n = 1,527)	(n = 312)	(n = 636)	(n = 579)		
Bottom layer	12,410	12,710	12,640	2.68	0.0691
(n = 1,527)	(n = 209)	(n = 694)	(n = 624)		
MOR-LR (N/mm²)					
Top layer	102.0	104.1	108.5	45.35	<0.0001
(n = 1,527)	(n = 312)	(n = 636)	(n = 579)		
Bottom layer	101.6	105.2	107.7	25.14	<0.0001
(n = 1,527)	(n = 209)	(n = 694)	(n = 624)		

LR in Table 2). The significant effect on MOR-LR is expected because bending yield occurs in compression before tension in small clear specimens as well as some structural-size lumber; thus, the wood type at the top of the specimen will have the largest effect on its MOR. The effect of earlywood and latewood location on MOE-LR was not necessarily expected because the increased stiffness at the outer surface should have had approximately the same effect in tension or compression. In general for these specimens, latewood on the top or bottom resulted in higher values of MOE-LR and MOR-LR, and earlywood in either location resulted in lower values.

The variation associated with latewood and earlywood on the top and bottom of the beams is one reason more within-tree variation was associated with our LR beams than our LT beams. In our second sample of 200 trees, the within-tree variation was reduced by 10% for MOE and 9% for MOR when we adjusted the values for wood type on the top and bottom of the beam.

CONCLUSIONS

For static bending tests of small, clear Douglas-fir samples (10 by 10 mm in cross-section), MOR-LT is slightly higher than MOR-LR; the difference is particularly evident in samples with narrow (<3.6-mm) growth rings. Growth-ring orientation does not affect MOE. The within-tree variation of MOR, and possibly MOE, is greater if the samples are tested as LR beams (loads applied to the longitudinal-tangential surface). Controlling the type of wood on the outer surfaces in LR beams can reduce the variation. The choice of ring orientation does not affect the relative ranking of trees with respect to MOR or MOE. However, if one is concerned about reducing within-tree error, small specimens should be tested as LT beams.

ACKNOWLEDGMENTS

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