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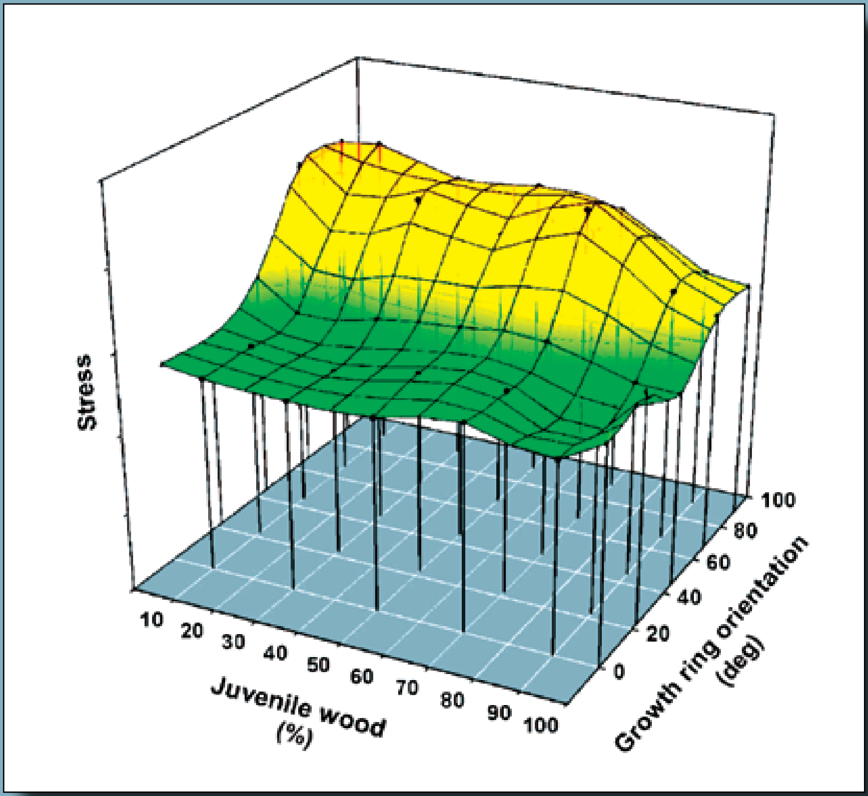
Influence of Juvenile Wood Content on Shear Parallel, Compression, and Tension Transverse to Grain Strength and Mode I Fracture Toughness for Loblolly Pine

David E. Kretschmann



Abstract

To satisfy the increased demand for forest products, much of future timber supply is expected to be from improved trees grown on managed plantations. This fast growth resource will tend to be harvested in short-age rotations and will contain higher proportions of juvenile wood than those of current harvests. In anticipation of this resource, definitive information is needed about the influence of juvenile wood on lumber properties so that grading rules or the associated allowable design stresses can be modified as needed. Most information developed to date has concentrated on ultimate tensile stress, modulus of rupture, and modulus of elasticity. This paper reports test results for shear stress parallel-to-grain, compression and tension-stress perpendicular-to-grain, and mode I fracture toughness for various percentages of juvenile wood content and ring orientations.

The clear wood properties were measured on over 340 specimens from a 28-year-old fast-grown plantation of loblolly pine (*Pinus taeda* L.) in North Carolina. The average value of all properties decreased with increasing amounts of juvenile wood in the cross section by as much as 30%. Shear strength was insensitive to annual ring orientation and seemed to be strongly dependent on just the reductions in density. Compression and tension perpendicular-to-grain strength and mode I fracture toughness were very sensitive to annual ring orientation. The results are of significance to all producers of the plantation-grown product because of the concern that fast-grown lumber from plantations may have lower allowable design stresses than those currently published for visually graded lumber.

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Keywords: juvenile wood, ring orientation, tension perpendicular-to-grain, compression perpendicular-to-grain, modulus of elasticity, loblolly pine, Southern Pine.

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Contents

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Introduction

To satisfy the demand for forest products in the United States, much of the future timber supply will be from genetically improved trees grown on managed plantations. This fast-growth resource will tend to be harvested in short-age rotations and will contain higher proportions of juvenile wood than current harvests do. Juvenile wood is the early-growth material produced by the tree, usually defined as the material 10 to 20 rings from the pith, depending on species. In anticipation of this resource, information is needed on the effect that increasing juvenile wood content has on lumber properties so grading rules and the associated allowable design stresses can be modified as needed. A significant amount of literature exists on the effect of juvenile wood on clear wood and dimension lumber in softwoods. This information, however, has been focused primarily on a few mechanical properties like modulus of elasticity (MOE), ultimate tensile stress (UTS), and modulus of rupture (MOR). The purpose of this paper is (1) to report how varying proportions of juvenile wood influenced horizontal shear, tension, and compression perpendicular-to-grain stress, mode I fracture toughness of fast-growth, and plantation-grown loblolly pine (*Pinus taeda* L.) 2 by 4s and (2) to discuss the effect that orientation of annular ring has on these results.

Background

In clear wood, properties found to influence mechanical behavior include microfibril angle, cell length, and specific gravity. Specific gravity is comprised of latewood percentage, cell wall thickness, and lumen diameter (Boone and Chudnoff 1972, Pearson and Gilmore 1971, Bendtsen and Senft 1986, Thornquist 1990, Kucera 1994). Figure 1 shows that the properties of specific gravity, cell length, strength, cell wall thickness, transverse shrinkage, and percentage of latewood generally increase with distance from the pith. Conversely, fibril angle, longitudinal shrinkage, moisture content, and spiral grain generally decrease with distance from the pith. Juvenile wood has a high fibril angle that causes excessive longitudinal shrinkage that may be more than 10 times that of mature wood (Ying and others 1994). Compression wood and spiral grain are also more prevalent in juvenile than in mature wood and contribute to excessive longitudinal shrinkage. Furthermore, early juvenile wood is distinctly more prone to shrinkage than late juvenile wood.

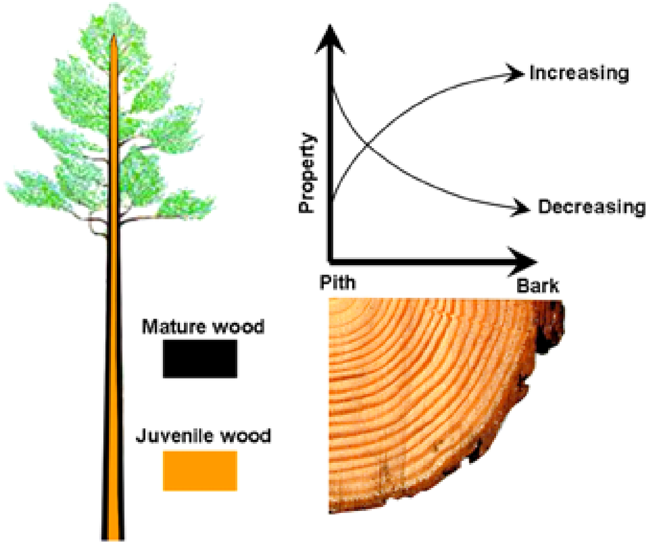

Figure 1—Juvenile wood's effect on wood properties.

In structural lumber, a potential problem with the lower mechanical properties of juvenile wood was first observed by Koch (1966) while he was involved in research to develop straight studs from Southern Pine veneer cores. Even more damaging evidence was found by Moody (1970) and Gerhards (1979). Whereas these research studies observed differences between juvenile and mature wood, neither study was designed to measure the difference between them. Because of research results like those cited and other research around the world, concerns developed in the United States and elsewhere that allowable stresses assigned to lumber do not adequately reflect the changing resource. In the 1980s, researchers began to directly assess the mechanical properties of juvenile material.

In New Zealand, in-grade testing was completed on radiata pine (*Pinus radiata* L.) lumber cut from 40- to 60-year-old (Walford 1982) and 28-year-old stands (Bier and Collins 1984). In Canada, work by Barrett and Kellogg (1989) and Smith and others (1991) looked at plantation Douglas-fir

(*Pseudotsuga menziesii*) and red pine (*Pinus resinosa*). Also, several studies were conducted in the United States on the bending and tension parallel-to-grain properties of Douglas-fir and Southern Pine dimension lumber cut from plantations (Pearson 1984, Bendtsen and others 1988, MacPeak and others 1990, Biblis 1990, Kretschmann and Bendtsen 1992).

Detailed studies of clear wood have produced a good understanding of the physical property changes that occur as juvenile wood matures and the effect on MOR, compression parallel-to-grain, and MOE (Larson and others 2001). A number of studies on solid-sawn timber provide a good understanding of the effect of juvenile wood on MOR, UTS, and MOE. The information available on the effect of juvenile wood on other properties critical for design such as horizontal shear stress, tensile stress perpendicular-to-grain (T-perp), compressive stress perpendicular-to-grain (C-perp), and mode I fracture toughness (K_{IC}), however, is minimal in comparison. This report provides information on the effect of various proportions of juvenile wood on these properties.

Experimental Methods

Origin of Sample Material

The sample material is from 700 short 610-mm (2-ft) sections taken from the undamaged ends of 2.4-m (8-ft) 38- by 89-mm (nominal 2- by 4-in.) tension specimens for which the percentage of juvenile content had been previously determined (Kretschmann and Bendtsen 1992). Juvenile wood for this material was defined as anything less than or equal to the eighth growth ring. The lumber for this study came from 100 trees cut from a 28-year old plantation in Beaufort County, North Carolina, owned by the Weyerhaeuser Company. The seed source is unknown, but the seeds were not from a genetically improved source. The plantation site was previously a farm field and had a site index of 69. The plantation was thinned twice (1973 and 1981) and fertilized at least once (1979–1980). This management regime was typical of that anticipated by the Weyerhaeuser Company at that time for the production of sawtimber trees. The sample trees averaged 409 mm (16.1 in.) diameter at breast height (dbh), ranging from 280 to 490 mm (11 to 19.3 in.). About half the trees fell in the diameter range of 355 to 420 mm (14 to 16.5 in.).

Specimen Preparation and Testing

The approximately 700 short 610-mm (2-ft) sections of 2 by 4s were sorted into seven categories according to the proportion of juvenile wood and divided equally into two groups. One of these two groups was used to cut out shear and compression perpendicular-to-grain clear wood specimens. The results of these tests had previously been reported (Kretschmann 1997). Other sections were cut into a mode I compact tension fracture and three tension perpendicular-to-grain specimens. The short sections were stored in a conditioned space held at 23°C (73°F) and 65% relative humidity (RH). Care was taken to center the specimens in a location on the wide face of the board that provided the most uniform ring orientation across the specimen's test segment.

Shear

The dimensions of the shear parallel-to-grain specimens used are shown in Figure 2. Testing of the shear block specimens was in accordance with the ASTM standard D 143 (1996) except for the specimen width and variable ring orientation. Loading rate was 0.6 mm/min (0.024 in/min). The 38-mm- (1.5-in.-) thick specimen has been shown to be an acceptable substitution for the standard 51-mm- (2-in.-) wide specimen (Bendtsen and Porter 1978). Each test specimen was classified into one of five relative ring orientations: 0°, 22.5°, 45°, 67.5°, and 90° (Fig. 2). After testing, density was determined for each specimen using ASTM D 2395 (1996) procedures.

C-Perp

The C-perp specimen size was 51 by 38 by 203 mm (2 by 1.5 by 8 in.), which has been shown to give similar results to the 51- by 51-mm (2- by 2-in.) specimen by Kenesh (1968). The load was applied to the 38-mm- (1.5-in.-) wide face (Fig. 3), with a loading rate of 0.3 mm/min (0.012 in/min). Load deflection data were collected electronically until 2.5 mm (0.1 in.) deflection. In addition to load deflection information, each test specimen was classified into one of five relative ring orientations: 0°, 22.5°, 45°, 67.5°, and 90°. To determine the 1-mm- (0.04-in.-) deflection compressive stress, a linear regression was fitted to the portion of the curve between 20% and 40% of the maximum load. This line was then fitted through the origin, and the load for the 1-mm (0.04-in.) deflection was then interpolated from the line. After testing, density was determined for each specimen.

T-Perp

Three types of tension perpendicular-to-grain specimens were tested (Fig. 4): (A) A modified ASTM D 143 (1996) specimen, in which the load was applied to the 25-mm (1-in.) by 38-mm (1.5-in.) wide face; (B) a dog-bone style specimen that was 38 by 83 by 4 mm (1.5 by 3.5 by 0.16 in.) and 25 mm (1 in.) wide at the center; and (C) a wafer specimen that was 38 by 83 by 4 mm (1.5 by 3.5 by 0.16 in.). Two side-by-side samples were produced for the dog-bone and wafer-type specimens. Loading rate was 0.30 mm/min (0.012 in/min). Load deflection information was collected electronically until a deflection of 2.5 mm (0.1 in.) for the dog-bone and wafer specimens was achieved. Each test specimen was classified into one of five relative ring orientations: 0°, 22.5°, 45°, 67.5°, and 90°.

Mode I Fracture

The mode I fracture test specimen used is shown in Figure 5. The three dimensions of the specimen were measured using a caliper. Each test specimen was classified into one of five relative ring orientations (0°, 22.5°, 45°, 67.5°, and 90°) and weighed. A small blade was used to create a sharp crack tip prior to testing. Testing was conducted in an environmentally controlled room at 23°C (73°F) and 65% RH. Testing was conducted on a 1,000-lb (453.59-kg) universal test machine with a crosshead speed of 0.60 mm/min (0.024 in/min). The specimens were suspended in hangers by two clevises. The

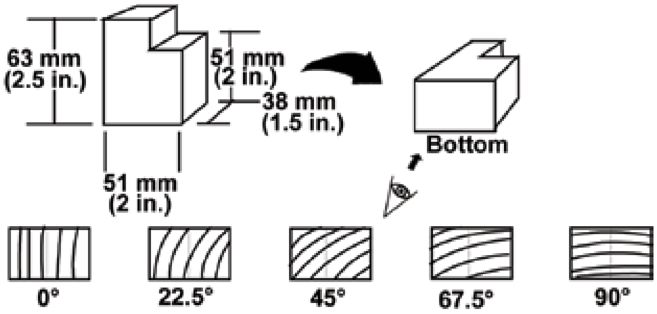

Figure 2—Shear parallel-to-grain specimen and orientations (by degree) recorded.

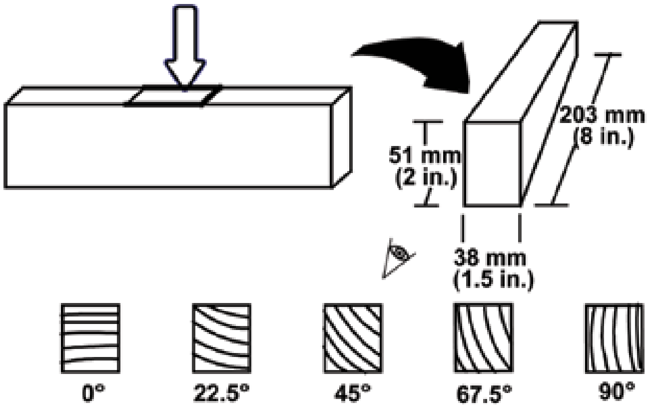

Figure 3—Compression perpendicular-to-grain specimen dimensions and orientations (by degree) recorded.

rate of crosshead movement to pull the specimen apart resulted in a time-to-failure of 1.5 to 3 min. Loads were recorded with a 100-lb (45.36-kg) load cell, and crack-opening displacement was measured using a clip gauge extensometer centered by a supporting packet. Crack-opening displacement and load were recorded on an interfaced microcomputer. Recording was stopped after the load had dropped to approximately 2/3 of the maximum load. After testing, specimens were oven-dried to determine moisture content and specific gravity.

Results and Discussion

Results for density, shear-stress parallel-to-grain stress, compression and tension perpendicular-to-grain, stress and MOE, and mode I fracture toughness for various possible combinations of orientation and percentage of juvenile wood content are summarized in Tables 1 through 10 and shown in box-plot form in the Appendix, Figures A1–A14.

Sample Sizes

When starting this study, there were a limited number of short sections in the previous tension study to choose from (Kretschmann and Bendtsen 1992). We hoped this study would provide sufficient numbers to get a representative average in all the various juvenile wood content-orientation combinations. Ultimately, specimens were distributed fairly well throughout the possible cells. Twenty eight of the possible 35 test cells had five or more specimens (Tables 1 and 2). We determined that there were sufficient numbers in the cells to examine average trends. Even though the C-perp and shear specimens were taken from the same location in the piece, there are differences in sample sizes among these specimens in the various cells. The differences are a result of variation of ring position at point of contact in the thicker C-perp specimen and ring orientation across the shear plane. The same can be said about the tension perpendicular and mode I fracture specimens.

Density

The results for density measurements for shear parallel-to-grain, compression perpendicular-to-grain, and mode I fracture toughness are summarized in Tables 1–3, respectively. Densities of the tension perpendicular-to-grain specimens were assumed to be the same as those determined for the mode I fracture specimens. Overall density of the plantation test specimens, 520 kg/m^3 (0.46 specific gravity (SG)), was 10% less than the species average of 570 kg/m^3 (0.51 SG) (Forest Products Laboratory 1999). As expected, the density decreases as the percentage of juvenile wood increases. The largest decreases in density occurred for specimens between 61% to 80% and 81% to 99% more juvenile wood content (Fig. 6). This reflects the sudden change in properties at five or six rings from the pith, as illustrated in Figure 1. The 100% juvenile wood material's density was approximately 15% lower than the 0% juvenile wood material.

Moisture Content

The average moisture contents for all specimens are listed in Tables 1–3. All cells were conditioned to similar MC values of approximately 11% with an average coefficient of variation (COV) of 9%. The shear specimens tended to be slightly dryer than the compression perpendicular-to-grain specimens. The tension perpendicular-to-grain and fracture specimens were closer to 12% MC, again with a COV of about 9%.

Juvenile Wood Content

For this material, juvenile wood content has a noticeable effect on all properties investigated. There was considerable variability in how various properties responded to increased juvenile wood content. However, increased amounts of juvenile wood generally produced lower property values. In all cases, however, the lowest values were associated with material that had the most juvenile wood. Reductions ranged from 15% to 25%.

Ring Orientation

For this material and type of specimen, annual ring orientation has little effect on shear strength parallel-to-grain. The overall average varied little for each of the orientations. As might be expected given the distinctive earlywood–latewood bands of Southern Pine, compression and tension perpendicular-to-grain and K_{IC} were sensitive to ring orientation.

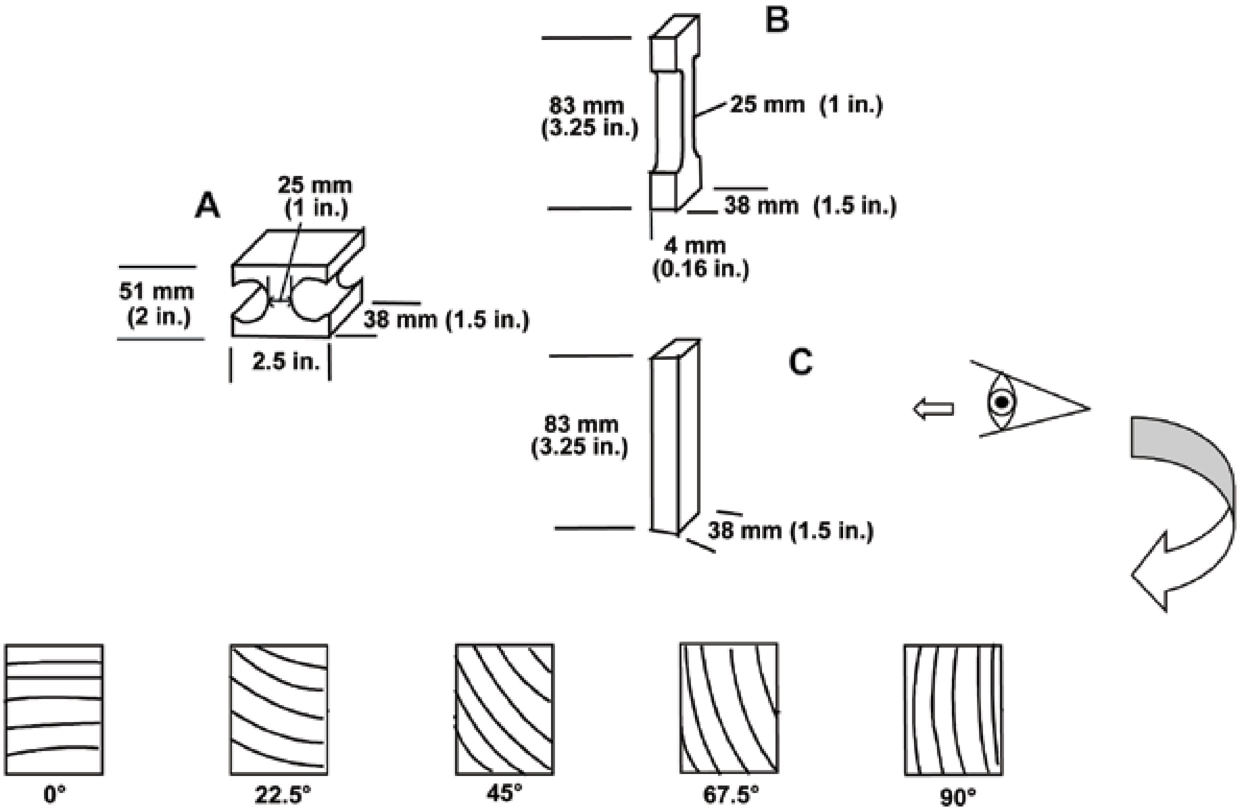

Figure 4—Three types of test specimens for tension perpendicular-to-grain test. Orientation recorded is shown by degrees.

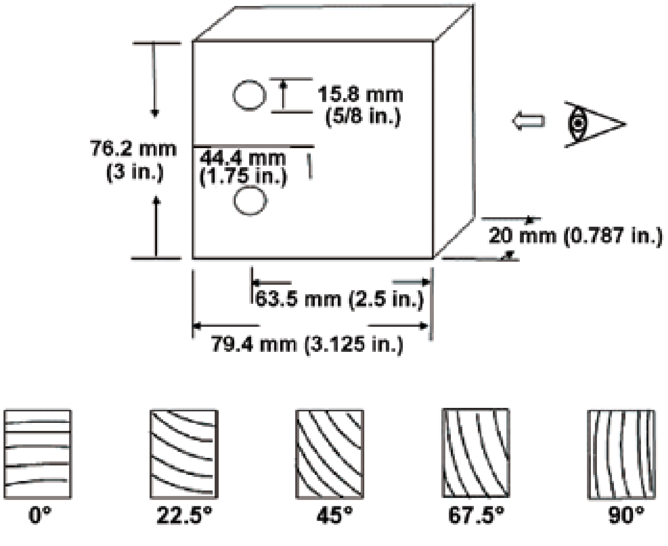

Figure 5—Test specimens for mode I fracture testing. Orientation recorded is shown by degrees.

Horizontal Shear Strength

Test results for horizontal shear are summarized in Table 4. Shear results appear to be governed primarily by density, with all orientations appearing to follow the same general trend with changes in juvenile wood content (Fig. 7). As might be expected by the lower average density, the overall test average, 8.18 MPa (1,190 lb/in^2), was less than the species average given in ASTM D 2555 (1996), 9.58 MPa (1,390 lb/in^2). Change in shear strength of 1.2 MPa (180 lb/in^2) between mature and juvenile material is what would be predicted from the change in density using a published shear-density relationship for softwoods (Forest Products Laboratory 1999). There is a noticeable shift in average properties for material containing more than 80% juvenile wood, which mirrors the behavior of density.

Compression Perpendicular-to-Grain Strength and Stiffness

Test results for compression perpendicular-to-grain are summarized in Tables 5 and 6. ASTM D 143 (1996) suggests loading specimens on a radial surface (90° orientation, Fig. 3). Overall average of compression-perpendicular strength for a 90° orientation is 10.5 MPa (1,524 lb/in^2), which is more than the 9.3 MPa (1,350 lb/in^2) species average predicted using the dry/green ratio from ASTM D 2555 (1996). The 67.5° and 90° orientation averages behave similarly and are much more sensitive to juvenile wood content than the 0° and 22.5° orientations (Fig. 8); the 45° orientation is intermediate. The 67.5° and 90° orientation averages show a drop in properties of 25%, which is more than would be suggested by their change in density. The estimated change in properties that would be predicted from the change in density is 1.3 MPa (190 lb/in^2), whereas the observed shift is nearly eight times that at 10.1 MPa (400 lb/in^2).

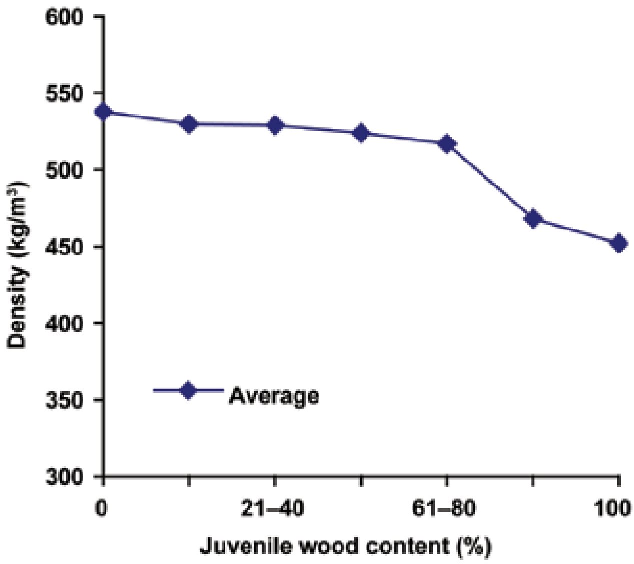

Figure 6—The effect of percentage juvenile wood on density (C-perp data).

As would be expected, compression perpendicular-to-grain MOE is very sensitive to ring orientation (Fig. 9), reaching a minimum at the 45° orientation. The 100% juvenile wood material was 25% weaker than the mature wood when the load was applied to the radial surface. Juvenile wood content had much less effect when the load was applied to the tangential surface.

Tension Perpendicular-to-Grain Strength and Stiffness

A side study was conducted to look at tension perpendicular-to-grain strength for three different tension perpendicular-to-grain specimens. The comparison of test methods will be described first and then the results for the effect of orientation and juvenile wood content on tension perpendicular-to-grain will be summarized.

Side Study of Tension Perpendicular-to-Grain Strength

The three types of specimens investigated were ASTM, dog-bone, and wafer. Comparisons of matched specimens show that the ASTM specimens are clearly correlated to the dog-bone and wafer specimens' results (Fig. 10) but with considerable scatter. The more severe stress concentration created by the geometry of the ASTM specimens resulted in the ASTM tension perpendicular strength values being about 10% below those of the dog-bone specimens. This is similar to tension perpendicular test differences reported by Markwardt and Youngquist (1956) and Kunhne (1951). The values obtained with the dog-bone or wafer specimens more closely represent the perpendicular-to-grain strength of the material because of reduced stress concentration in the dog-bone type specimen.

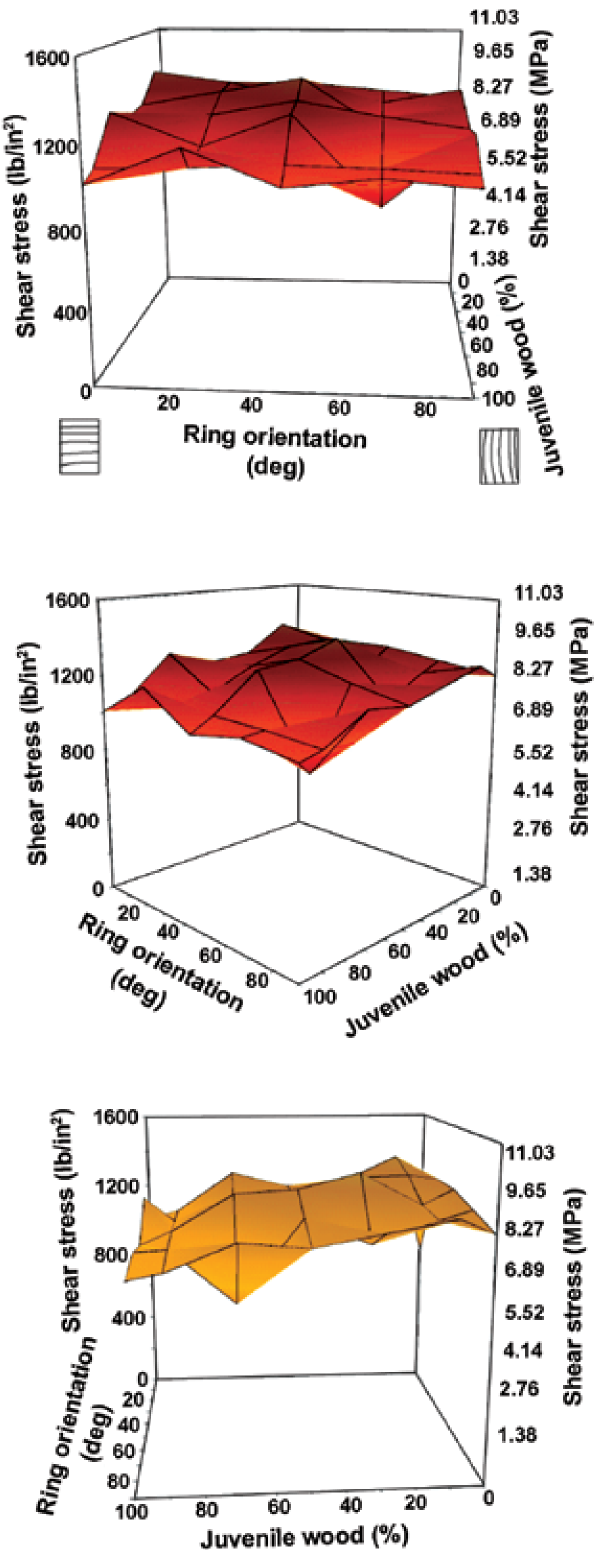

Figure 7—The effect of juvenile wood on shear strength parallel-to-grain for various orientations.

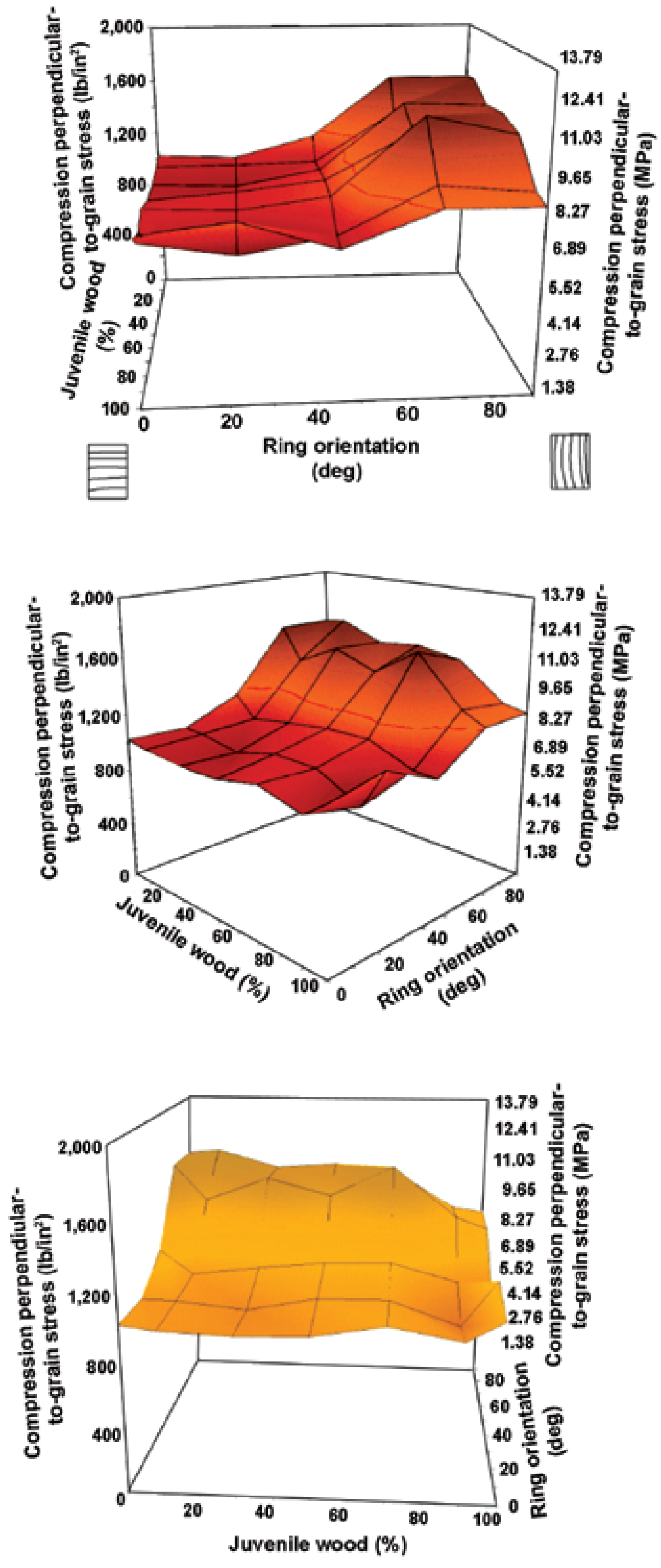

Figure 8—The effect of juvenile wood on compressive stress perpendicular-to-grain at 1-mm (0.04-in.) displacement for various orientations.

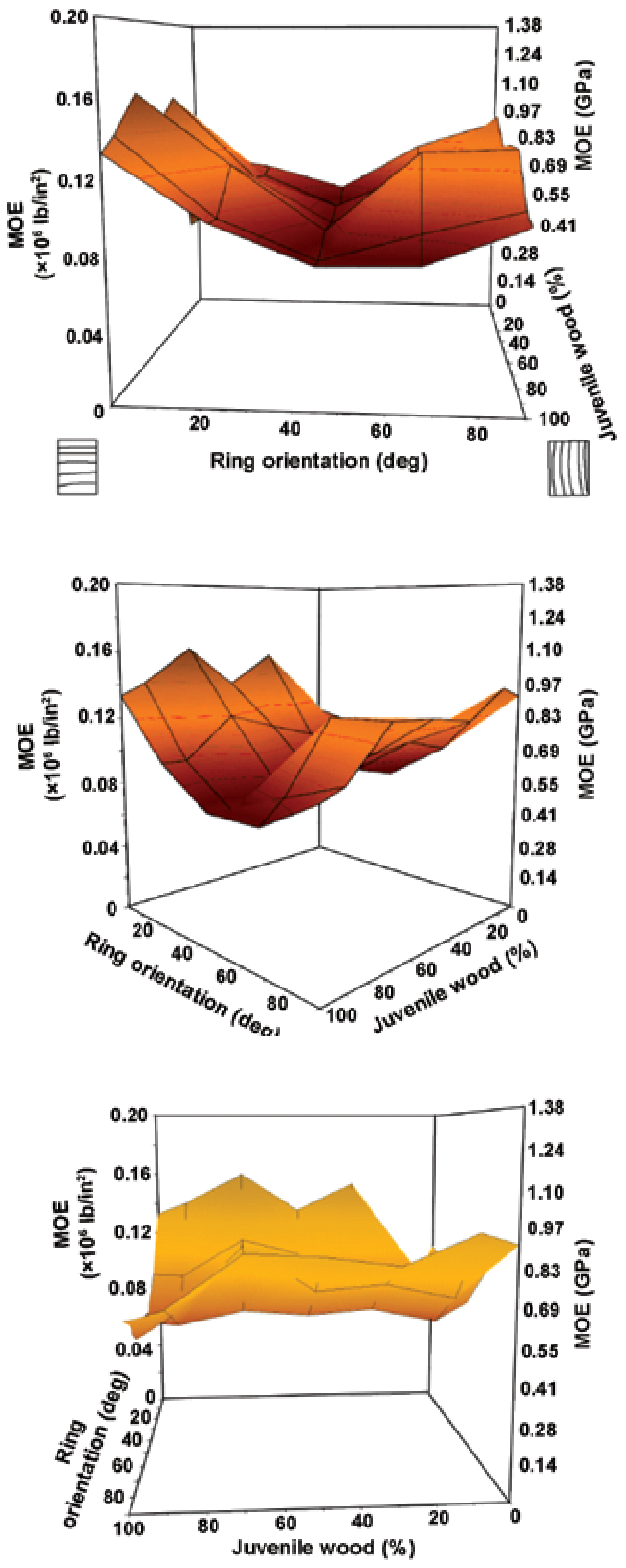

Figure 9—The effect of juvenile wood on modulus of elasticity (MOE) perpendicular-to-grain for various orientations.

There was little difference between the tension perpendicular-to-grain strength estimate obtained from the thin dog-bone specimens or wafer specimens. The correlation between wafer specimens and dog-bone specimens is strong with relatively low variation (Fig. 11), and the wafer failure pattern was quite often similar to that of the dog-bone specimen (Fig. 12). Of the three tests, results for the dog-bone specimens will be used to discuss the effect of juvenile wood and orientation of tension perpendicular-to-grain strength.

Tension Perpendicular-to-Grain Strength and Stiffness Results

The tension perpendicular-to-grain strength results were relatively consistent (Fig. 13), showing a smooth response. All levels of juvenile wood respond similarly to changes in ring orientation, and ring orientation responds similarly to changes in levels of juvenile wood. The maximum values of 5.8 MPa (850 lb/in^2) for tension perpendicular-to-grain were for low juvenile wood content and loads applied in the radial direction. The tension perpendicular strength decreased with increasing juvenile wood content and increasing angle to a minimum of 2.6 MPa (370 lb/in^2) at 100% juvenile wood with the load applied in the tangential direction. Again, like the compression perpendicular-to-grain specimens, the overall average of the tension specimens shows more of a drop (25%) in properties than would be suggested by their change in density alone.

Like the compression perpendicular-to-grain MOE, the tension perpendicular-to-grain MOE is very sensitive to ring orientation (Fig. 14), reaching a minimum at the 45° orientation. The material with the load applied in the tangential direction was more sensitive to juvenile wood content than the material with load applied in the radial direction.

Mode I Fracture Toughness

The summary of test results for mode I fracture toughness testing are given in Table 10. A graphic representation of the mode I fracture results are given in Figure 15. The unusual percentage of juvenile wood response for the 0° orientation is due to the lack of samples for mode I in this orientation. Otherwise, the response of mode I fracture toughness to juvenile content and ring orientation is similar to the tension perpendicular-to-grain response (Fig. 13). The mode I fracture toughness for juvenile wood material, 338 kPa m$^{-1/2}$ (308 lb/in^2 in$^{-1/2}$), represents a decrease of approximately 15% from the mature wood values 390 kPa m$^{-1/2}$ (355 lb/in^2 in$^{-1/2}$).

Property Relationships

Table 11 summarizes the regression relationships between specific gravity (SG), shear parallel-to-grain (Shear) and compression (C-perp) and tension perpendicular-to-grain (UTS), K_{IC} , MOE c-perp, and MOE t-perp. From this table, it is clear that only a few relationships among properties are described very well by simple linear models.

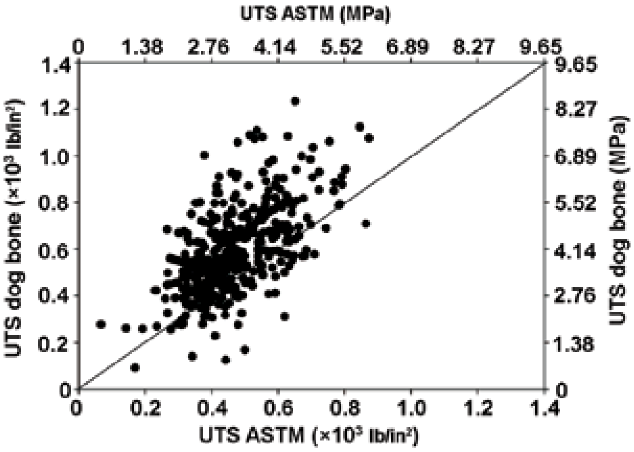

Figure 10— Ultimate tensile stress (UTS) test shows the relationship between matching ASTM 143 tension perpendicular specimen and dog-bone specimens. The solid line represents a one-to-one relationship.

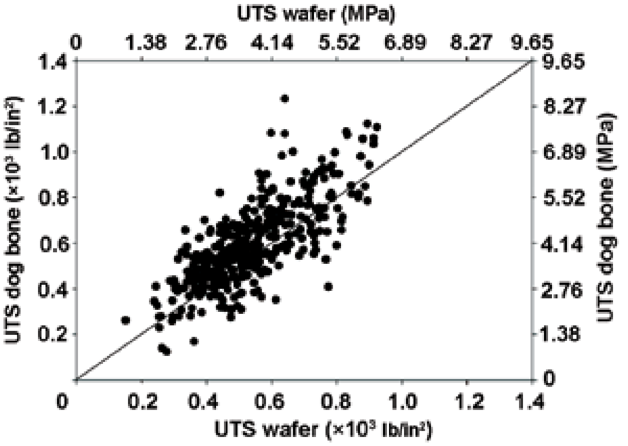

Figure 11— Ultimate tensile stress (UTS) test shows the relationship between matched wafer and dog-bone T-perp specimens. The solid line represents a one-to-one relationship.

The highest correlation ($r^2 = 0.62$) is between the shear parallel strength and specific gravity (Fig. 16). The second highest ($r^2 = 0.57$) is between the ultimate tensile strength determined from the wafer and the dog-bone specimen (Fig. 17). Then third highest ($r^2 = 0.47$) is between K_{IC} fracture toughness of a sample and the dog-bone tension perpendicular strength (Fig. 18). A future paper will present surface fits to the data collected (Kretschmann, D.E. The impact of juvenile wood content and ring orientation on shear parallel, compression and tension perpendicular-to-grain strength and mode I fracture toughness of loblolly pine. Submitted to Forest Products Journal.)

It was a bit surprising that the correlation between the MOE for compression perpendicular to the grain and the 0.04-in. deflection was not stronger ($r^2 = 0.32$) because the measured deflection when the stress is read is dependent on the

Figure 12—Example of dog-bone and wafer specimen failures. These specimens have growth ring angles of 22.5°.

stiffness of the block. If, however, the orientation of the sample is taken into account, two different trends with MOE are evident (Fig. 19). This separation is due to the distinct differences in the earlywood and latewood stiffness. There is no such pattern observed in the UTS perpendicular-to-grain data (Fig. 20).

Conclusions

This report archives the raw data for a study looking at the effect of various proportions of juvenile wood content on shear parallel-to-grain, compression and tension perpendicular-to-grain, and mode I fracture toughness at different ring orientations. Further analysis of these data will be conducted and reported in a technical journal article. A number of conclusions, however, can be drawn from this sample of loblolly pine:

- All properties tested were lowered by 15% to 30% with increased juvenile wood content.
- Changes in ASTM shear block shear strength resulting from increases in juvenile wood content can be adequately predicted by monitoring density.
- Shear strength was relatively insensitive to annual ring orientation.
- C-perp strength for loads applied to the radial surface are more sensitive to changes in juvenile content than material loaded on the tangential surface.
- Changes in compression and tension perpendicular-to-grain strength as grain angle and juvenile wood content vary are not adequately explained by density alone.
- The MOE for both compression and tension perpendicular-to-grain for all levels of juvenile wood content is quite sensitive to ring orientation.
- The dog-bone and slice perpendicular-tensile specimens correlated reasonably well with the ASTM specimen.

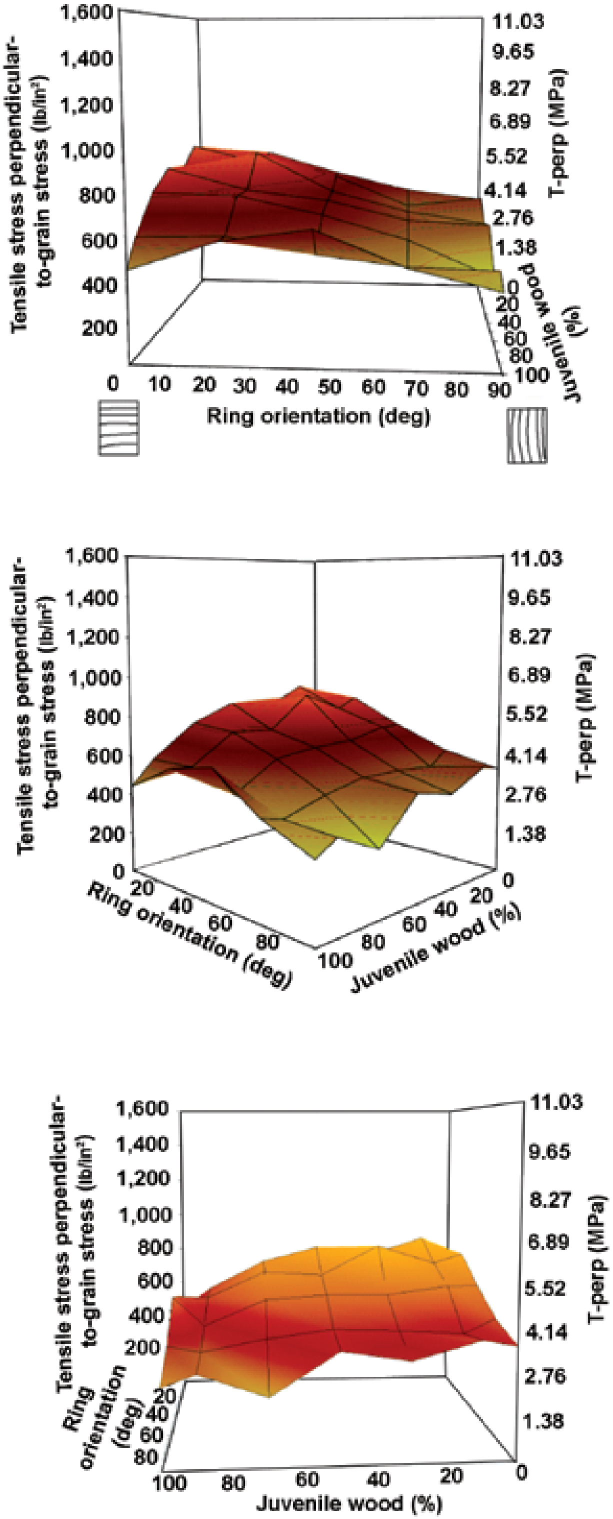

Figure 13—The effect of juvenile wood on tension perpendicular-to-grain at various grain orientations.

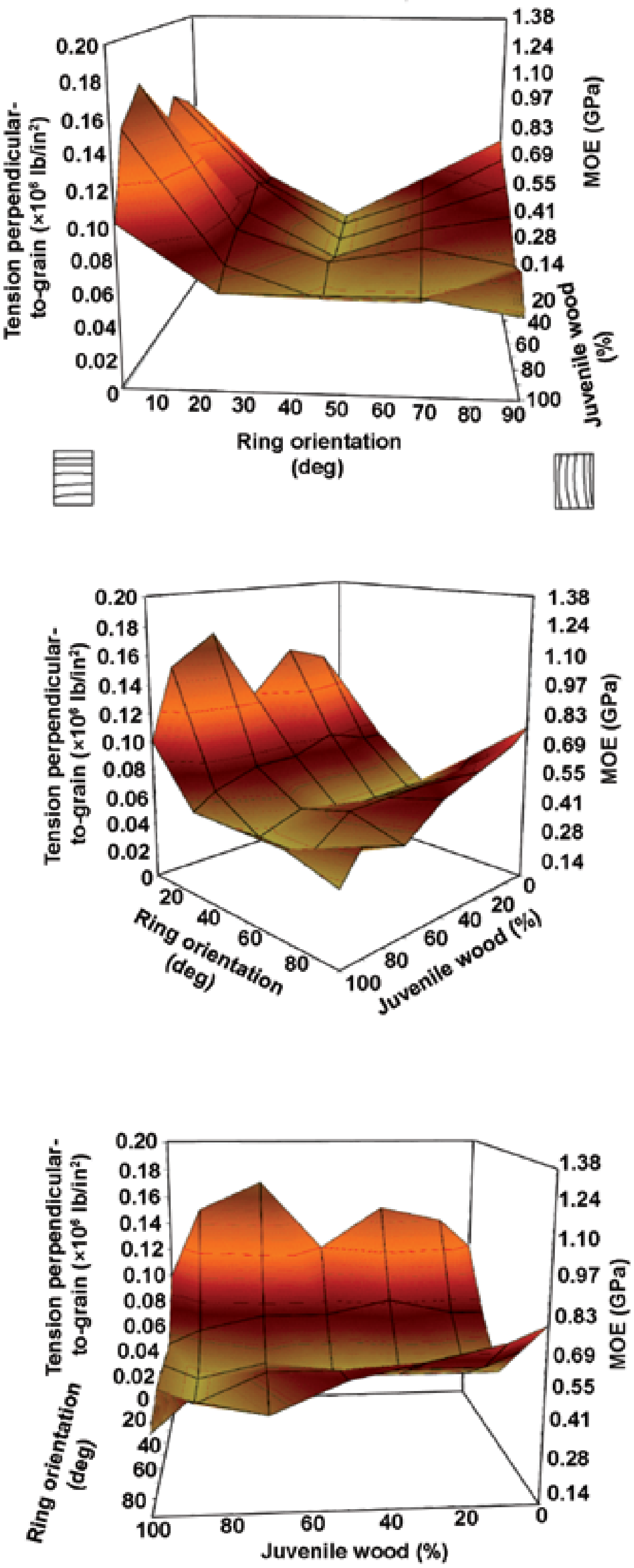

Figure 14—The effect of juvenile wood on modulus of elasticity (MOE) for tension perpendicular-to-grain at various orientations.

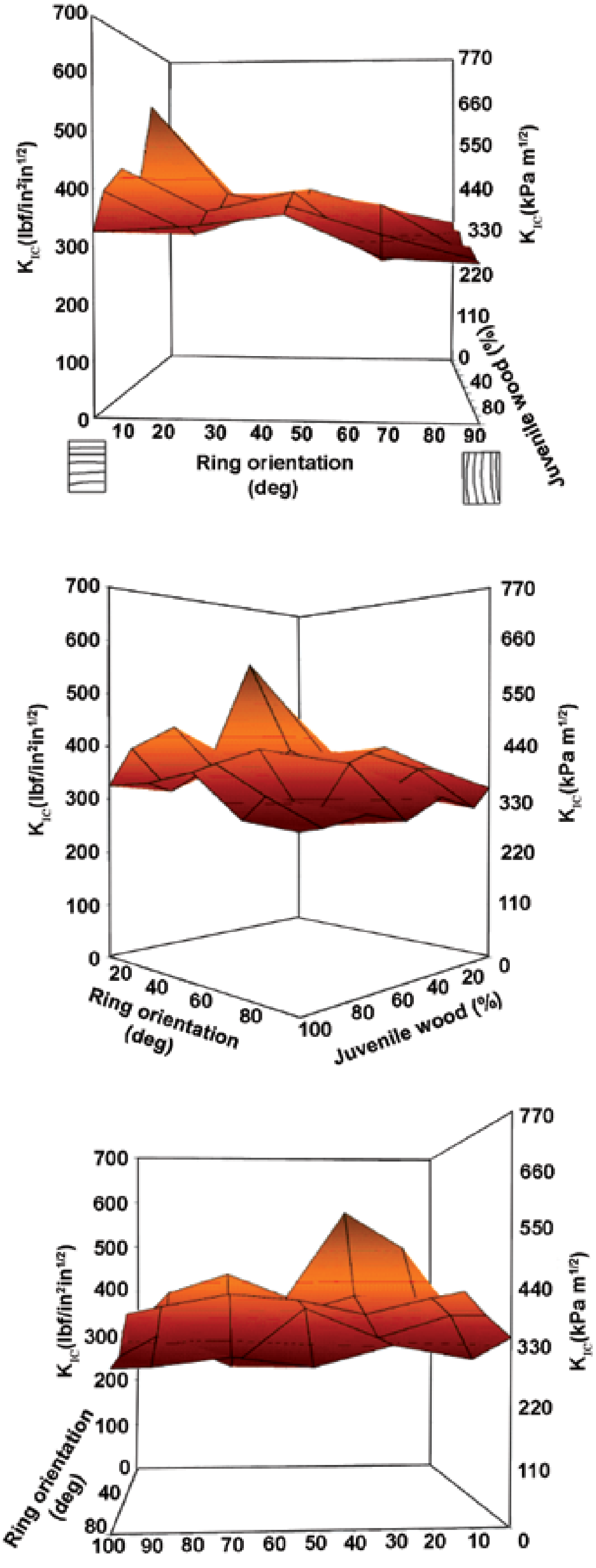

Figure 15—The effect of juvenile wood on K_{IC} fracture toughness at various grain orientations.

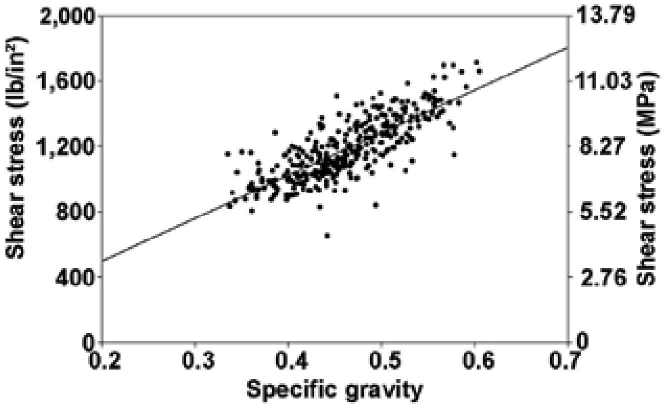

Figure 16—The relationship between specific gravity and shear parallel-to-grain strength.

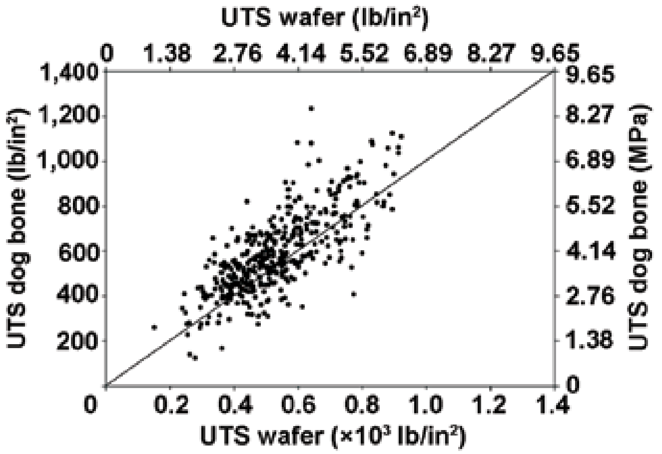

Figure 17–Relationship between wafer and dog-bone ultimate tensile strength (UTS).

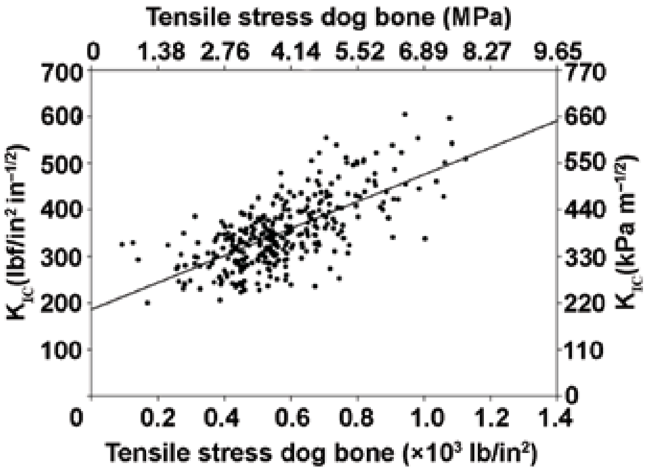

Figure 18—The relationship between tension perpendicular and K_{IC} test results.

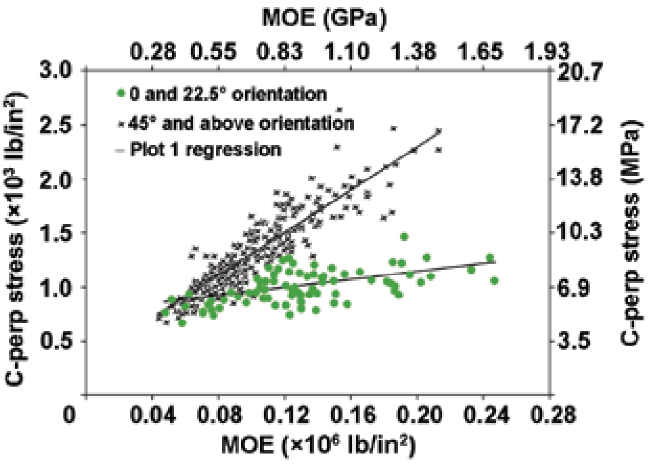

Figure 19—The relationship between modulus of elasticity (MOE) and compression stress at 0.04-in. displacement. The 0° and 22.5° orientation represents the material that is compressed in the most radial of orientations.

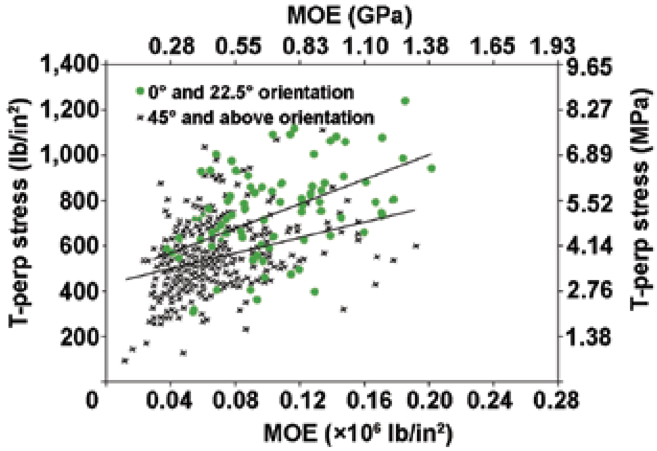

Figure 20—The relationship between ultimate tension stress perpendicular-to-grain stress and modulus of elasticity (MOE) perpendicular-to-grain. The 0° and 22.5° orientation represents the material that is loaded in the most radial of orientations.

- Orientation of load has a significant impact on perpendicular tensile strength.
- The K_{IC} values are strongly correlated with tension perpendicular-to-grain results.

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Table 1—Density and moisture content results for horizontal shear parallel-to-grain block-shear test specimens[a]

	Orientation (deg)	Values for various juvenile wood contents (%)							
		0	1–20	21–40	41–60	61–80	81–99	100	Total
	0								
A		1	6	11	4	4	6	6	38
B		550	580	540	510	560	490	440	520
C		0.50	0.52	0.48	0.46	0.50	0.44	0.39	0.46
D		10.2	10.7	10.4	10.8	9.8	11.0	11.3	10.7
E		—	—	—	—	—	—	—	—
	22.5								
A		9	10	7	12	8	13	9	68
B		510	560	530	540	490	470	480	510
C		0.45	0.50	0.47	0.48	0.43	0.42	0.43	0.46
D		10.9	10.6	10.7	10.5	10.4	10.6	10.6	10.6
E		—	—	—	—	—	—	—	—
	45								
A		18	21	8	9	11	9	14	90
B		560	520	570	550	530	490	470	530
C		0.50	0.46	0.51	0.49	0.47	0.44	0.42	0.47
D		10.4	11.1	10.3	10.5	10.8	10.5	10.4	10.6
E		—	—	—	—	—	—	—	—
	67.5								
A		17	15	8	5	3	8	7	63
B		550	510	490	510	560	480	480	510
C		0.49	0.46	0.43	0.45	0.50	0.42	0.43	0.46
D		10.9	10.8	10.9	10.4	10.4	10.8	10.9	10.8
E		—	—	—	—	—	—	—	—
	90								
A		43	8	4	11	2	12	4	84
B		530	560	560	520	530	480	460	530
C		0.48	0.50	0.50	0.46	0.47	0.43	0.41	0.47
D		10.8	10.7	10.7	10.8	11.0	11.0	10.6	10.8
E		—	—	—	—	—	—	—	—
	Total								
A		88	60	38	41	28	48	40	343
B		540	530	530	530	520	480	470	520
C		0.48	0.48	0.48	0.47	0.47	0.43	0.42	0.46
D		10.7	10.8	10.5	10.6	10.5	10.8	10.7	10.7
E		—	—	—	—	—	—	—	—

[a] A, sample size; B, density in kg/m^3; C, specific gravity oven-dry weight volume at time of test; D, moisture content; E, sample size of moisture content specimens when different from density sample size.

Table 2—Density and moisture content results for compression perpendicular-to-grain test specimens[a]

	Orientation (deg)	Values for various juvenile wood contents (%)							
		0	1–20	21–40	41–60	61–80	81–99	100	Total
	0								
A		2	5	11	7	6	7	13	51
B		560	550	530	510	490	470	440	490
C		0.50	0.49	0.47	0.45	0.44	0.42	0.39	0.44
D		11.3	11.1	10.9	10.5	10.7	11.1	11.0	10.9
E		—	—	—	—	—	—	—	—
	22.5								
A		6	9	8	8	6	9	3	49
B		530	530	530	540	510	460	480	510
C		0.47	0.48	0.48	0.48	0.45	0.41	0.43	0.46
D		11.4	10.7	10.8	11.0	10.5	11.0	10.9	10.9
E		—	—	—	—	—	—	—	—
	45								
A		21	24	8	9	12	13	13	100
B		540	530	570	530	530	460	450	520
C		0.48	0.47	0.51	0.48	0.48	0.41	0.40	0.46
D		10.9	11.5	11.1	11.4	11.1	11.1	10.8	11.2
E		—	—	—	—	—	—	—	—
	67.5								
A		16	11	4	6	2	9	4	52
B		550	510	510	490	520	490	470	510
C		0.49	0.45	0.45	0.44	0.47	0.44	0.42	0.46
D		11.3	11.2	11.0	10.8	10.6	11.2	11.6	11.2
E		—	—	—	—	—	—	—	—
	90								
A		45	12	8	10	2	10	7	94
B		530	540	500	530	530	470	460	520
C		0.47	0.48	0.44	0.47	0.47	0.42	0.41	0.46
D		11.2	11.1	11.0	11.2	11.2	11.6	11.2	11.2
E		—	—	—	—	—	—	—	—
	Total								
A		90	61	39	40	28	48	40	346
B		540	530	530	520	520	470	450	510
C		0.48	0.47	0.47	0.47	0.46	0.42	0.40	0.46
D		11.2	11.2	11.0	11.0	10.8	11.2	11.0	11.1
E		—	—	—	—	—	—	—	—

[a] A, sample size; B, density in kg/m^3; C, specific gravity oven-dry weight volume at time of test; D, moisture content; E, sample size of moisture content specimens when different from density sample size.

Table 3—Density and moisture content results for mode I fracture toughness specimens [a]

Orientation (deg)	Values for various juvenile wood contents (%)							
	0	1–20	21–40	41–60	61–80	81–99	100	Total
0								
A	4	1	2	0	0	4	4	15
B	480	500	570	—	—	480	430	480
C	0.43	0.45	0.51	—	—	0.43	0.38	0.43
D	12.7	—	—	—	—	9.7	5.8	12.1
E	12.5	10.4	12.6	—	—	12.2	11.2	11.9
F	1.8	—	—	—	—	3.2	8.6	7.1
G	—	—	—	—	—	—	—	—
22.5								
A	3	12	7	6	7	9	6	50
B	530	510	530	510	490	450	460	490
C	0.48	0.46	0.47	0.45	0.44	0.40	0.41	0.44
D	4.8	12.3	9.8	11.8	18.6	7.8	9.4	12.9
E	12.3	11.9	12.4	12.0	11.9	11.5	11.6	11.9
F	2.2	6.6	1.9	4.1	7.76	8.1	8.6	6.5
G	—	—	—	—	—	—	—	—
45								
A	17	21	17	18	9	16	9	107
B	550	530	530	530	510	480	500	530
C	0.49	0.47	0.47	0.47	0.46	0.43	0.45	0.47
D	11.0	10.8	10.2	9.8	11.7	13.1	14.4	11.6
E	11.8	11.9	12.0	11.6	12.2	12.1	12.2	11.9
F	9.8	7.6	6.8	8.3	5.3	4.9	6.2	7.3
G	—	—	—	—	—	—	—	—
67.5								
A	32	17	6	10	8	11	11	95
B	550	530	530	530	480	470	450	510
C	0.49	0.48	0.47	0.47	0.43	0.42	0.40	0.46
D	9.7	12.1	8.9	9.3	11.4	9.2	12.6	12.3
E	12.0	12.1	11.7	12.2	12.1	11.8	12.0	12.0
F	18.5	8.0	7.1	5.7	6.7	8.8	5.3	12.0
G	31	—	—	—	—	—	—	94
90								
A	30	10	7	7	4	6	10	74
B	560	530	530	530	490	460	430	520
C	0.50	0.48	0.47	0.48	0.44	0.41	0.38	0.46
D	9.8	10.6	8.9	9.1	11.7	7.1	6.0	13.0
E	11.7	11.7	12.5	11.5	12.0	12.2	11.7	11.8
F	7.7	12.1	2.6	9.2	9.0	2.1	7.7	8.0
G	29	—	—	—	—	—	—	73
Total								
A	87	61	39	41	28	46	40	342
B	550	530	530	530	510	470	460	520
C	0.49	0.47	0.47	0.47	0.45	0.42	0.41	0.46
D	10.1	11.2	9.2	9.7	13.2	10.7	12.5	12.4
E	11.8	11.9	12.2	11.8	12.1	11.9	11.8	11.9
F	13.2	8.4	5.7	7.4	6.6	6.5	7.1	9.0
G	85	—	—	—	—	—	—	340

[a] A, sample size B; density in kg/m^3; C, specific gravity oven-dry weight volume at time of test; D, coefficient of variation in percent; E, moisture content; F, moisture content coefficient of variation in percent; G, sample size of moisture content specimens when different from density sample size.

Table 4—Results for horizontal shear parallel to grain block shear test specimens[a]

	Orientation (deg)	Values for various juvenile wood contents (%)							
		0	1–20	21–40	41–60	61–80	81–99	100	Total
	0								
A		1	6	11	4	4	6	6	38
B		9.47	9.36	8.32	8.22	8.76	7.24	6.95	8.16
C		(1370)	(1360)	(1210)	(1190)	(1270)	(1050)	(1010)	(1180)
D		—	16.8	9.4	18.5	12.0	13.1	9.6	15.8
	22.5								
A		10	10	7	12	8	13	9	69
B		8.80	8.96	8.88	8.36	7.62	7.29	8.22	8.26
C		(1280)	(1300)	(1290)	(1210)	(1100)	(1060)	(1190)	(1200)
D		15.4	10.0	11.1	14.8	16.5	10.51	16.6	15.1
	45								
A		18	21	8	9	11	9	14	90
B		8.84	8.29	9.47	8.87	8.75	7.45	6.97	8.33
C		(1280)	(1200)	(1370)	(1290)	(1270)	(1080)	(1010)	(1210)
D		14.0	17.6	13.8	14.2	11.0	6.0	11.2	16.3
	67.5								
A		17	15	8	5	3	8	7	63
B		8.57	8.18	7.44	8.36	9.71	7.38	7.34	8.08
C		(1240)	(1190)	(1080)	(1210)	(1410)	(1070)	(1060)	(1170)
D		16.4	8.0	13.0	13.7	6.4	24.2	16.1	16.1
	90								
A		43	8	4	11	2	12	4	84
B		8.25	8.78	8.32	7.91	8.15	7.27	7.01	8.06
C		(1200)	(1270)	(1210)	(1150)	(1180)	(1050)	(1020)	(1170)
D		17.0	15.8	13.2	11.0	16.7	12.0	12.5	16.0
	Total								
A		89	60	38	41	28	48	40	344
B		8.51	8.54	8.48	8.34	8.49	7.32	7.32	8.18
C		(1230)	(1240)	(1230)	(1210)	(1230)	(1060)	(1060)	(1190)
D		16.0	14.6	14.0	13.9	14.0	13.2	14.8	15.9

[a] A, sample size; B, shear stress in MPa; C, shear stress in lb/in^2; D, COV (%).

Table 5—Results for compression perpendicular-to-grain test specimens compressive stress[a]

	Orientation (deg)	Values for various juvenile wood contents (%)							
		0	1–20	21–40	41–60	61–80	81–99	100	Total
	0								
A		2	5	11	7	6	7	13	51
B		7.04	6.85	6.70	6.78	7.23	6.72	7.54	7.01
C		(1020)	(990)	(970)	(980)	(1050)	(970)	(1090)	(1020)
D		13.8	16.1	13.0	10.8	16.0	16.9	15.2	14.6
	22.5								
A		7	9	8	8	6	9	3	50
B		6.81	6.55	6.54	7.14	7.09	6.07	7.99	6.74
C		(1000)	(950)	(950)	(1030)	(1030)	(880)	(1160)	(980)
D		16.1	20.9	12.5	15.5	26.5	11.3	5.2	17.6
	45								
A		21	24	8	9	12	13	13	100
B		7.98	6.99	7.34	7.57	7.65	6.84	6.76	7.31
C		(1160)	(1010)	(1060)	(1100)	(1110)	(990)	(980)	(1060)
D		24.5	18.4	11.3	20.3	17.3	20.5	13.3	20.0
	67.5								
A		16	11	4	6	2	9	4	52
B		11.09	9.52	10.52	9.81	11.20	8.89	8.34	9.98
C		(1610)	(1380)	(1530)	(1420)	(1620)	(1290)	(1210)	(1450)
D		20.6	11.9	16.4	21.9	1.3	23.7	26.1	20.9
	90								
A		45	12	8	10	2	10	7	94
B		11.09	11.21	10.42	10.65	10.28	8.58	8.32	10.51
C		(1610)	(1630)	(1510)	(1540)	(1490)	(1240)	(1210)	(1520)
D		21.1	24.8	36.5	14.4	14.3	18.3	18.2	23.7
	Total								
A		91	61	39	40	28	48	40	347
B		9.96	8.20	7.96	8.45	7.88	7.43	7.54	8.45
C		(1440)	(1190)	(1150)	(1220)	(1140)	(1080)	(1090)	(1230)
D		26.9	29.5	31.5	25.0	22.7	24.1	17.6	28.7

[a] A, sample size; B, compression perpendicular-to-grain stress at 1 mm (0.04 in.) deflection in MPa; C, compression perpendicular-to-grain stress in lb/in^2; D, coefficient of variation (%).

Table 6—Results for compression perpendicular-to-grain test specimens modulus of elasticity

	Orientation (deg)	Values for various juvenile wood contents (%)							
		0	1–20	21–40	41–60	61–80	81–99	100%	Total
	0								
A		2	5	11	7	6	7	13	51
B		0.75	0.42	1.06	0.93	1.11	0.97	0.92	0.98
C		(0.109)	(0.061)	(0.153)	(0.135)	(0.160)	(0.140)	(0.133)	(0.140)
D		61.0	42.4	38.2	19.8	39.9	16.5	16.2	30.6
	22.5								
A		7	9	8	8	6	9	3	50
B		0.70	0.67	0.70	0.76	0.81	0.67	0.67	0.98
C		(0.101)	(0.097)	(0.101)	(0.110)	(0.12)	(0.097)	(0.098)	(0.142)
D		20.0	38.2	39.2	52.2	36.8	23.2	10.9	30.6
	45								
A		21	24	8	9	12	13	13	100
B		0.59	0.52	0.57	0.57	0.57	0.52	0.53	0.55
C		(0.086)	(0.075)	(0.083)	(0.080)	(0.083)	(0.075)	(0.077)	(0.080)
D		26.6	23.9	18.2	23.7	23.2	19.0	19.0	23.0
	67.5								
A		16	11	4	6	2	9	4	52
B		0.80	0.67	0.73	0.71	0.88	0.62	0.53	0.71
C		(0.116)	(0.098)	(0.106)	(0.103)	(0.128)	(0.090)	(0.078)	(0.103)
D		27.3	10.9	18.3	21.0	9.4	26.0	22.7	24.9
	90								
A		45	12	8	10	2	10	7	94
B		0.92	0.96	0.85	0.88	0.90	0.71	0.67	0.87
C		(0.133)	(0.139)	(0.123)	(0.128)	(0.130)	(0.103)	(0.098)	(0.126)
D		22.6	30.7	26.8	15.8	26.1	24.9	22.0	25.4
	Total								
A		91	61	39	40	28	48	40	347
B		0.80	0.69	0.81	0.77	0.79	0.67	0.69	0.75
C		(0.116)	(0.101)	(0.117)	(0.112)	(0.114)	(0.097)	(0.101)	(0.108)
D		29.5	39.8	39.6	32.5	41.9	29.9	30.1	34.8

[a] A, sample size; B, compression perpendicular-to-grain MOE in GPa; C, compression perpendicular-to-grain stress in 10^6 lb/in^2; D, coefficient of variation (%).

Table 7—Results for ASTM tension perpendicular-to-grain test specimens ultimate tensile strength[a]

	Orientation (deg)	Values for various juvenile wood contents (%)							
		0	1–20	21–40	41–60	61–80	81–99	100	Total
	0								
A		4	5	7	1	4	7	4	32
B		3.94	3.52	3.84	2.54	3.00	3.59	2.83	3.48
C		(570)	(510)	(550)	(370)	(430)	(520)	(410)	(500)
D		26.5	17.6	13.8	—	31.1	31.6	14.6	24.6
	22.5								
A		10	16	16	15		11	7	89
B		3.07	3.33	3.69	3.49		2.80	3.36	3.34
C		(440)	(480)	(530)	(500)		(400)	(480)	(480)
D		13.0	27.6	21.6	25.4		26.8	27.5	25.5
	45								
A		20	24	19	22	11	16	10	122
B		3.93	3.64	3.48	3.36	3.65	3.20	3.78	3.57
C		(560)	(520)	(500)	(480)	(530)	(460)	(540)	(510)
D		24.4	22.7	23.4	25.3	20.2	28.1	23.2	24.2
	67.5								
A		32	17	8	11	10	14	13	105
B		3.09	3.44	3.00	3.25	2.75	2.81	2.47	3.01
C		(440)	(500)	(430)	(470)	(400)	(400)	(360)	(430)
D		24.6	26.8	26.4	18.9	24.0	25.4	22.5	24.1
	90								
A		29	10	9	10	5	10	12	85
B		3.04	2.60	2.80	2.50	2.48	2.65	2.28	2.71
C		(440)	(370)	(400)	(360)	(360)	(380)	(330)	(390)
D		22.5	34.1	24.0	28.8	37.8	16.3	22.7	26.3
	Total								
A		95	72	59	59	44	58	46	433
B		3.28	3.38	3.41	3.22	3.17	2.98	2.87	3.21
C		(470)	(490)	(490)	(460)	(460)	(430)	(410)	(460)
D		25.6	26.8	22.7	26.4	28.4	26.2	30.9	26.8

[a] A, sample size; B, tension perpendicular-to-grain stress in MPa; C, tension perpendicular-to-grain stress in lb/in^2; D, coefficient of variation (%).

Table 8—Results for dog-bone tension perpendicular-to-grain test specimens ultimate tensile strength[a]

Orientation (deg)	Values for various juvenile wood contents (%)							
	0	120	21–40	41–60	61–80	81–99	100	Total
0								
A	4	4	4	1	1	3	1	18
B	4.85	5.88	5.15	5.52	5.00	3.87	3.07	4.93
C	(700)	(850)	(750)	(800)	(720)	(560)	(440)	(720)
D	15.6	17.4	17.2	—	—	24.1	--	22.0
22.5								
A	9	13	13	13	11	12	6	77
B	5.49	5.17	5.85	4.75	4.88	3.96	4.02	4.93
C	(800)	(7.50)	(850)	(690)	(710)	(570)	(580)	(720)
D	15.1	28.2	17.1	30.4	28.8	25.8	31.3	27.4
45								
A	17	21	13	15	6	8	3	83
B	4.66	4.71	4.44	4.41	4.28	3.40	4.38	4.43
C	(680)	(680)	(640)	(640)	(620)	(490)	(640)	(640)
D	28.1	26.8	19.8	19.9	21.2	43.2	33.8	26.6
67.5								
A	19	9	5	7	6	8	12	66
B	3.99	3.49	3.68	3.73	3.47	3.03	3.21	3.56
C	(580)	(510)	(530)	(540)	(500)	(440)	(470)	(520)
D	22.6	9.5	10.0	12.3	25.7	15.2	19.6	20.5
90								
A	15	6	6	3	3	8	10	51
B	3.64	3.89	3.25	3.59	2.19	2.98	2.56	3.22
C	(530)	(560)	(470)	(520)	(320)	(430)	(370)	(470)
D	23.2	18.9	13.1	12.1	24.4	22.7	22.7	25.8
Total								
A	64	53	41	39	27	39	32	295
B	4.35	4.61	4.69	4.36	4.14	3.45	3.26	4.19
C	(630)	(670)	(680)	(630)	(600)	(500)	(470)	(610)
D	26.5	28.4	26.5	25.0	33.3	44.6	31.1	30.3

[a] A, sample size; B, tension perpendicular-to-grain stress in MPa; C, tension perpendicular-to-grain stress in lb/in^2; D, coefficient of variation (%).

Table 9—Results for dog-bone tension perpendicular-to-grain test specimens modulus of elasticity

Orientation (deg)	Values for various juvenile wood contents (%)							
	0	1–20	21–40	41–60	61–80	81–99	100	Total
0								
A	4	5	7	1	1	5	4	27
B	0.83	0.94	1.01	0.83	1.18	1.00	0.66	0.92
C	(0.12)	(0.14)	(0.15)	(0.12)	(0.17)	(0.15)	(0.10)	(0.13)
D	24.2	36.3	27.2	—	—	20.0	28.1	26.6
22.5								
A	10	15	14	14	13	12	6	84
B	0.55	0.56	0.63	0.57	0.55	0.46	0.44	0.55
C	(0.08)	(0.08)	(0.09)	(0.08)	(0.08)	(0.07)	(0.06)	(0.08)
D	32.5	36.3	39.5	34.8	37.9	28.7	23.7	35.9
45								
A	17	22	15	17	10	13	6	100
B	0.37	0.35	0.34	0.36	0.38	0.37	0.40	0.36
C	(0.05)	(0.05)	(0.05)	(0.05)	(0.06)	(0.05)	(0.06)	(0.05)
D	34.3	42.7	36.0	25.1	40.7	32.9	10.6	33.9
67.5								
A	25	14	6	9	6	9	12	81
B	0.52	0.50	0.46	0.45	0.46	0.34	0.41	0.46
C	(0.08)	(0.07)	(0.07)	(0.07)	(0.07)	(0.05)	(0.06)	(0.07)
D	46.3	25.7	24.9	33.2	33.3	26.3	29.5	37.8
90								
A	17	7	7	4	3	8	10	56
B	0.74	0.66	0.59	0.58	0.42	0.51	0.36	0.58
C	(0.11)	(0.10)	(0.09)	(0.08)	(0.06)	(0.07)	(0.05)	(0.08)
D	36.4	28.4	29.5	42.0	1.6	31.7	43.7	40.6
Total								
A	64	63	49	45	33	47	38	348
B	0.56	0.51	0.57	0.47	0.49	0.48	0.42	0.51
C	(0.08)	(0.07)	(0.08)	(0.07)	(0.07)	(0.07)	(0.06)	(0.07)
D	45.8	45.6	49.4	39.1	44.6	48.8	35.1	46.1

[a] A, sample size; B, tension perpendicular-to-grain MOE in GPa; C, tension perpendicular-to-grain stress in 10^6 lb/in^2; D, coefficient of variation (%).

Table 10—Results for mode I fracture toughness[a]

Orientation (deg)	Values for various juvenile wood contents (%)							
	0	1–20	21–40	41–60	61–80	81–99	100	Total
0								
A	4	1	2	0	0	4	4	15
B	438	548	636	—	—	435	357	449
C	(399)	(499)	(579)	(—)	(—)	(396)	(325)	(409)
D	11.4	—	6.2	—	—	10.2	17.4	22.3
22.5								
A	3	12	7	6	7	9	6	50
B	405	421	428	320	392	348	367	393
C	(369)	(383)	(390)	(351)	(357)	(317)	(334)	(358)
D	11.5	22.7	22.1	8.5	23.4	15.8	17.4	19.7
45								
A	17	21	17	18	9	16	8	106
B	438	424	389	419	433	406	390	416
C	(399)	(386)	(354)	(382)	(394)	(370)	(355)	(379)
D	21.8	19.0	17.4	14.5	18.7	23.7	31.3	20.2
67.5								
A	31	14	6	10	8	11	11	94
B	390	390	345	405	290	349	310	366
C	(355)	(355)	(314)	(369)	(264)	(318)	(282)	(333)
D	19.0	24.7	30.4	14.5	33.3	9.4	13.9	22.4
90								
A	29	10	7	7	4	6	9	72
B	352	313	339	300	320	302	300	328
C	(321)	(285)	(309)	(273)	(291)	(275)	(273)	(299)
D	26.7	29.0	18.6	23.8	10.0	14.6	14.0	25.1
Total								
A	84	61	39	41	28	46	38	338
B	390	397	393	391	366	370	338	381
C	(355)	(362)	(358)	(356)	(333)	(337)	(308)	(347)
D	22.8	25.4	25.1	18.4	18.4	20.7	22.4	23.5

[a] A, sample size; B, Mode I fracture toughness in kPa $m^{-1/2}$; C, mode I fracture toughness lb/in^2 $in^{-1/2}$; C, coefficient of variation (%).

Table 11—Summary of linear regressions for properties (*Y* = *b* + *m X*)[a]

Y	*X*	*b*	*m*	r^2
Shear (lb/in^2)	G shear	–26.6	2620	0.62
C-perp ($\times 10^3$ lb/in^2)	G c-perp	–0.19	3.10	0.25
MOE c-perp ($\times 10^6$ lb/in^2)	G c-perp	0.003	0.23	0.12
UTS d-bone (lb/in^2)	G t-perp	–0.033	1.42	0.16
MOE d-bone ($\times 10^6$ lb/in^2)	G t-perp	–0.01	0.189	0.08
K_{IC} (lbf/in^2 $in^{-1/2}$)	G K1c	–14.2	792	0.33
C-perp ($\times 10^3$ lb/in^2)	MOE c-perp ($\times 10^6$ lb/in^2)	0.658	5.24	0.32
UTS d-bone ($\times 10^3$ lb/in^2)	MOE t-perp ($\times 10^6$ lb/in^2)	0.402	2.568	0.23
UTS ASTM (lb/in^2)	UTS d-bone (lb/in^2)	166	0.91	0.37
UTS d-bone (lb/in^2)	UTS wafer (lb/in^2)	94.7	0.93	0.57
K_{IC} (lbf/in^2 $in^{-1/2}$)	UTS d-bone (lb/in^2)	185	0.291	0.47

[a] C-perp is compression perpendicular-to-grain strength; UTS d-bone is the ultimate tensile stress perpendicular-to-grain for the dog-bone test specimen; UTS wafer is the ultimate tensile stress perpendicular-to-grain for the wafer test specimen; UTS ASTM is the ultimate tensile stress perpendicular-to-grain for the ASTM test specimen; MOE c-perp is the MOE for compression perpendicular-to-grain specimen; MOE t-perp is the MOE for the dog-bone tension perpendicular-to-grain specimen; G is the oven-dry weight volume at time of specific gravity.

Appendix—Box Plots

Results for density, shear-stress parallel-to-grain stress, compression and tension perpendicular-to-grain, stress and MOE, and mode I fracture toughness for various possible combinations of orientation and percentage of juvenile wood content are summarized and shown in box-plot form.

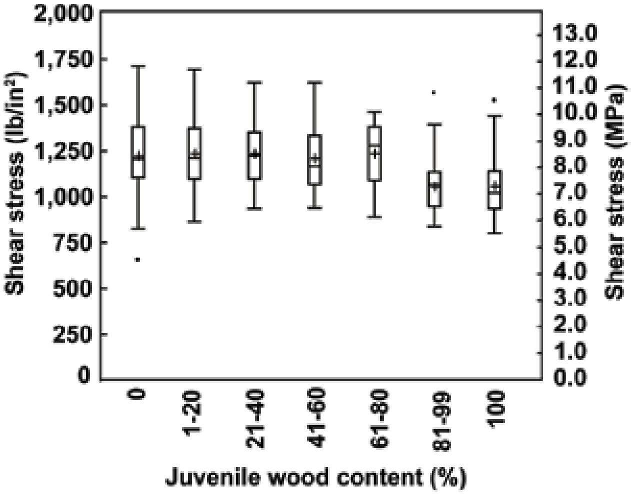

Figure A1—Shear stress compared with juvenile wood content.

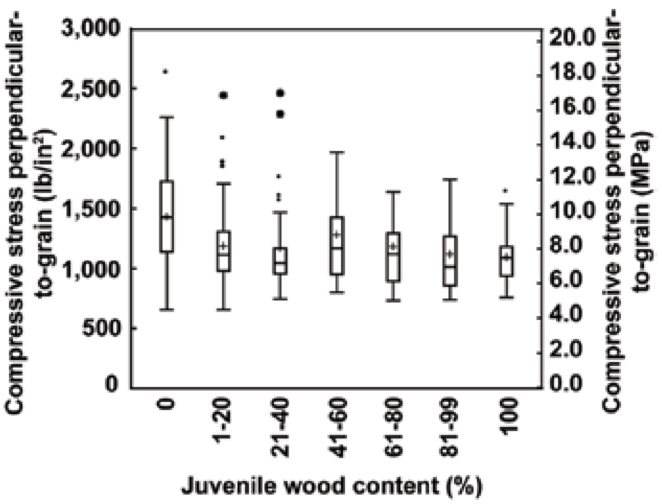

Figure A2—Compressive stress perpendicular-to-grain compared with juvenile wood content.

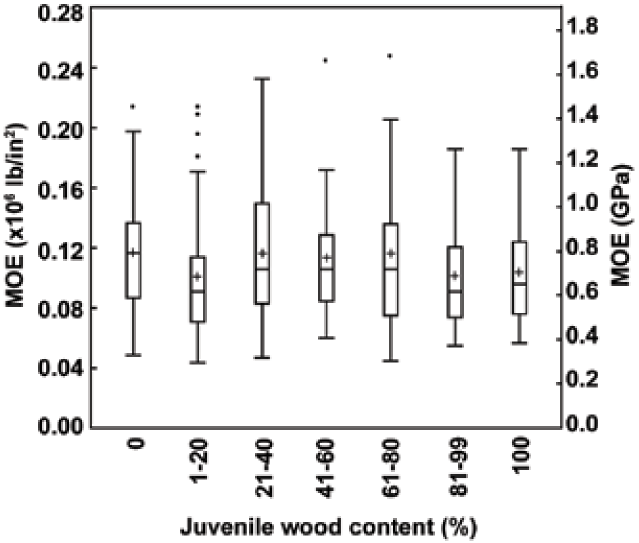

Figure A3—Compressive modulus of elasticity (MOE) perpendicular-to-grain compared with juvenile wood.

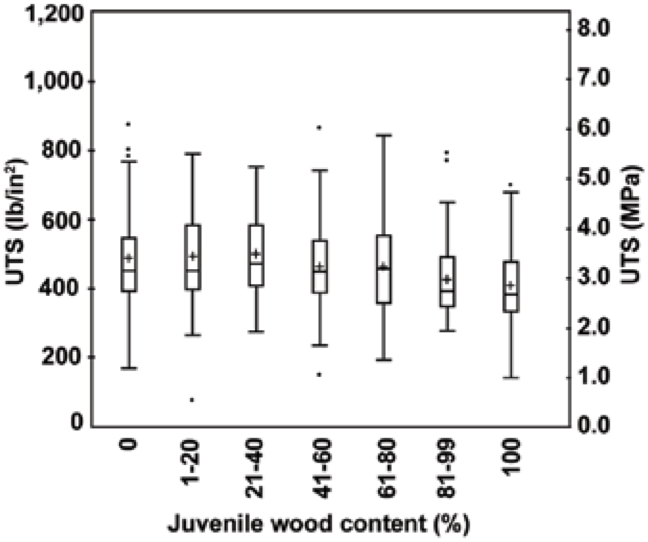

Figure A4—ASTM specimen ultimate tensile stress (UTS) perpendicular-to-grain compared with juvenile wood content.

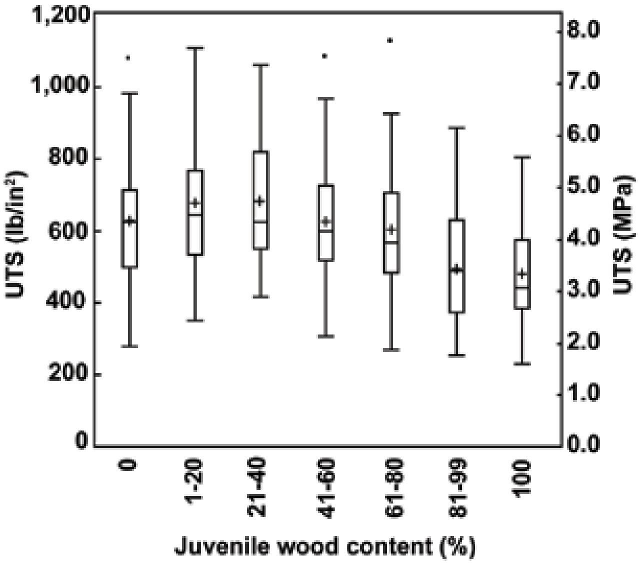

Figure A5—Dog-bone specimen ultimate tensile stress (UTS) perpendicular-to-grain compared with juvenile wood content.

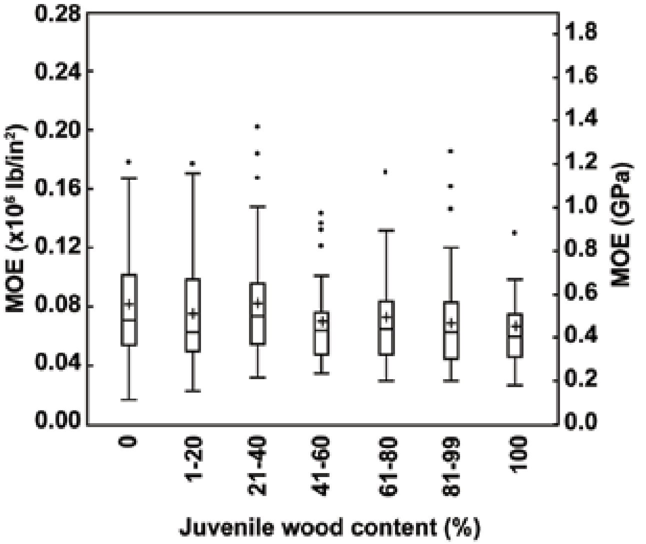

Figure A6—Modulus of elasticity (MOE) for dog-bone tension perpendicular-to-grain specimen compared with juvenile wood content.

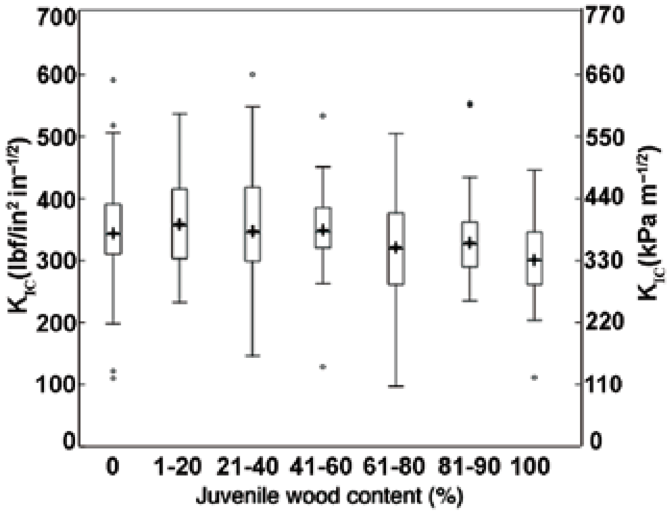

Figure A7—Mode I fracture toughness compared with juvenile wood content.

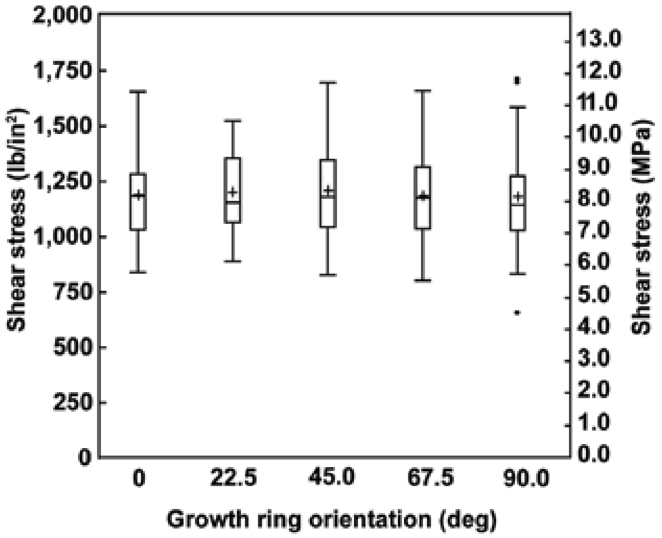

Figure A8—Shear stress compared with growth-ring orientation.

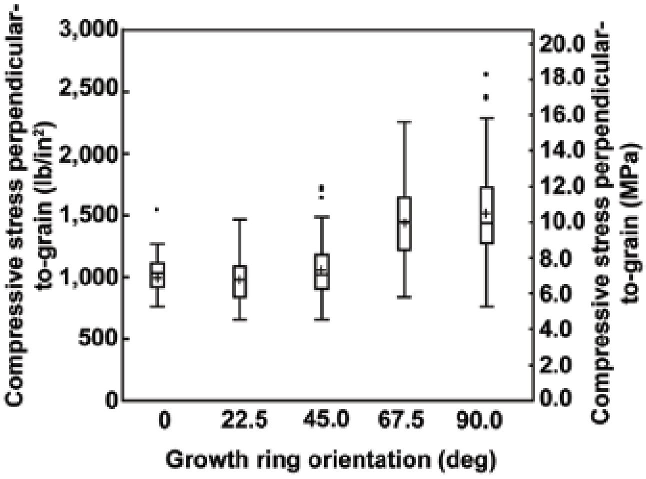

Figure A9—Compression perpendicular-to-grain stress compared with growth-ring orientation.

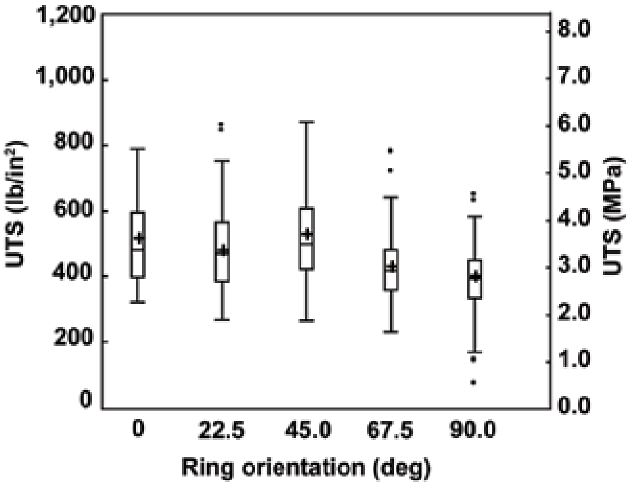

Figure A11—Ultimate tensile stress (UTS) perpendicular-to-grain for ASTM specimen compared with growth-ring orientation.

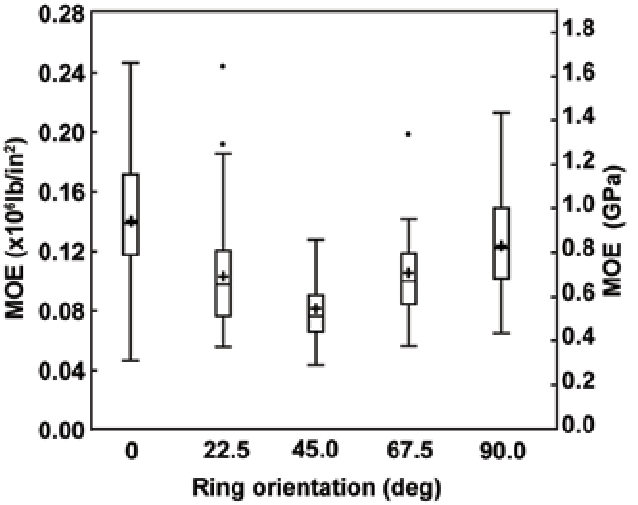

Figure A10—Modulus of elasticity (MOE) for compression perpendicular-to-grain compared with growth-ring orientation.

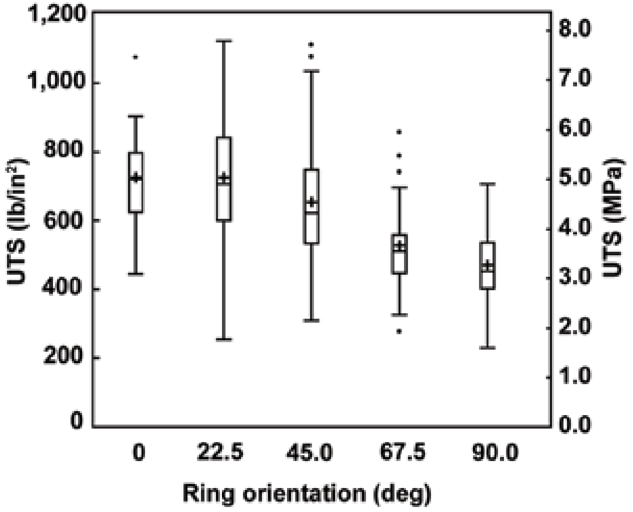

Figure A12—Ultimate tensile stress (UTS) perpendicular-to-grain for dog-bone specimens compared with growth-ring orientation.

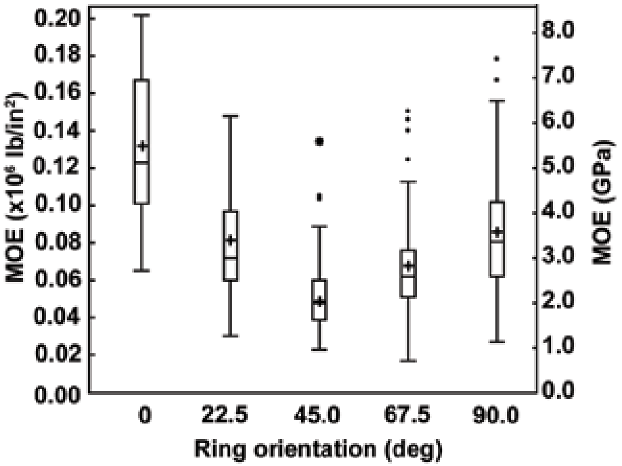

Figure A13—Modulus of elasticity (MOE) for tension perpendicular-to-grain dog-bone specimen compared with growth-ring orientation.

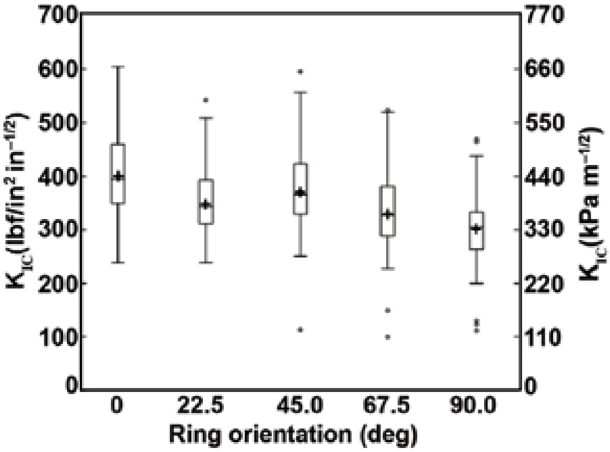

Figure A14—Mode I fracture toughness compared with growth-ring orientation.