Holzforschung, Vol. 59, pp. 531–538, 2005 • DOI 10.1515/HF.2005.088

Earlywood and latewood elastic properties in loblolly pine

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Abstract

The elastic properties of earlywood and latewood and their variability were measured in 388 specimens from six loblolly pine trees in a commercial plantation. Properties measured included longitudinal modulus of elasticity, shear modulus, specific gravity, microfibril angle and presence of compression wood. Novel testing procedures were developed to measure properties from specimens of 1 mm×1 mm×30 mm from earlywood or latewood. The elastic properties varied substantially circumferentially around a given ring and this variation was nearly as large as the variation across rings. The elastic properties varied by ring and height, but while the modulus of elasticity increased with height, the shear modulus decreased with height. A strong correlation was found between modulus of elasticity and shear modulus, but only at low heights and inner rings. Specific gravity and microfibril angle were the strongest predictors of elastic properties and explained 75% of the variation in modulus of elasticity for latewood. Despite being the best predictors in this study, these parameters accounted for less than half of the variability of earlywood modulus of elasticity, earlywood shear modulus and latewood shear modulus.

Keywords: earlywood; latewood; loblolly pine; modulus of elasticity; shear modulus; tree rings.

Introduction

The growth rings of loblolly pine provide visual evidence of a secondary structure rarely acknowledged in the processing of wood and the design of wood products. The formation of earlywood (EW) and latewood (LW) is one of the manifestations of weather and climate-based events that occur each season. The former is usually defined – as in this paper, too – as the material grown at the beginning of the growing season, with large cells and relatively thin walls, while the latter is the darker colored material typically contained in the last 1 mm of the growth ring. The radial cell diameter and secondary wall thickness are the main morphological characteristics distinguishing these two tissue types (Larson 1969).

There is a body of literature dealing with the physical properties of EW and LW, but much less is known about the mechanical properties unique to the individual layers of EW and LW, and even less on how the separate properties interact to create the whole mechanical response. McMillan (1968) sampled 40 loblolly pine trees and found the radial tracheid diameter of EW cells to be approximately twice that of LW and the cell wall thickness of EW tracheids to be approximately half that of LW. Megraw (1985) showed that the specific gravity (SG) of LW loblolly pine could be over three-fold that of EW for a given ring, with maximum SG attained in the middle of the LW band. Paul (1958) found the average SG of EW to be 0.310 g cm^{-3} and that of LW, 0.625 g cm^{-3}. Goggans (1964), Hodge and Purnell (1993), and Pew and Knechtges (1939) obtained similar results.

Megraw (1985) and Ying et al. (1994) established that the SG values of LW increased distinctively, beginning from the pith up to the 10th ring, and then were relatively constant. EW showed less variation with age. The specific gravity of EW declined during the first few growth rings and then remained relatively constant.

In addition to physical properties, Biblis (1969) also measured mechanical properties. SG ranged from 0.21 to 0.35 g cm^{-3} for EW and from 0.56 to 0.72 g cm^{-3} for LW. The modulus of elasticity along the fiber length direction (E_L) for green EW specimens was as low as approximately 1.38 GPa and for green LW as high as 9.65 GPa, but with considerably higher variability in the latter. Adjacent LW specimens positioned less than 1 mm apart had E_L values that differed by 50%. A transitional zone exists between the zones of EW and LW, where the material properties show a gradual change between the two extremes of EW and LW.

Megraw et al. (1999) conducted four-point bend tests on small EW and LW specimens. Investigating six heights, six rings and 24 trees, these researchers found that E_L values varied systematically with ring height and location. Approximately 93% of the variation in E_L was explained by the SG and microfibril angle (MFA). Booker et al. (1998) also established a strong relationship between E_L and a combination of SG and MFA for radiata pine. However, this earlier work did not consider the properties of EW and LW separately.

Groom et al. (2002a,b) and Mott et al. (2002) measured both the SG and E_L of individual fibers obtained by macerating EW and LW samples in a solution of hydrogen peroxide, distilled water and glacial acetic acid from 48-year-old loblolly pine trees harvested in an Arkansas plantation. LW slivers were removed from six growth

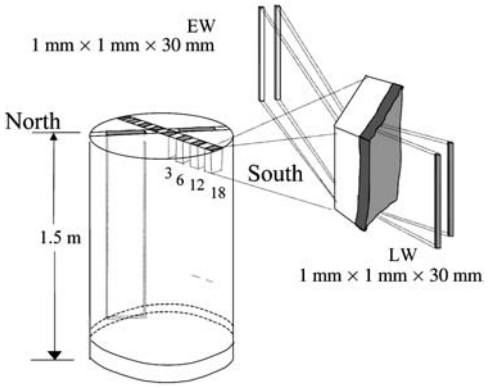

Figure 1 The cut-out pattern for earlywood (EW) and latewood (LW) small rectangular loblolly pine specimens.

rings and at 3-m intervals over the height of the tree. The average LW E_L values increased with ring number from 15.4 GPa for ring 5 to 21.6 GPa for ring 20. Similarly, EW E_L increased from 11.9 GPa for ring 5 to 16.1 GPa for ring 20. The difference in E_L values for the EW and LW fibers were attributed to differences in MFA.

The mechanical properties of EW and LW and their variations ultimately influence the behavior of wood products. The objective of this study was to establish a database of individual elastic properties of matched EW and LW specimens, not only to provide mean values for loblolly pine, but also to indicate the variability of properties and possible controlling factors. For this purpose, a novel, broadband, viscoelastic spectroscopy instrument (BVS) was used that also permits the measurement of torsional shear modulus. An extensive data set – considering multiple trees, heights, rings, and multiple directions within a ring, and including EW and LW – is presented. Results from shear modulus tests along with matched E_L values are discussed.

Materials and methods

Scope and preparation of specimens

The loblolly pine (*Pinus taeda* L.) trees investigated were geographically distributed over approximately 0.3 km^2 of a commercial plantation near Hot Springs, Arkansas. The pruning history of the plantation was recorded, as well as the location and directional orientation of each stem.

Two 1.5-m bolts were initially collected from each stem of six trees – one at breast height (1 m) and the other beginning at approximately 6 m. Of these, 10 bolts were broken down into test specimens at the USDA Forest Products Laboratory (FPL), as illustrated in Figure 1. Small blocks were cut from the original north, south, east and west directions of the bolt. From these blocks, the adjacent earlywood (EW) and latewood (LW) bands were separated into 1 mm thick×15 mm×30 mm long wafers (Figure 2) by cutting along a line with a 0.5-mm kerf scroll saw. As defined in the Introduction, EW was selected as light-colored wood from the beginning of the growing season and LW was darker-colored material contained in the last 1 mm of the growth ring. A belt sander was used to remove excess material until the wafer appeared to be composed completely of a light-colored band, EW, or a dark-colored band, LW. Each wafer was then affixed to a vacuum block and specimens of 1 mm×1 mm×30 mm were produced using a miniature table

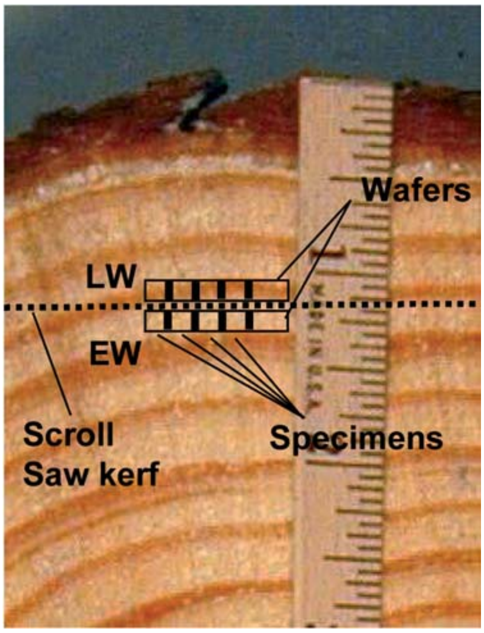

Figure 2 Adjacency and location of typical earlywood (EW) and latewood (LW) specimens.

saw with an extremely fine blade. It is possible that some samples from ring 3 may have had minor contamination of transitional cells between EW and LW, but the dark LW band of most rings was greater than 2 mm wide. Micrographs (not shown) were used to ensure the fiber direction was parallel to the specimen length and also confirmed the expected difference in cell structure between EW and LW.

These specimens were tested to determine the E_L and the longitudinal-transverse shear modulus ($G_{L\perp}$) using a unique micromechanical testing device. As shown in Table 1, tests of potential indicator properties, SG and MFA, were also conducted on the same specimens. Specimens were manufactured from the individual EW and LW bands of rings 3, 6, 12 and, where possible, ring 18 corresponding to the north, south, east and west directions of the bolt. Each specimen was subject to tests for E_L three times to minimize test-induced variability. For example, this resulted in 48 separate tests of EW E_L for bolt 1 (Table 1). A similar sequence was used to establish the shear modulus. The SG and MFA were also measured for these specimens. Investigations into the natural variability in properties led to different numbers of specimens for different bolts.

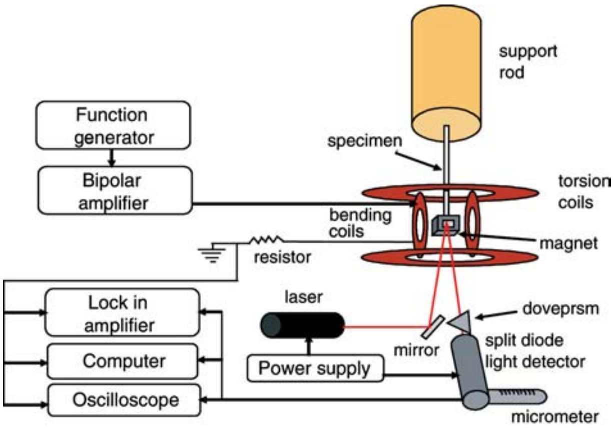

Figure 3 Schematic of the broadband viscoelastic spectroscopy device.

Table 1 Earlywood and latewood loblolly pine tests conducted: modulus of elasticity (E_L), shear modulus ($G_{L\perp}$), specific gravity (SG) and microfibril angle (MFA).

Tree	Bolt	Height in stem (m)	Rings tested	Number of tests conducted							
				Earlywood				Latewood			
				E_L	$G_{L\perp}$	SG	MFA	E_L	$G_{L\perp}$	SG	MFA
1	1	0.6	3, 6, 12, 18	48	48	16	16	156	156	52	52
	2	6.7	3, 6, 12	27	27	9	9	45	45	15	15
2	4	3.4	3, 6, 12, 18	48	48	16	16	120	120	40	40
	5	6.4	3, 6, 12	30	30	10	10	30	30	10	10
3	6	0.9	3, 6, 12, 18	48	48	16	16	81	81	27	27
	7	6.1	3, 6, 12	36	36	12	12	36	36	12	12
4	8	0.9	3, 6, 12, 18	48	48	16	16	48	48	16	16
	9	5.5	3, 6, 12	36	36	12	12	36	36	12	12
5	10	1.2	3, 6, 12, 18	48	48	16	16	96	96	32	32
9	18	0.9	3, 6, 12, 18	45	45	15	15	93	93	31	31

Test methodology

A BVS instrument (Figure 3), previously developed to study viscoelastic materials, was used to determine the moduli values of the specimens (Chen and Lakes 1989; Brodt et al. 1995). This instrument was chosen due to the small dimensions of the specimens, its capability of measuring small strains in the range of 10^{-5} – 10^{-7} and its ability to measure a torsional shear modulus in the same test configuration. Each wood specimen was glued using cyanocrylate to a brass support rod on one end, forming a fixed-free cantilevered beam with a glued magnet on the free end. The magnet was centered between two pairs of Helmholtz coils, one pair for bending and one for torsion. The coils were excited with a known voltage, producing a magnetic field that caused the specimen to deflect. The angular displacement was measured by reflecting a laser beam off a mirror, which was glued to the magnet, onto a light detector. Knowing the moment and the angular displacement of the tip of the specimen, the modulus of elasticity along the fiber direction (E_L) and the longitudinal-transverse shear modulus ($G_{L\perp}$) were calculated using the established equations for a fixed-free cantilevered beam with equal end moments (Timoshenko and Goodier 1970). The dimensions of the radial and tangential faces for each specimen were measured using microscopy (64×) at 5-mm intervals along the 30-mm length. Although non-prismatic beam calculations were considered, ultimately, average rectangular cross-section dimensions with homogeneous, prismatic beam assumptions proved equally suitable and were used throughout the study.

The relative humidity was monitored with a sensor placed next to the specimens inside a Plexiglas chamber and was controlled during testing. The relative humidity was constant for an individual test, but varied by 10% about the 50% RH target over the course of the study. The resulting small differences in moisture content were measured and recorded. In a series of preliminary tests, the change in measured modulus of elasticity due to a 10% change in relative humidity was determined to be less than 10% and more precise controls were not deemed necessary.

The SG was measured using the oven dry weight and green volume. Specimens were dried for 24 h at 105°C and weights were established to the nearest 0.00001 g. Compression wood was identified using light transmission by established methods (Pillow 1941; Timell 1986). In contrast to the work of Megraw et al. (1999), specimens that contained compression wood were included in the data set, since they would be present in the full-size boards being used in future aspects of the research.

Measured estimates of MFA were obtained using microscopy, wide-angle X-ray diffraction (Meylan 1967; Cave 1997), and small-angle X-ray scattering (Jakob et al. 1994; Lichtenegger et al. 1998). MFA estimates for the S2 layer in our study were calculated using previously established methods described by Kretschmann et al. (1998) and Verrill et al. (2001). These methods used intensity patterns produced from integrating the diffraction pattern for the cellulose (002) crystal plane to estimate MFA.

An extensive set of trial tests was conducted during development of the test procedure to ensure consistent and repeatable results. It was established that different operators could produce the same outcome within plus or minus a few percent for any test outcome. The variabilities observed in the test results were established to the confidence of the authors to represent actual material variabilities.

Results

Earlywood versus latewood

Our test results quantified the anticipated differences in the elastic properties of EW and LW. Table 2 lists the ratios of LW E_L to adjacent EW E_L, the ratios of LW $G_{L\perp}$ to adjacent EW $G_{L\perp}$, and similar ratios for SG and MFA. These individual ratios for E_L ranged from approximately 0.6 to 7.0 (not shown) with an average of 2.3 and a coefficient of variation (COV) (standard deviation divided by the mean) of 51%. This range and average were consistent with those found by Megraw et al. (1999). Similarly, for $G_{L\perp}$, the individual ratios ranged from 0.8 to 4.1, with an average of 2.0 and a COV of 38%. The corresponding ratio of SG averaged 1.9 and that for MFA averaged 1.0.

Also consistent with the findings of previous investigators (Megraw et al. 1999; Mott et al. 2002), wood located higher up the stem (upper bolts; see Table 1 for bolt elevations) had different properties than wood located near the base (lower bolts). In the upper bolts, the ratio of LW E_L to EW E_L was greater (2.7 on average) compared to that in the lower bolts (2.1). This ratio also increased from an average value of 1.6 in ring 3 to a value of 2.7 in ring 18. Adjacent LW to EW $G_{L\perp}$ showed similar behavior, although the ratios and variation were less than those for E_L. LW properties are several multiples of the EW properties, but the larger cross-sectional area occupied by the EW suggests that its mechanical role relative to LW cannot be discounted. EW represented 73% of the cross-sectional area for rings 3, 6, 12 and 18.

LW typically possessed thicker cell walls, smaller lumens and higher density, but this was not always the case according to our definition, particularly for ring 3.

Table 2 Average ratios and coefficient of variation (COV) for latewood (LW) properties to adjacent earlywood (EW) properties.

Ratio group	Average ratio (COV)			
	E_L	$G_{L\perp}$	SG	MFA
LW/EW: all specimens	2.3 (51%)	2.0 (38%)	1.9 (26%)	1.0 (29%)
LW/EW: upper bolts (6 m)	2.7 (52%)	2.3 (35%)	2.1 (25%)	1.1 (37%)
LW/EW: lower bolts (1 m)	2.1 (47%)	1.8 (37%)	1.8 (25%)	1.0 (20%)
LW/EW: ring 3	1.6 (42%)	1.6 (41%)	1.6 (34%)	1.1 (25%)
LW/EW: ring 18	2.7 (34%)	2.0 (29%)	2.0 (11%)	1.0 (24%)
(LW/SG)/(EW/SG): all specimens	1.2 (38%)	1.1 (27%)	–	–
(LW/SG)/(EW/SG): ring 3	1.1 (41%)	1.1 (27%)	–	–
(LW/SG)/(EW/SG): ring 18	1.3 (35%)	1.0 (31%)	–	–

E_L, modulus of elasticity along the fiber direction; $G_{L\perp}$, shear modulus for the longitudinal-transverse plane; SG, specific gravity; MFA, microfibril angle.

Figure 4 shows the general trend between E_L and SG developed from published averages (Gibson and Ashby 1997) with the gathered data and respective trend lines overlaying the general trend line. The gathered EW and LW data generally fall within the ellipse of previously gathered data and are oriented logically with respect to SG. Some LW had SG in the range of EW and vice versa. This did not mean the specimens were contaminated or misidentified according to our definition. Figure 4 emphasizes that variability in SG and E_L from EW and LW specimens within trees of loblolly pine covers the known range of averages for different types of wood.

The specific modulus of elasticity is defined as the modulus of elasticity divided by the corresponding SG and has been used by other investigators in biomechanics. Ratios of LW specific E_L to EW specific E_L would be 1.0 if the property difference between LW and EW could be completely described by SG. As indicated in Table 2, this specific E_L ratio for all specimens was 1.2, with less overall variability compared to the E_L ratios that did not account for SG. The average ring-3 specific E_L ratio was 1.1 and was 1.3 for ring 18, but the COVs on a ring-by-ring basis were similar to those that did not consider SG. The influence of SG on shear modulus ratios was stronger, but again SG alone did not fully explain the high property values observed in LW specimens.

The average ratio of LW specimen SG to that of EW was 1.9 with a COV of 14%; the average ratio of LW MFA to that of EW was 1.0 with a COV of 8%.

Mean elastic properties

The average EW E_L and EW $G_{L\perp}$ for all specimens was 4.34 GPa (COV 25%) and 0.77 GPa (COV 17%), respectively. The average LW E_L for all specimens was 9.88 GPa (COV 53%) and LW $G_{L\perp}$ was 1.59 GPa (COV 34%). Both our EW and LW E_L values were considerably less than the respective macerated fiber average values observed by Groom et al. (2002a). Because the LW variability was considerably greater than that for EW, we conducted additional tests on LW to further substantiate the trends (Table 1).

Figure 5 breaks down the mean E_L values by ring number and height. EW E_L tended to be relatively constant with ring number, but increased substantially with height. LW E_L was lowest near the pith and the range of values overlapped those for EW. As shown in Figure 5, LW E_L

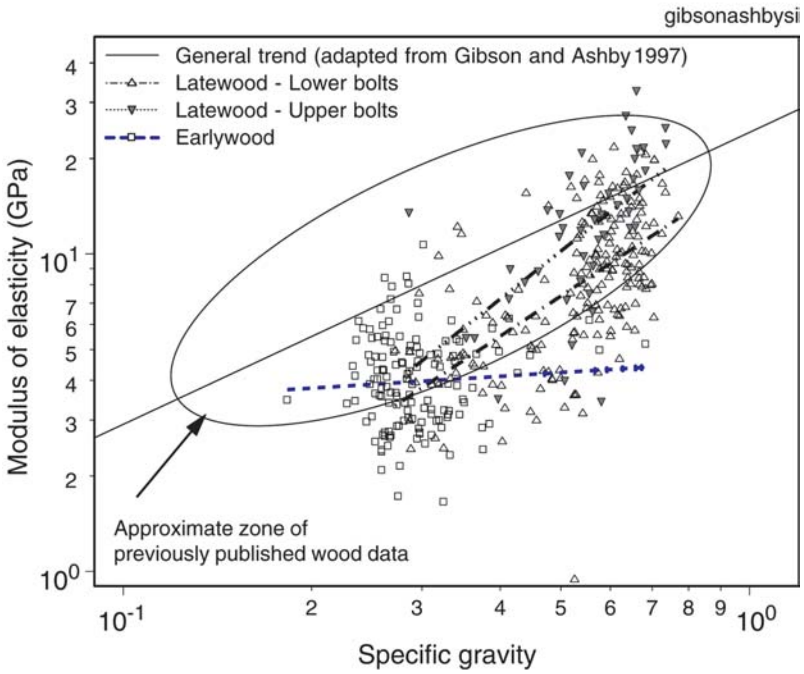

Figure 4 Earlywood and latewood modulus of elasticity values compared to general trends in specific gravity for wood.

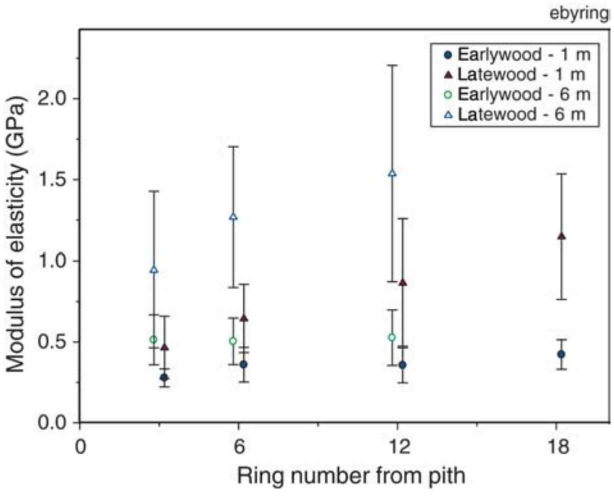

Figure 5 Earlywood and latewood modulus of elasticity values with standard deviation bars by ring number and height in stem (1 and 6 m). Ring numbers are offset for viewing and there were insufficient 6-m data for ring 18.

increased substantially with ring number and height. There were insufficient data for ring 18 at the 6-m height. LW E_L tended to be quite variable, even amongst specimens from the same bolt and ring, and positioned only millimeters apart. Overall average values of elastic properties must therefore be considered in light of the overall weighting of the number of specimens from different rings and different heights.

Figure 6 shows the trend for shear modulus ($G_{L\perp}$) by ring number and height. EW $G_{L\perp}$ tended to be relatively constant with ring number. LW $G_{L\perp}$ increased substantially with ring number. Both EW and LW $G_{L\perp}$ values decreased with height, opposite to the trend for E_L. Like LW E_L, the variability of LW $G_{L\perp}$ was large.

Circumferential variability

One of the most surprising outcomes from the test data was the variability within a ring at the four geographic locations oriented circumferentially around the same tree

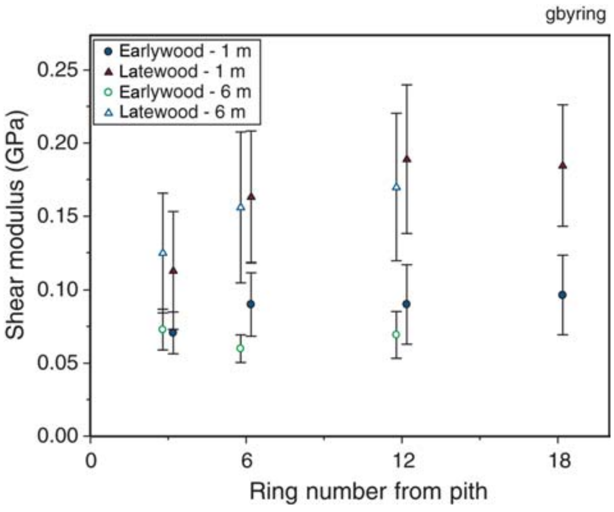

Figure 6 Earlywood and latewood shear modulus values with standard deviation bars by ring number and height in stem (1 and 6 m). Ring numbers are offset for viewing and there were insufficient 6-m data for ring 18.

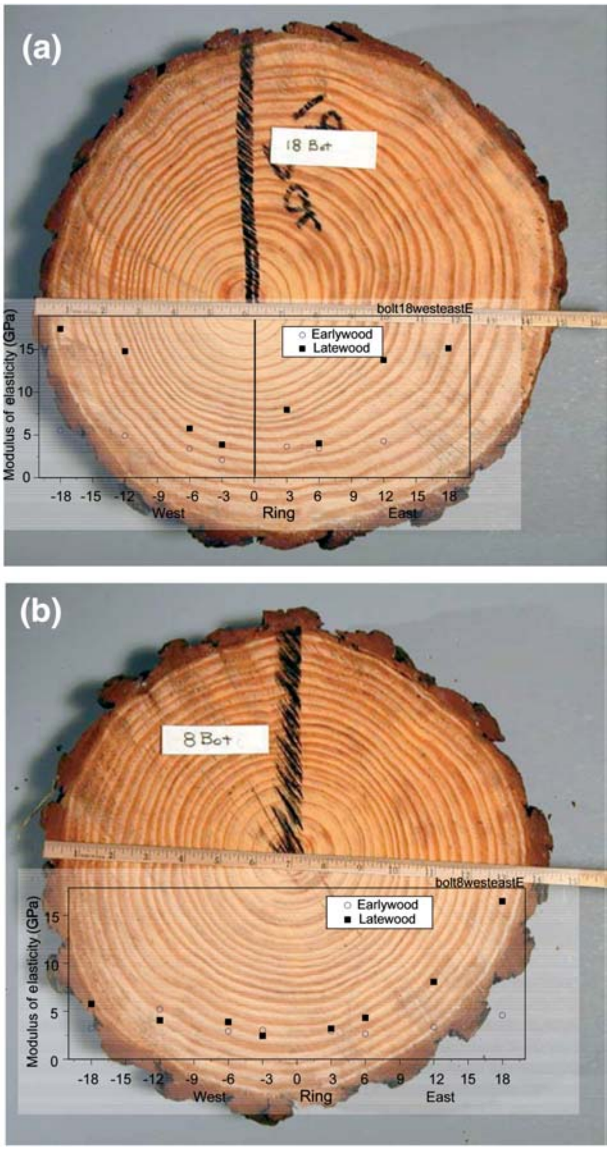

Figure 7 (a) Modulus of elasticity is approximately equal in the east versus the west despite pith bias to the west. (b) Latewood modulus of elasticity is much greater in the east despite a pith location close to center.

ring. The average within-ring COV of EW E_L was 21% compared to an average within-bolt COV of 26%. Similarly, for LW E_L the average within-ring COV was 32% compared to an average within-bolt COV of 47%. The within-ring variation in E_L contributed significantly to the overall within-bolt variability in E_L. This suggests that the variation around a single ring can be as large as the variation across many rings and implies that discrete measurement of properties at one circumferential location in the ring is insufficient to establish overall property values for the ring.

Examination of the bolt cross-sections revealed that all pith locations were biased toward the north or the west, or a combination of the two directions. This suggests that the tree placed more wood on the south and east sides, likely in response to increased crown development from solar exposure on those sides. However, these biases in the amount of wood material on the southeast side of the trees did not provide an explanation for the circumferential variation in properties. Figure 7 shows two typ-

Table 3 Average earlywood E_L multiple correlations (R^2) at ring and height locations.

Independent variable	Ring 3		Ring 6		Ring 12		Ring 18	
	1 m (N=29) CW=30%	6 m (N=16) CW=13%	1 m (N=20) CW=10%	6 m (N=19) CW=11%	1 m (N=20) CW=5%	6 m (N=20) CW=5%	1 m (N=19) CW=0%	6 m[a]
SG	0.01	0.04	0.32	0.04	0.37	0.04	0.00	–
MFA	0.00	0.19	0.01	0.27	0.09	0.25	0.16	–
SG+MFA	0.01	0.34	0.32	0.33	0.65	0.57	0.17	–
SG+MFA+CW	**0.65**	0.48	0.33	**0.65**	**0.67**	**0.65**	0.17	–
Bolt ID	0.01	0.02	0.04	0.02	0.12	0.07	0.10	–
Cardinal direction within ring	0.02	0.42	0.06	0.02	0.00	0.00	0.00	–
$G_{L\perp}$	**0.75**	0.14	**0.80**	0.02	**0.61**	0.12	0.18	–

E_L, modulus of elasticity along the fiber direction; $G_{L\perp}$, shear modulus for the longitudinal-transverse plane; SG, specific gravity; MFA, microfibril angle; CW, percentage of specimens containing compression wood; N, sample size; bolt ID, uniqueness of each bolt. Values of R^2 above 0.5 are in bold font.
[a]Insufficient data.

ical examples of bolt cross-sections, with the east-west variation in E_L shown for each. In Figure 7a, E_L is approximately symmetric about the pith, despite a strong pith bias to the west. In Figure 7b, the LW E_L is much greater in the east, despite a pith location close to center. While biological and mechanical responses to the environment as recorded in the ring structure may hold the explanation to these property variations, they cannot be explained simply by pith location.

Correlations of elastic properties

The large variability observed in these data sets (Figures 5 and 6) begs the question as to what factors drive the variability in elastic properties. Tables 3 and 4 present a ring-by-ring and height breakdown for E_L correlations with other physical and mechanical properties. E_L was treated as the dependent variable, and independent variables included SG, MFA, occurrence of compression wood (CW), bolt ID, cardinal direction location within the ring, $G_{L\perp}$ and select combinations. Values of R^2 above 0.5 are highlighted in bold font to emphasize the variables that were most significant in determining the elastic properties.

In examining EW E_L correlations in Table 3, the strongest correlations were found with multivariate consideration of SG, MFA and compression wood, with R^2 values ranging from 0.17 to 0.67. The strongest correlation was with $G_{L\perp}$, but only for the 1-m height conditions. The highest correlations with $G_{L\perp}$ occurred near the pith and decreased to little correlation in ring 18. LW E_L similarly correlated strongly with $G_{L\perp}$ near the pith at the 1-m height. In the outer rings (12 and 18), MFA was the strongest predictor of LW E_L. SG and the occurrence of compression wood provided little or no benefit to this correlation. This result was surprising, since compression wood was present in over 40% of the specimens from the 1-m height. The overall success claimed by Megraw et al. (1999) with the combination of SG and MFA as a property predictor was substantiated in this data set, primarily in the outer rings. Megraw et al. found 93% of the variation in all their data to be explained by SG and MFA. Combining our EW and LW into one data set with 388 points results in approximately 75% of the variation explained by SG and MFA. However, even this correlation weakens substantially on closer examination. Considering all the data, the correlation (R^2) of LW E_L with SG and MFA was 0.73. However, the R^2 values for EW E_L, EW $G_{L\perp}$, and LW $G_{L\perp}$ were all below 0.5.

The shear modulus (Tables 5 and 6) generally did not correlate strongly with any of the variables considered. EW $G_{L\perp}$ in ring 12 showed a strong correlation with SG

Table 4 Average latewood E_L multiple correlations (R^2) at ring and height locations.

Independent variable	Ring 3		Ring 6		Ring 12		Ring 18	
	1 m (N=29) CW=48%	6 m (N=16) CW=31%	1 m (N=42) CW=40%	6 m (N=29) CW=14%	1 m (N=44) CW=39%	6 m (N=32) CW=22%	1 m (N=44) CW=39%	6 m[a]
SG	0.28	0.32	0.36	0.26	0.32	0.47	0.06	–
MFA	0.22	**0.53**	0.21	0.06	**0.84**	**0.64**	**0.66**	–
SG+MFA	0.45	**0.64**	0.45	0.46	**0.84**	**0.78**	**0.67**	–
SG+MFA+CW	0.45	**0.66**	0.46	0.47	**0.84**	**0.78**	**0.67**	–
Bolt ID	0.28	0.04	0.11	0.01	0.30	0.13	0.40	–
Cardinal direction within ring	0.04	0.18	0.01	0.04	0.01	0.02	0.00	–
$G_{L\perp}$	**0.82**	0.21	**0.63**	0.19	0.37	0.11	0.11	–

E_L, modulus of elasticity along the fiber direction; $G_{L\perp}$, shear modulus for the longitudinal-transverse plane; SG, specific gravity; MFA, microfibril angle; CW, percentage of specimens containing compression wood; N, sample size; bolt ID, uniqueness of each bolt. Values of R^2 above 0.5 are in bold font.
[a]Insufficient data.

Table 5 Average earlywood $G_{L\perp}$ multiple correlations (R^2) at ring and height locations.

Independent variable	Ring 3		Ring 6		Ring 12		Ring 18	
	1 m (N=29) CW=30%	6 m (N=16) CW=13%	1 m (N=20) CW=10%	6 m (N=19) CW=11%	1 m (N=20) CW=5%	6 m (N=20) CW=5%	1 m (N=19) CW=0%	6 m[a]
SG	0.00	0.06	0.12	0.01	0.62	0.51	0.00	–
MFA	0.03	0.04	0.01	0.14	0.04	0.11	0.01	–
SG+MFA	0.03	0.08	0.12	0.14	**0.63**	**0.52**	0.01	–
SG+MFA+CW	0.08	0.08	0.12	0.14	**0.64**	**0.58**	No CW	–
Bolt ID	0.00	0.06	0.03	0.22	0.00	0.04	0.14	–
Cardinal direction within ring	0.14	0.04	0.15	0.00	0.00	0.00	0.00	–

$G_{L\perp}$, shear modulus for the longitudinal-transverse plane; SG, specific gravity; MFA, microfibril angle; CW, percentage of specimens containing compression wood; N, sample size; bolt ID, uniqueness of each bolt. Values of R^2 above 0.5 are in bold font.
[a]Insufficient data.

and MFA at both 1- and 6-m heights, but this trend did extend to other rings. The strongest correlations for LW $G_{L\perp}$ occurred with SG and MFA in the inner rings (3 and 6) but gradually diminished in the outer rings (12 and 18).

The extensive data presented above reveal that there is little commonality in absolute terms or in trends between EW and LW mechanical properties, even when the specimens were adjacent to each other in the same ring and the same tree. The variabilities observed were largely true material property variations, as repeat tests and experimental techniques were extensively refined to minimize variations associated with the test procedures. While SG and MFA provide some explanation of the variation in elastic property variation, this explanation is neither complete nor all that useful, since MFA is no easier to measure than the elastic properties themselves.

Summary and conclusions

The individual elastic mechanical properties of matched EW and LW specimens were established from 388 specimens derived from six trees of loblolly pine. Properties were measured with a novel micromechanical measurement device, in which small specimens were displaced as cantilever beams and strains were measured to the order of 10^{-7}. The data set is unique in that it included multiple measurements of the modulus of elasticity and shear modulus from specimens originally positioned circumferentially around individual rings.

EW and LW E_L values established here follow trends that have been identified by others, but our data reveal greater variability and subtrends not previously identified. SG and MFA were the strongest predictors of modulus of elasticity. These parameters explained 75% of the overall variability in E_L, but less than 50% for EW. SG and MFA were the strongest predictors of shear modulus, but generally explained less than 50% of the variability.

The modulus of elasticity increased with ring number and height, while shear modulus increased with ring number, but decreased with height. The strong correlation between modulus of elasticity and shear modulus at lower heights and inner rings decreased substantially at other locations.

The variation in modulus of elasticity on a percentage basis is nearly as large within a ring as it is across rings from the pith to outer circumference. Ring samples achieved from one location are unlikely to be representative of the entire ring. Neither EW nor LW elastic properties from ring to ring correlated with the global direction from the bolt. The presence of compression wood influenced EW E_L, but did not correlate with variations in LW E_L or $G_{L\perp}$.

Biological and mechanical responses to the environment are likely causes of the variation in elastic properties of EW and LW, but these variations are only partly explained by SG and MFA. Our working premise is that understanding property variations at the EW-LW scale

Table 6 Average latewood $G_{L\perp}$ multiple correlations (R^2) at ring and height correlations.

Independent variable	Ring 3		Ring 6		Ring 12		Ring 18	
	1 m (N=29) CW=48%	6 m (N=16) CW=31%	1 m (N=42) CW=40%	6 m (N=29) CW=14%	1 m (N=44) CW=39%	6 m (N=32) CW=22%	1 m (N=44) CW=39%	6 m[a]
SG	0.34	0.25	0.33	0.22	0.27	0.23	0.09	–
MFA	0.13	0.22	0.04	0.07	0.25	0.00	0.01	–
SG+MFA	0.43	0.35	0.33	0.23	0.32	0.28	0.13	–
SG+MFA+CW	0.43	0.40	0.33	0.25	0.33	0.32	0.14	–
Bolt ID	0.08	0.26	0.04	0.09	0.01	0.00	0.02	–
Cardinal direction within ring	0.03	0.14	0.00	0.04	0.01	0.00	0.00	–

$G_{L\perp}$, shear modulus for the longitudinal-transverse plane; SG, specific gravity; MFA, microfibril angle; CW, percentage of specimens containing compression wood; N, sample size; bolt ID, uniqueness of each bolt.
[a]Insufficient data.

will eventually allow development of control strategies to optimize the performance of wood products.

Acknowledgements

The authors gratefully acknowledge the US Department of Agriculture for financial support of this work through USDA NRI Grant #2001-35103-10178. We are thankful for the support from Weyerhaeuser Company through in-kind material donations and the technical assistance of Dr. Mark Stanish and Dr. Stan Floyd of the Weyerhaeuser Technology Center. The fabrication work of the USDA FS Forest Products Laboratory Carpenter Shop was essential to the research. The assistance in measurements of Tarvis Holt is gratefully acknowledged.

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Received October 22, 2003. Accepted June 1, 2005.