Physical and Mechanical Properties of Young-Growth Douglas-Fir and Western Hemlock from Western Washington

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Abstract

Diversity in land management objectives has led to changes in the character of raw material available to the forest products industries in the US Pacific Northwest. Increasing numbers of logs from small-diameter trees, both plantation grown and those from suppressed or young stands, now constitute a large proportion of logs coming into the mill yard. Wood coming from plantations or young stands has different properties than wood coming from older, suppressed stands. This research examined wood properties of small-diameter plantation-grown Douglas-fir and western hemlock with the goal of a better understanding of utilization of small-diameter, fast-grown trees for use in manufacturing engineered wood composites. Twelve trees of each species were harvested and three bolts cut from each tree. Each bolt provided samples for X-ray densitometry profiles, compression, and tension parallel to grain and flexure tests. Both species were found to have a very high proportion of juvenile wood. Most wood properties decreased with increasing vertical position and increased with increasing distance from pith for both species. Increased competition for wood fiber, which accounts for as much as 25 to 35 percent of total wood composite (such as particleboard, medium-density fiberboard and oriented strand board) manufacturing costs, necessitates an understanding of raw material properties and their variations. This knowledge could assist in optimizing the manufacturing process and maximizing efficiency of wood raw material use, thus increasing profits.

The character of raw material available to the forest products industries in the US Pacific Northwest has been changing over the past several decades. A shift from harvesting and processing logs from natural, managed stands to focusing on timber production in plantations began in the 1970s. An increasing number of logs from small-diameter Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) trees, both commercially important species in the Northwest, are currently coming into mill yards. Wood quality differences, both microscopic and macroscopic, exist among small trees grown under varying management regimes. Wood coming from plantations has had significantly different silvicultural treatments than wood coming from suppressed or natural stands. Precommercial thinning, vegetation management, fertilization, and use of genetically improved stock are all silvicultural treatments applied to plantations in recent years. Understanding the effect of these early stand entry land management practices on wood quality provides information on how best to match raw material to final product.

Emphasis on volume production and short rotations in plantations has led to concerns about juvenile wood versus mature wood proportions. Bendtsen (1978) addressed many issues associated with intensively managed trees. Although plantations managed under short rotations produce accelerated growth rates, the young trees harvested from such stands were shown to contain a high proportion of juvenile wood, thus affecting end product performance. Kennedy (1995) reported on wood quality concerns and juvenile wood proportions in second-growth trees. The end product concern with juvenile wood is that mechanical properties

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differ, and it can be less dimensionally stable when compared to mature wood (Senft et al. 1985, Forest Products Research Society 1986, 1987). Lower density, shorter fiber lengths, thinner cell walls, and higher microfibril angles in juvenile wood are the primary factors leading to lower strength, decreased stiffness, and increased longitudinal shrinkage (Bendtsen 1978).

Juvenile wood consists of the annual rings closest to the pith that were produced under strong influence from the apical meristem (Megraw 1986) and within the vigorously growing crown (Megraw 1985, 1986; Forest Products Research Society 1986; Johnson 1986; Jozsa et al. 1989; Cave and Walker 1994). Some research suggests that wood properties change at the base of the live crown (Larson 1969, DiLucca 1989). Research by Gartner et al. (2002) suggested that crown position had no effect on the transition from juvenile to mature wood as judged by wood density.

Most softwood species display a radial gradient in physical properties (Sanio 1872, Trendelenburg 1936). The transition point from juvenile wood to mature wood formation and whether mature wood properties are in fact constant are discussed in the wood science literature (e.g., Saucier 1990, Sauter et al. 1999, Koubaa et al. 2000, Gartner et al. 2002, Yang 2002), but it is difficult to generalize among species. DiLucca (1989) used segmented regression modeling in an effort to identify the transition age for Douglas-fir. He found that the transition age was about 20 rings from the pith at breast height, the age that also corresponded to crown recession in the sample trees. Abdel-Gadir and Krahmer (1993) created piecewise linear regression models to estimate the age of transition between juvenile and mature wood in Douglas-fir using X-ray densitometry data previously analyzed by Abdel-Gadir et al. (1993). In this case the demarcation age between juvenile and mature wood in Douglas-fir was found to be about 30 years; however, most small-diameter trees harvested in western Washington are around 30 years old or younger. The authors noted that change was gradual and varying over all characteristics.

Some of the microscopic differences that are important to product utilization in young trees include lower specific gravity, larger microfibril angle, and shorter fiber length (Megraw 1986). Specific gravity is important as a measure of physical and mechanical properties (Haygreen and Bowyer 1996). As a general rule, wood with higher specific gravity is more suitable in applications where strength is important. Within a tree, patterns in specific gravity variation can relate to both growth rate and age (Jozsa et al. 1989, Cave and Walker 1994).

Radial density patterns for Douglas-fir have been reported on by Wellwood and Smith (1962), Kennedy and Warren (1969), Megraw (1986), and Jozsa et al. (1989). Typically, the pattern shows higher densities in the first few rings from the pith, which then decreases until about ring 6 to 10 before increasing and remaining stable at about ring 20 to 25.

Density variation within western hemlock was also studied by Wellwood and Smith (1962), who similarly found higher wood densities in the first five rings closest to the pith. In examination of individual rings (Krahmer 1966, Megraw 1986, Jozsa et al. 1998, Debell et al. 2004), the first two rings had the highest densities, which then declined through ages 10 to 20 before gradually increasing. Debell et al. (2004) found that following the initial decline, little change occurred until around age 25, at which point a slow increase in density occurred until about age 40, where it remained nearly constant. This general trend has also been observed by Jozsa and Middleton (1994) and Jozsa et al. (1998).

Mechanical property differences between juvenile and mature wood have been reported for many species, among them radiata (*Pinus radiate*) and loblolly (*Pinus taeda*) pine by Burdon et al. (2004), fir (*Abies* spp.) by Passialis and Kiriazakos (2004), slash pine (*Pinus elliottii*) by MacPeak et al. (1990), and southern pines by Larson et al. (2001). Bendtsen (1978) provides mechanical property data from small clear specimens sampled from seven species of plantation- versus forest-grown trees. The plantation trees generally had lower property values and lower specific gravity.

Research has also been conducted on full-size lumber. Barrett and Kellogg (1991) studied bending strength and stiffness of second-growth Douglas-fir 2 by 4 lumber. They examined changes in modulus of elasticity (MOE) and modulus of rupture (MOR) based on visual grade, log position, and percent juvenile wood and found that MOE and MOR decreased with increasing height in the tree and with increased overall percentage of juvenile wood. Their recommendation was that machine stress rating grades could be used to improve grade yield. Fahey et al. (1991) confirmed this, as did other studies (Bendtsen et al. 1988, Kellogg 1989). Middleton and Munro (2001) found similar reductions in MOE and MOR with increased proportions of juvenile wood in hemlock lumber. The MOE and MOR were related to proportion of juvenile wood within 15 years of the pith. Kretschmann and Bendtsen (1992) considered the effects of juvenile wood on four grades of loblolly pine 2 by 4 lumber. The study, which focused on fast-grown plantation loblolly pine, found ultimate tensile stress and stiffness values to be 45 to 63 percent lower in lumber composed of juvenile wood as compared with pieces containing only mature wood.

Microfibril angle also influences wood mechanical properties. Wardrop (1951) found an increase in tensile strength with a decrease in microfibril angle for Douglas-fir and radiata pine. In Douglas-fir, Ifju and Kennedy (1962) observed a direct correlation between the high microfibril angles associated with juvenile wood and reduced tensile strength. A decrease in fibril angle with a corresponding increase in bending strength, compression parallel to the grain, and toughness was found in red pine by Kraemer (1950). Deresse et al. (2003) found a negative relationship between microfibril angle and both flexural strength and bending MOE.

Diameter alone cannot be used to determine the proportion of juvenile wood. A recent study by Green et al. (2005) determined that one stand of suppressed, small-diameter (<10 diameter at breast height [DBH]) Douglas-fir trees did not produce lumber having poor flexural properties. Instead, the 2 by 4 lumber from these 70- to 90-year-old trees graded as 68 percent Select Structural for light framing, and 89 percent passed as stud grade (West Coast Lumber Inspection Bureau 1993).

Radial distance from the pith is expected to contribute the most to an increase in mechanical properties, while height within the tree is expected to have less of an effect given that the juvenile wood zone extends the entire length of a tree. Much of the previous research examined 2 by 4 lumber (Kellogg 1989, Fahey et al. 1991). While the forest products industry has developed primary breakdown methods to improve log volume recovery and more effectively use small-diameter trees, opportunities exist to produce engineered wood composites, in particular, products manufactured from wood strands and wood flour. To continue the development of these innovative products, an understanding of the physical and mechanical properties of the raw materials used in production is required. The objective of this study is to determine the degree to which stiffness and strength vary in small-diameter, fast-grown Douglas-fir and western hemlock trees from the coast of the Olympic Peninsula, Washington, with respect to vertical and radial position within the tree. A subsequent article will report on the variation in these properties and their correlation with property variations encountered in the preparation of wood furnish, such as strands for oriented strand composites and wood flour for wood-plastic composites.

Materials and Methods

Twelve trees each of Douglas-fir and western hemlock were harvested from the Olympic Peninsula near Aberdeen, Washington (Stand Management Cooperative Installations No. 706 and 727, respectively), during the fall of 2004. The region has a Pacific-type climate characterized by dry summers and wet winters (Barrett 1995). Measured site index on the two installations prior to restocking was 125 feet at 50 years for Douglas-fir (King 1966) and 110 feet at 50 years (Wiley 1978) for western hemlock. Trees were on average 20 years old based on ring count at breast height. Height of the samples trees varied between 25 and 30 feet. DBH of Douglas-fir trees varied between 7.5 and 11.4 inches with an average DBH of 9.4 inches. Western hemlock tree DBH varied between 6.3 and 11.2 inches with an average DBH of 8.3 inches.

Three 6-foot bolts were cut from each tree (taken at the stump, midregion, and the top) with an approximately 2-foot gap between the three vertical regions. Gap distance was dependent on vertical position to a 4-inch top inside bark as the top log needed to be at least this size for mechanical property specimens. Figure 1 shows the pattern for property determination specimens. The ripped sticks (roughly 1½ in. by 1½ in. by 4 ft) were conditioned at approximately 70°F and 65 percent relative humidity for several months to obtain about 12 percent moisture content. Following conditioning, the sticks were further processed to obtain 18-inch-long tensile, 16-inch-long flexure, and 4-inch-long compression specimens as per ASTM D 143 (ASTM International 2001). Every specimen was optimized for exclusion of knots or cracks.

Zones of property evaluation

For the purpose of testing and evaluating physical and mechanical properties, each tree was divided into nine unique areas based on height and diameter. The three bolts from each tree represent unique locations with respect to height (vertical position). Each bolt was further divided into zones based on radial distance from the pith. According to the secondary method of ASTM D 143-94 (ASTM International 2001), the required cross-sectional specimen size for tension parallel to grain, compression parallel to grain, and static flexure is 1 by 1 inch. Radial zones were selected with this requirement in mind as well as an

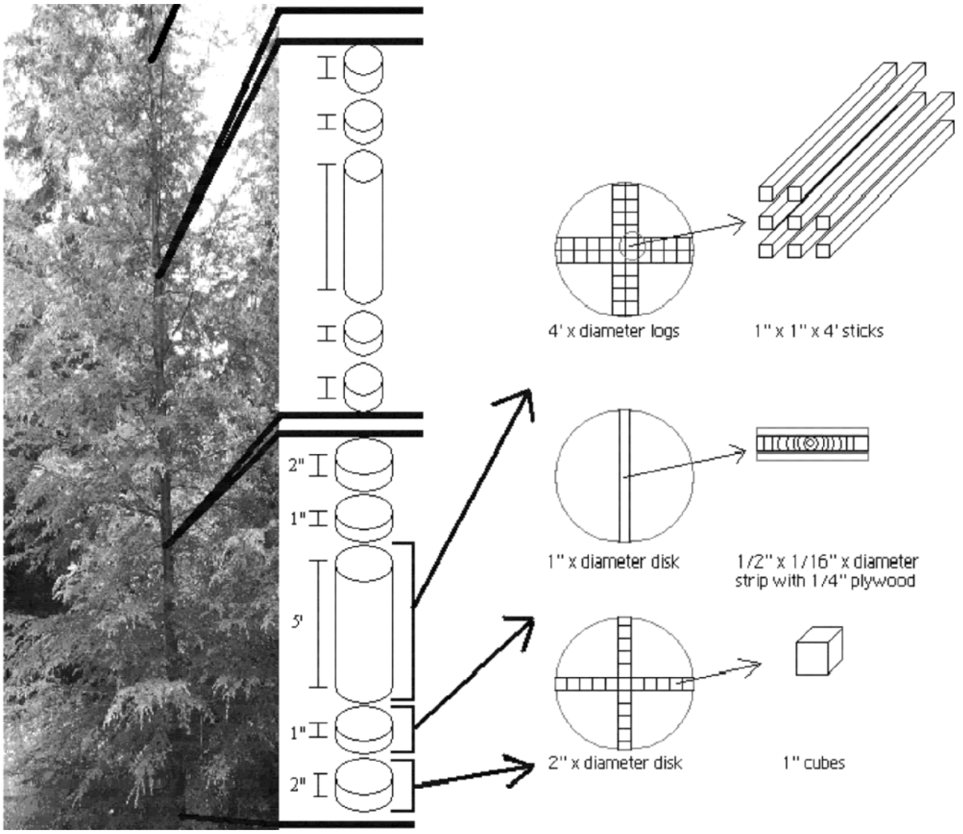

Figure 1.—Bolt location along tree length and specimen extraction per experimental plan from each bolt.

allowance for saw kerf and final trimming. Occasionally, the pith would deviate from its original position during rough specimen cutting. This resulted in the two typical specimen orientations noted in Figure 2. To maximize the number of unique zones and also accommodate some variation in growth patterns, three radial zones were designated (Fig. 2).

Property evaluation

X-ray density profiles of randomly oriented 0.5-inch by disk-diameter strips removed from the 1-inch-thick disks (Fig. 1) were analyzed by a QTRS-01X Tree Ring Analyzer (Quintek Measurement Systems, Knoxville, Tennessee). The radial strips were allowed to air-dry to equilibrium moisture content and scanned in the radial direction with the X-ray density profiler, creating pith-to-bark density profiles. Extractives were not removed prior to processing of the specimens. The equipment was calibrated to the actual sample density at 12 percent moisture content. The demarcation between the earlywood (EW) and the latewood (LW) was determined by comparing the density profiler data to the digital photo of the specimen growth rings. The location was then converted into a floating density threshold in the density profile. Density threshold value was checked for each specimen to ensure accurate analysis of average growth ring width, EW width, LW width, ring density, EW and LW densities, maximum and minimum density, and LW percentage. Density and zones of density changes were evaluated to determine approximate transitions from juvenile to mature (Langum 2007).

Compression and tension parallel to grain and flexure tests were performed according to ASTM D 143-94, Standard Test Methods for Small Clear Specimens of Timber (ASTM International 2001). Because of the size of the specimens, the secondary method was followed. All specimens were tested using the universal electromechanical test machine. Strain was recorded using a 2-inch axial extensometer (Epsilon Model 3542) for axial tests. Flexure (midspan deflection) was recorded using an Electronic Instrument Research, Ltd., Model LE-05 laser extensometer. Properties calculated included Young's Modulus and ultimate strength for each loading case. Following the destructive testing of the specimen, moisture content specimens were removed from near the failure.

Statistical evaluation

To aid future models and serve as a tool to estimate strand properties, the normal and Weibull probability density functions were fitted to all mechanical properties studied. Goodness of fit was judged with the chi-squared *P* value and Kolmogorov–Smirnov *P* value for normal and Weibull distributions, respectively. Statistical Analysis Software (SAS) was used to further identify statistical differences in mechanical properties and sources of variation. Uneven sample size among radial zones and vertical positions was a result of natural variation in tree size. The trees are considered as replicates, with each tree being repeatedly measured at each of the three heights and at each of the three radial locations. Because each sample does not represent an independent replicate, samples were averaged to create one mean observation by radial zone and by vertical position per tree. A mixed linear model, which is a generalization of the standard linear model in the general linear model procedure, was used to conduct analysis of variance and test the significance of location on mechanical properties. The mixed procedure in SAS allows for the data to exhibit correlation and nonconstant variability (SAS Institute Inc. 2000–2004); *t* tests were used to identify differences in mechanical properties of radial zones ($n = 3$) among trees ($n = 12$) and of vertical position ($n = 3$) among trees ($n = 12$). Least-squares means were used to compute the mean values and perform pairwise comparisons to determine significant differences with respect to radial zone and vertical position within trees. Langum (2007) further explored properties by vertical position and radial zone.

Results and Discussion

X-ray density profiling

As a preliminary step to aid in identifying variation in mechanical properties, X-ray densitometry was used to explore the variation in density with respect to location. Figures 3 and 4 display average trends in ring width and relative densities by ring, EW, and LW for Douglas-fir and western hemlock trees, respectively. Table 1 represents the

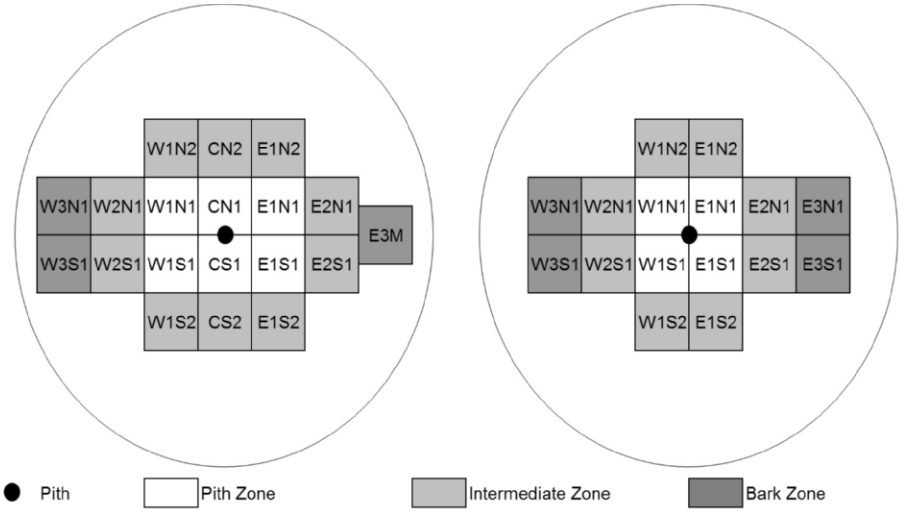

Figure 2.—Radial location of mechanical property test specimens.

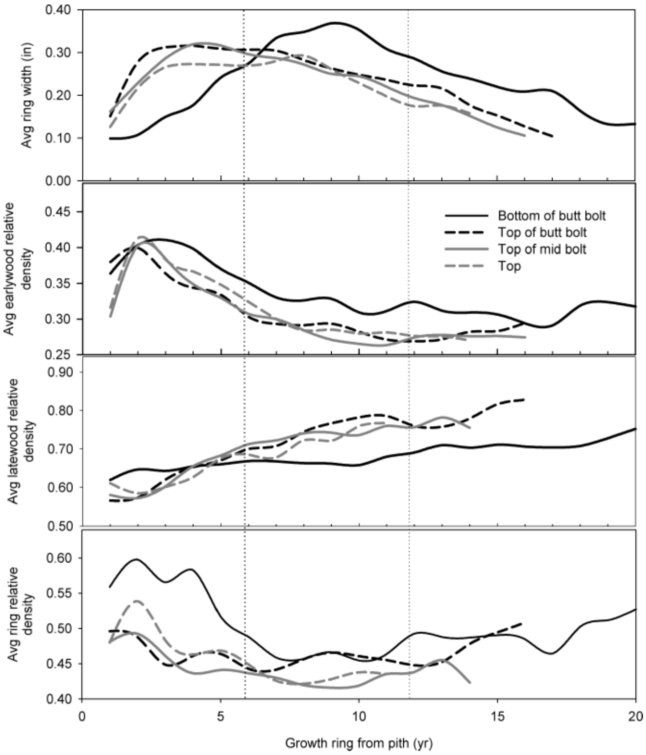

Figure 3.—Average Douglas-fir X-ray density profile data.

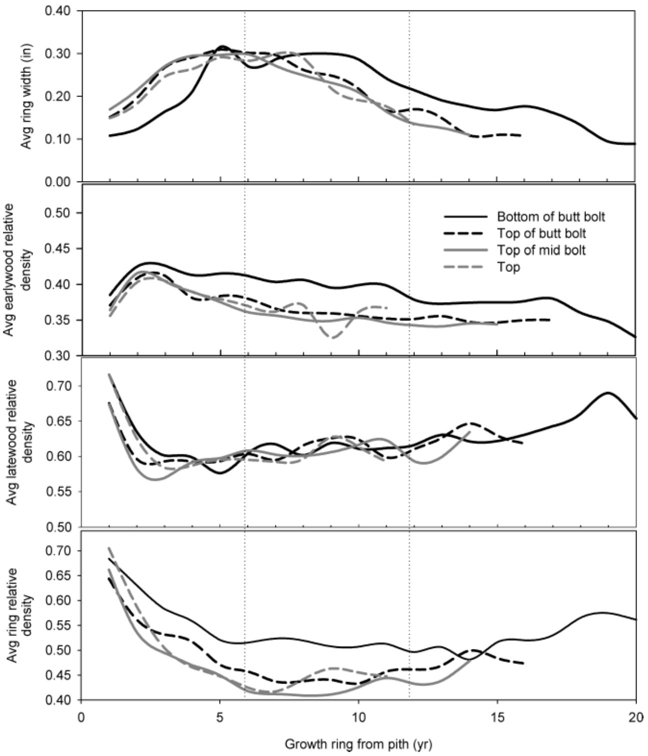

Figure 4.—Average western hemlock X-ray density profile data.

variation in specific gravity within the EW, LW, and tree ring as a whole, with respect to location within the tree for both species. The trends displayed in these graphs closely match those found by Abdel-Gadir and Krahmer (1993). Their research, which focused on estimation of the demarcation age between juvenile and mature wood of Douglas-fir, noted no apparent demarcation line in this species but rather a general trend toward maturation that occurred between the ages of 27 and 37 years. Based on this and the density trends shown in Figures 3 and 4, it is apparent that the trees are composed of nearly all juvenile wood. There are, however, well-defined zones of increasing or decreasing density through the radius of the trees. The data indicate that it may be reasonable to expect variations in mechanical properties based on these zones (indicated by vertical lines in Figs. 3 and 4) that correspond well with those described in Figure 2. For western hemlock, with the exception of higher density values, similar trends were observed by Jozsa et al. (1998). He showed that western hemlock density is slightly higher at the pith but quickly declines to below Douglas-fir values through the radius to the bark. Unlike Douglas-fir, average ring relative density (0.49) of western hemlock was much greater than the value of 0.41 published by Debell et al. (2004).

Mechanical property evaluation

Flexure.—Mean MOE and MOR values through flexural testing for Douglas-fir and western hemlock are presented in Table 2. The overall tree mean MOE and MOR calculated through flexural testing of 463 Douglas-fir specimens was 1.33×10^6 psi and 9,570 psi with coefficients of variation (COVs) of 20.7 and 14.2 percent, respectively. According to the Wood Handbook (USDA Forest Service 1999), expected MOE and MOR values for 12 percent moisture content coastal Douglas-fir are 1.95×10^6 psi (47% increase) and 12,400 psi (30% increase). Testing of 321 western hemlock flexural specimens yielded overall tree mean MOE and MOR values of 1.06×10^6 psi and 8,500 psi with COVs of 19.7 and 13.7 percent, respectively. The Wood Handbook values for MOE and MOR of western hemlock are greater at 1.63×10^6 psi (54%) and 11,300 psi (33%), respectively. Wood Handbook values are based on mature wood physical and mechanical properties, and the effect of juvenile wood is evident in the large difference in flexural properties.

Type 3 tests of fixed effects using the mixed procedure verified that variation in location within the tree were significant (P values < 0.003) in both species. Similarity based on statistical analysis is indicated in the table by specimen radial zone and vertical position. For Douglas-fir, strength and stiffness values were lowest at the top of the trees when only vertical position was considered (Table 2). This is due to the influence of the crown, where the proportion of juvenile wood is known to be relatively high. MOE of middle and bottom bolts was not significantly different; however, MOR was found to significantly decrease with increased vertical position. Proximity to the pith had the greatest effect on MOE, with a decrease of 16 to 17 percent in stiffness closer to the pith (inner zone). MOR followed a similar trend with a steady increase from pith to bark; however, the *t* test showed no significant difference between the radial zones. When considering both vertical position and radial zone, inner zone strength and stiffness remained constant from bottom to top bolt. The highest average MOE came from the outer radial zone in the bottom bolt. These values did not begin to decrease until beyond middle-bolt position.

In western hemlock, variation in MOE and MOR with respect to vertical position was the same as for Douglas-fir.

Table 1.—Relative density variation in earlywood, latewood, and annual ring by vertical position.

Vertical position	Earlywood		Latewood		Ring	
	Mean	COV (%)[a]	Mean	COV (%)	Mean	COV (%)
Douglas-fir						
Tree	0.31	16.6	0.70	13.9	0.46	15.7
Bottom of butt bolt	0.33	13.7	0.68	10.8	0.50	14.6
Top of butt bolt	0.31	15.4	0.72	14.6	0.46	13.2
Top of middle bolt	0.30	18.0	0.70	14.3	0.44	14.5
Top	0.32	18.1	0.68	14.2	0.45	20.8
Western hemlock						
Tree	0.37	12.7	0.62	9.0	0.49	19.0
Bottom of butt bolt	0.39	14.3	0.63	8.5	0.54	14.3
Top of butt bolt	0.37	11.9	0.62	8.8	0.49	18.7
Top of middle bolt	0.36	10.3	0.61	9.0	0.46	18.7
Top	0.37	14.4	0.61	10.0	0.49	22.8

[a] COV = coefficient of variation.

Less variation existed within the western hemlock specimens. Strength and stiffness values were lowest at the top of the trees when only vertical position was considered. Strength decreased significantly with vertical position from bottom to top. MOR values indicated no significant change from inner to intermediate radial zone. The *t* test indicates that MOE of the outer sections of bottom and middle bolts were not significantly different. The top bolt had a much lower MOE. Stiffness decreased significantly with radial zone from pith to bark.

Compression.—The results from clear specimen compression testing of Young's modulus and ultimate strength are shown in Table 3. The overall tree mean Young's modulus and ultimate strength calculated through compression testing of 165 Douglas-fir specimens was 1.42×10^6 psi and 4,840 psi with COVs of 20.9 and 11.4 percent respectively. Testing of 143 Western hemlock compression specimens yielded overall tree mean Young's modulus and ultimate strength values of 1.04×10^6 psi and 4,010 psi with COVs of 22.5 and 12.1 percent, respectively. The Wood Handbook (USDA Forest Service 1999) lists mature Douglas-fir and western hemlock compressive ultimate strength values as 7,230 psi and 7,200 psi at moisture content of 12 percent, a reduction in compression strength of specimens tested in this study by 33 and 44 percent for Douglas-fir and western hemlock, respectively, compared with Wood Handbook values.

For Douglas-fir trees, statistical analysis of the compression strength data indicated no significant change in value through the entire tree (Table 3). Young's modulus was lowest at the center (inner zone) of the bolts and in the bottom bolts. The middle bolt had the highest mean stiffness value and was not significantly different from the top bolt.

In western hemlock, no significant differences in vertical position were found for Young's modulus, but the inner zone had a significantly lower value than the other radial

Table 2.—Flexural property variation within the trees with respect to vertical position and radial zone.[a]

	Specific gravity		MOE				MOR					
	Mean	COV (%)	Mean (Mpsi)	COV (%)	*t* grouping[b]		Mean (kpsi)	COV (%)	*t* grouping			*n*
Douglas-fir												
By vertical position												
Top	0.47	8.6	1.220	14.0	•		8.78	8.4	•			23
Middle	0.47	6.5	1.368	13.8		•	9.48	8.4		•		27
Bottom	0.50	5.0	1.335	19.1		•	10.08	8.9			•	28
By radial zone												
Pith	0.48	6.1	1.188	13.1	•		9.27	8.2	•			36
Intermediate	0.48	8.2	1.414	13.6		•	9.63	9.7	•			34
Bark	0.49	8.1	1.442	18.8		•	9.88	16.6	•			8
Western hemlock												
By vertical position												
Top	0.45	8.7	1.000	11.8			7.94	10.7				18
Middle	0.46	7.0	1.085	14.2	•		8.40	7.5	•			23
Bottom	0.48	8.8	1.084	9.8	•		9.08	10.8		•		29
By radial zone												
Pith	0.48	7.5	0.982	11.8	•		8.57	8.8	•			35
Intermediate	0.45	8.4	1.120	15.0		•	8.42	12.5	•			28
Bark	0.45	8.6	1.235	16.2			9.12	15.0				7

[a] MOE = modulus of elasticity, MOR = modulus of rupture, COV = coefficient of variation.

[b] *t* grouping: dots, read only down a column, indicate regions with a corresponding property that is not statistically significant at a significance level of 0.05.

Table 3.—Compressive property variation within the trees with respect to vertical position and radial zone.

	Young's modulus				Ultimate compressive strength				
	Mean (Mpsi)	COV (%)[a]	*t* grouping[b]		Mean (kpsi)	COV (%)	*t* grouping		*n*
Douglas-fir									
By vertical position									
Top	1.446	17.7	•		4.73	7.7	•		22
Middle	1.502	18.0	•		4.97	18.0	•		23
Bottom	1.358	21.4	•		4.94	9.5	•		26
By radial zone									
Pith	1.263	18.1	•		4.79	6.5	•		31
Intermediate	1.579	16.3		•	5.00	16.5	•		32
Bark	1.500	8.4		•	4.81	10.7	•		8
Western hemlock									
By vertical position									
Top	1.026	19.9			3.88	8.2			15
Middle	1.100	19.1	•		4.02	11.7	•		21
Bottom	1.044	23.1	•		4.21	12.4		•	28
By radial zone									
Pith	0.978	18.1			4.10	18.0			33
Intermediate	1.139	18.7	•		4.06	12.1	•		25
Bark	1.163	29.0	•		4.08	10.5	•		6

[a] COV = coefficient of variation.

[b] *t* grouping: dots, read only down a column, indicate regions with a corresponding property that is not statistically significant at a significance level of 0.05.

zones (Table 3). There were no significant differences in ultimate strength among radial zones. A significant difference was found with respect to vertical position, the bottom bolt having greater compression strength. As with Douglas-fir, the lowest values occurred in the inner zone and in the top bolt of the trees. Young's modulus was lowest at the center of the top bolts and increased with distance from the pith. Compression strength decreased with both increased height and distance from the pith.

Tension.—Tensile testing was used to determine mean Young's modulus and ultimate strength values in tension. Results based on location within the tree are summarized for Douglas-fir and western hemlock in Table 4. The overall Douglas-fir mean tensile Young's modulus and ultimate strength calculated based on testing of 310 specimens was 1.51×10^6 psi and 9,890 psi with COVs of 24.1 and 31.6 percent, respectively. The overall mean Young's modulus and ultimate strength of western hemlock calculated through tensile testing of 234 specimens was 1.11×10^6 psi and 9,380 psi with COVs of 23.1 and 24.5 percent, respectively.

Table 4.—Tensile property variation within the trees with respect to vertical position and radial zone.

	Young's modulus					Ultimate tensile strength				
	Mean (Mpsi)	COV (%)[a]	*t* grouping[b]			Mean (kpsi)	COV (%)	*t* grouping		*n*
Douglas-fir										
By vertical position										
Top	1.402	16.6	•			8.70	22.2	•		21
Middle	1.531	11.8	•			9.18	16.9	•		26
Bottom	1.491	19.5	•			10.71	19.3		•	25
By radial zone										
Pith	1.345	15.5	•			9.16	18.2	•		34
Intermediate	1.569	11.4		•		9.82	19.4	•		32
Bark	1.759	15.0			•	10.53	36.2		•	6
Western hemlock										
By vertical position										
Top	1.104	18.7				8.60	21.2			18
Middle	1.136	17.8	•			9.34	16.1	•		23
Bottom	1.060	22.3	•			9.80	25.5	•		26
By radial zone										
Pith	1.025	16.5	•			9.43	17.0	•		34
Intermediate	1.202	19.2		•		9.46	25.6	•		28
Bark	1.007	21.6				7.78	29.8			5

[a] COV = coefficient of variation.

[b] *t* grouping: dots, read only down a column, indicate regions with a corresponding property that is not statistically significant at a significance level of 0.05.

Table 5.—Probability density function parameters and P *values of clear specimen data.*[a]

	Probability density function					
	Normal			Weibull		
Physical property	μ	σ	Chi-square P value	α	β	Kolmogorov–Smirnov P value
Douglas-fir						
Flexure						
MOE (psi)	1,327,640	274,217	**0.459**	5.350	1,438,958	**0.767**
MOR (psi)	9,570	1,353	**0.664**	7.847	10,142	**0.056**
Compression						
Young's modulus (psi)	1,415,265	295,094	**0.594**	5.279	1,535,081	**0.838**
Ultimate strength (psi)	4,839	552	0.037	6.351	5,095	0.000
Tension						
Young's modulus (psi)	1,513,914	363,603	**0.204**	4.574	1,656,281	**0.714**
Ultimate strength (psi)	9,888	3,115	0.032	3.372	10,992	**0.191**
Western hemlock						
Flexure						
MOE (psi)	1,061,568	208,286	0.000	5.323	1,148,696	0.022
MOR (psi)	8,496	1,166	**0.650**	7.796	9,003	**0.127**
Compression						
Young's modulus (psi)	1,040,928	233,570	0.037	4.757	1,134,979	**0.384**
Ultimate strength (psi)	4,010	485	**0.173**	8.723	4,229	0.013
Tension						
Young's modulus (psi)	1,108,920	255,554	0.002	4.543	1,211,242	**0.085**
Ultimate strength (psi)	9,379	2,292	**0.112**	4.247	10,262	**0.198**

[a] Goodness-of-fit values ($P > 0.05$) are indicated in boldface. MOE = modulus of elasticity, MOR = modulus of rupture.

For Douglas-fir (Table 4), Young's modulus was not significantly affected by vertical position within the tree. Ultimate strength decreased with increasing vertical position although there was not a significant difference between the middle and top bolts. Stiffness, more than strength, increased significantly with distance from the pith.

Young's modulus of western hemlock (Table 4) was not significantly affected by height (vertical position). No clear trend is evident with respect to Young's modulus and radial zone, although values of specimens from the inner zone (close to the pith) were significantly lower. Ultimate strength decreased with increasing vertical position with a larger difference between the bottom and top bolts. A decreasing trend in ultimate strength was found in radial zones from the inner to bark zones with the bark zone being considerably lower.

Mechanical properties of clear wood are governed not only by density but by microfibril angle as well. Therefore, the variation in stiffness and strength properties found in both species would also be significantly influenced by variations in the microfibril angle, which is known to be highest toward the center of a tree. Further statistical analysis conducted on flexure, compression, and tensile data for both species with density taken as covariate indicated that variations in density did not significantly influence the property variations, thus confirming that other factors, such as microfibril angle, play a significant role. The goal of this study was to characterize the mechanical properties of small-diameter Douglas-fir and western hemlock from the coastal region of Washington to examine product opportunities of small-diameter trees removed in forest thinning. A detailed analysis of microfibril angle and other anatomical features was not conducted as part of this study.

Statistical distributions of properties

To better understand and describe variation in material properties that can be encountered from the clear Douglas-fir and western hemlock specimens and to accurately replicate material property distributions, normal and Weibull probability density functions (PDF) were explored. Suddarth and Bender (1995) note these PDFs as common in wood engineering; however, they tend to favor the Weibull PDF because of its ''theoretical basis in strength of materials.'' Additionally, the normal distribution is symmetric about the mean, and its tails extend from negative infinity to positive infinity. The normal probability density function is described by Equation 1, and the two-parameter Weibull probability function is described by Equation 2:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\mu)^2/2\sigma^2} \qquad (1)$$

$$f(x) = \alpha\beta^{-\alpha} x^{\alpha-1} e^{-(x/\beta)^{\alpha}} \qquad (2)$$

In Equation 1, μ is the mean and σ is the standard deviation, and in Equation 2, α is the shape parameter and β is the scale parameter. Probability density function parameters and corresponding goodness-of-fit P-value statistics are shown in Table 5. For all cases, visual inspection of other PDFs indicated that the Weibull distribution was still the better fit. Cumulative distributions comparing properties in flexure, compression, and tension are shown in Figure 5. Flexure modulus is lower than compression and tensile modulus in Douglas-fir. Compression strength is significantly lower (by almost 50%) than flexure and tensile strength in both Douglas-fir and western hemlock.

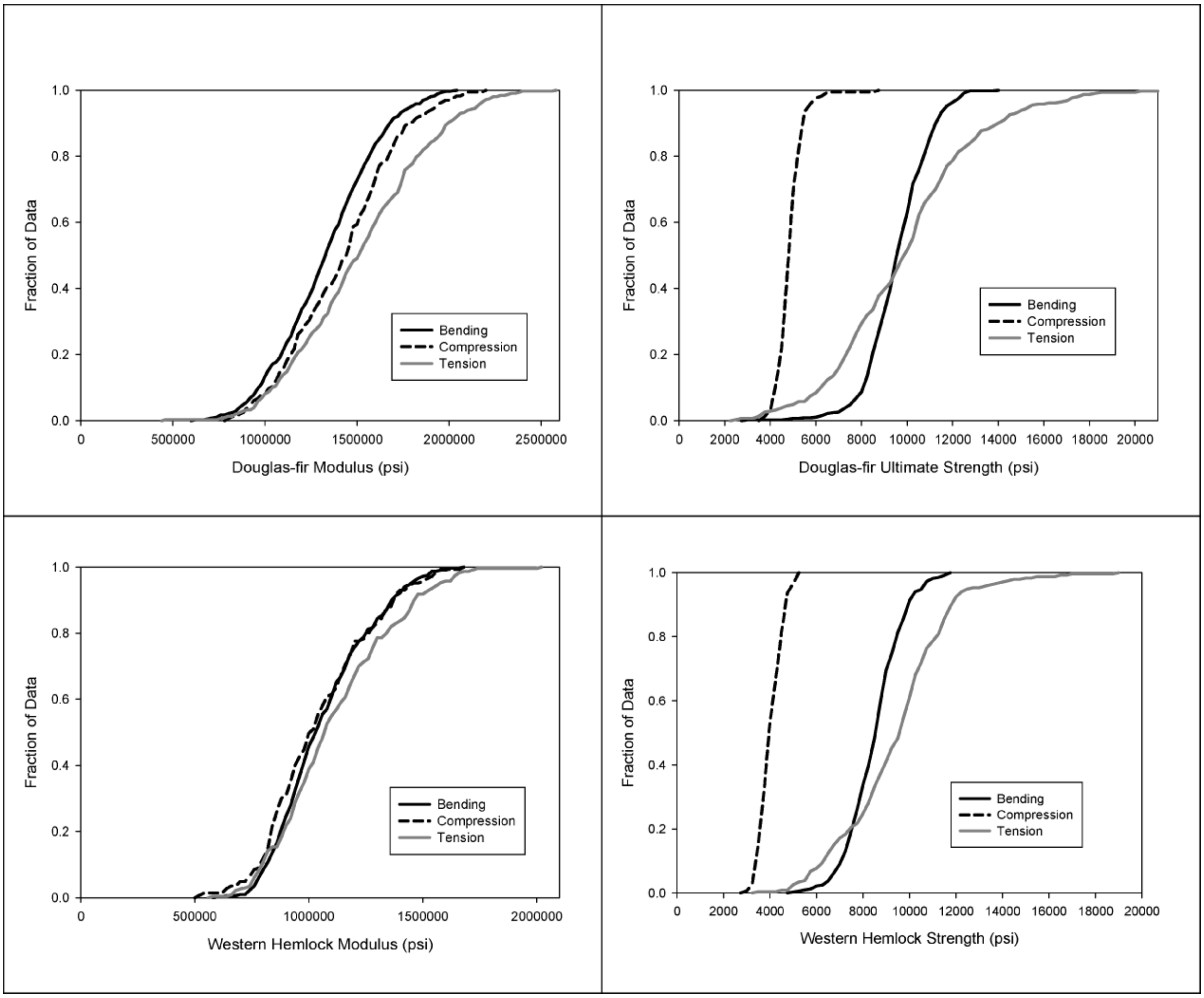

Figure 5.—Experimental cumulative distributions of Douglas-fir and western hemlock moduli and strength.

Conclusion

The objective of this study was to characterize clear specimen material properties and their variation by location within small-diameter Douglas-fir and western hemlock trees from western Washington with the goal of gaining a better understanding of utilization of small-diameter, fast-grown trees for use in manufacturing engineered wood composites.

Density profiling illustrated variations in specific gravity with respect to location. The profiles created in this study closely match other previously published trends for Douglas-fir and western hemlock. All trees contained a high proportion of juvenile wood resulting in strength and stiffness values between 25 and 45 percent lower than what is reported for mature wood of the corresponding species in the Wood Handbook (USDA Forest Service 1999).

Flexural stiffness and strength decreased with increasing vertical position but increased with increasing distance from pith for both species. Young's modulus in compression was generally lower in the center of the tree and did not vary significantly with vertical position, but no variation in compression strength was observed with respect to location in both species. Young's modulus in tension for both species did not vary significantly by vertical position, whereas tensile strength decreased with increasing vertical position. Douglas-fir exhibited increasing tensile strength and modulus with increasing distance from the center of the tree.

With increasing competition for wood fiber, which could account for more than 25 percent of total wood composite (such as particleboard, medium-density fiberboard, and oriented strand board) manufacturing costs, an understanding of material properties and their variations could assist in optimizing the manufacturing process and maximizing efficiency of wood raw material use, thus increasing revenue.

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