# CHARACTERIZATION OF WOOD STRANDS FROM YOUNG, SMALL-DIAMETER DOUGLAS-FIR AND WESTERN HEMLOCK TREES

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**Abstract.** Tensile properties of strands processed from small-diameter Douglas-fir and western hemlock trees grown on the Washington coast were analyzed and effects of location within the tree on properties was examined. Reduction factors for strand properties relative to small, clear solid wood specimen properties were determined by correlating strand properties to previously examined small, clear solid wood specimen properties from the same set of trees. These reductions can be assumed to be damage reduction factors that could help in understanding the expected reduction in tensile or flexure property values from testing solid wood specimens to estimate strand tensile properties. The reduction factors ranged between 0.62 and 0.70 for Douglas-fir and 0.79 and 0.82 for western hemlock for the modulus and were approximately 0.46 for both Douglas-fir and western hemlock for strand tensile strength properties. Measured and calculated strand properties, based on transformation equations, will provide needed values for constructing constitutive relationships when modeling strand-based composites. These properties can also be estimated based on solid wood test specimens if necessary.

***Keywords:*** Douglas-fir, western hemlock, juvenile wood, wood strands, mechanical properties, tensile properties.

## INTRODUCTION

Wood-strand composite behavior is influenced by the properties of its constituents, namely strands, and their arrangement. Often, strand-based composite products are produced from raw materials typically not used for solid wood products (Barnes 2000), including precommercial thinnings from plantations. The emphasis on volume production in some intensive forest management practices often results in these trees having a high proportion of juvenile wood. Concerns about wood quality in relation to juvenile wood proportion in second-growth softwood trees were reported by Kennedy (1995). From a structural application standpoint, one measure of quality, wood density, is important as an indicator of mechanical properties (Haygreen and Bowyer 1996). As a general rule, greater wood density is

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more suitable in applications where stiffness and strength are important (Bendtsen 1978). In softwoods, variation in wood density and microfibril angle was most influential in affecting stiffness (Evans and Ilic 2001; Yang and Evans 2003).

Within a tree, patterns in specific gravity variation can relate to both growth rate and age (Jozsa et al 1989; Cave and Walker 1994). Most softwood species display a radial gradient in physical properties (Sanio 1872; Trendelenburg 1936) with several reports on Douglas-fir (*Pseudotsuga menziesii*) (Wellwood and Smith 1962; Kennedy and Warren 1969; Megraw 1986; Jozsa et al 1989) and western hemlock (*Tsuga heterophylla*) (Wellwood and Smith 1962; Krahmer 1966; Megraw 1986; Jozsa et al 1998; Debell et al 2004), the two species focused on in this research. Cambial age (vertical) variation in wood density has also been reported in Douglas-fir (Jozsa et al 1989; Gartner et al 2002) and hemlock (Forintek Canada Corp 2001) as well as other softwood species (Larson et al 2001; Groom et al 2002; Burdon et al 2004; Alteyrec et al 2005). While the curve form of relative density is similar for Douglas-fir (Jozsa et al 1989) and hemlock (Forintek Canada Corp 2001), the initial decline from the pith varies in number of years and amount of variation differs.

Studies that have examined individual strand properties (Price 1976; Mahoney 1980; Jahan-Latibari 1982; Yadama 2002; Yadama and Wolcott 2006) noted that the modulus of elasticity (E) or Young's modulus in tension of a strand is significantly lower (up to 50%) than parent properties they are stranded from (based on clear specimen testing as per ASTM standards). Price (1976), Geimer et al (1985), and Yadama (2002) have hypothesized this reduction in modulus may be due to processing-induced damage. Geimer et al (1985) specifically examined damage induced through heat and pressure during the hot-pressing process.

Of particular importance to this study is the effect of damage from flaking and pressing on mechanical properties of Douglas-fir flakes conducted by Geimer et al (1985). After the flaking process, the resulting flakes were classified into two groups based on quality and then tested in both a control form and after hot-pressing without adhesive. In general, flake properties were degraded by hot pressing with the average modulus of rupture lowered by 13% and the Young's modulus lowered by 34%. However, another study (Yadama and Wolcott 2006) tested resinated strands isolated from hot-pressed wood–strandboard and found that strand stiffness significantly increased after hot-pressing and is directly proportional to applied resin content. Price (1976) tested sweetgum (*Liquidambar styraciflua* L.) flakes in tension before and after hot-pressing without any resin applied. Flakes from the outer surface as well as from the middle of the board were tested for their tensile properties. It was reported that compared with the published Young's modulus value of small, clear solid wood specimens, the tensile modulus of the flakes were 53 to 69% lower. This reduction in Young's modulus was attributed by the author to cell damage during the flake machining process, grain angle through the thickness of the flakes, moisture content, and inability to measure correct strain by the procedure used. An understanding of the processing effects on strand properties during stranding from logs or lumber will assist producers and researchers to gauge the extent of damage induced and the expected reduction in strand properties. Determination of wood–strand properties is critical to accurately model structure–property relationships of wood–strand composites.

The objective of this research is to characterize the wood–strand properties of small-diameter, fast-grown Douglas-fir and western hemlock trees processed from different positions within a tree (vertically and radially) and correlate their properties with small, clear specimen properties to assess damage induced during the stranding process. The following article presents results of a study that evaluated wood strands processed from 20-yr-old, small-diameter Douglas-fir and western hemlock from the coastal region of

Washington state. We analyzed the expected reduction in material properties when solid wood is converted into strands for production of wood–strand composites and evaluated the influence of radial and vertical position within the stem.

## MATERIALS AND METHODS

### Parent Sample Material

The sample was harvested from two Stand Management Cooperative installations on the Olympic Peninsula near Aberdeen, WA. 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 38 m at 50 yr for Douglas-fir (King 1966) and 33.5 m at 50 yr (Wiley 1978) for western hemlock. The sample consisted of 12 trees each of Douglas-fir (Installation No. 706) and western hemlock (Installation No. 727) that were about 20 yrs old (based on ring count at stump) and between 7.6 and 9.1 m in height. The average diameter at breast height for Douglas-fir was 24 cm and for western hemlock 21 cm. Three 1.8-m bolts were cut from each tree; the bottom bolt was taken at the stump and the top bolt the last 1.8 m from a 10-cm top. The middle bolt was centered on the remaining log. There was approximately a 2-foot gap among the three vertical positions. Small clear specimens were cut from bottom, middle, and top bolts of sampled Douglas-fir and western hemlock trees. From each bolt, specimens were also taken from the pith, intermediate, and outer (bark) zone in the radial direction. Specimen preparation was optimized for exclusion of knots or cracks. Details regarding specimen preparation and properties of small, clear specimens of these two species tested in tension, compression, and flexure can be found in Langum et al (2009). Matched clear specimens from these same locations were processed into strands. Specimens were conditioned under identical conditions of approximately 21°C and 65% RH for several months to equilibrate to approximately 12% MC.

### Strand Generation

Clear specimen material (about 38 mm × 38 mm × 152 mm) was immersed in water for approximately 3 wk prior to stranding. Strands were generated with a CAE disk strander or flaker. Approximate strand dimensions were 152 mm in length, 0.76 mm in thickness, and 32 mm in width; however, strands were individually measured prior to testing. Grain orientation was generally parallel to the strand length; however, the transverse orientation was random with respect to the grain/knife orientation. After processing of each batch, the strands were placed in an open-air box dryer for approximately 2 h. The strands were then conditioned to approximately 12% MC under approximately 21°C and 65% RH for several days. After conditioning, strands were tested in tension to determine their properties that included Young's modulus ($E_x$), ultimate tensile strength (UTS) or rupture stress and Poisson's ratio ($\nu_{xy}$) (see Fig 1 for axis orientation).

### Tensile Properties of Strands

Once the strands equilibrated to nominal moisture content of 12%, testing was performed according to the method proposed by Yadama (2002) and Yadama and Wolcott (2006). To obtain tensile properties, the strands were loaded in the longitudinal direction (x-axis in Fig 1) to failure using a 2-kip universal electromechanical test machine (Instron 4466 R). A 12.7-mm gauge length axial extensometer (Epsilon Model 3442) was installed in the midsection on the wide face of the strand with the knife-edges parallel to the grain direction to measure transverse strain in the specimen. Transverse strain was measured to use in calculating Poisson's ratio. The specimens were loaded at a uniform


Figure 1. Axis labeling and orientation for strands tested (gray lines indicate grain direction). Material axes (1, 2, and 3) and geometric axes (x, y, and z) are shown.

crosshead speed of 0.006 mm/s until an axial force of 20 kgf was applied, which was ensured to be within the linear elastic behavior of the strand. At this point, the strands were released and given sufficient time to relax and recover. The strands were reloaded with the 12.7-mm gauge length axial extensometer installed on the specimen to measure strain parallel to grain; strands were tested to failure to determine their UTS. A total of 211 Douglas-fir and 192 western hemlock strands were tested (number of strands by location and angle varied but included multiple replicates sufficient for valid statistical analysis).

Tensile testing of the strands with strains measured along the two principal axes allowed for the calculation of $E_x$ and $\nu_{xy}$. Grain angle was then calculated on the failed specimens according to the method proposed by Koehler (1955). According to this method, a scribe was used to follow the grain angle in each strand and this angle was photographed. The photograph was then analyzed using image analysis software to accurately determine the grain angle of each strand within the gauge length. Note that the grain angle was recorded, not the microfibril angle.

Strands with a grain angle of 1° or less were used to estimate $E_1$ and $\nu_{12}$, tensile stiffness, and Poisson's ratio in the material direction (along 1, 2, and 3 axes as shown in Fig 1). After testing all strands for $E_x$ and $\nu_{xy}$, grain angle, θ, was also determined. Tested strands were grouped by similar grain angles and mean values for $E_x$ and $\nu_{xy}$ were determined for each grain angle group. Using the computed mean angles and approximated values of $E_1$ and $\nu_{12}$ (strands with grain angle less than 1°), transformation equations (Eqs 1 and 2) (Jones 1999) were solved simultaneously to determine $E_2$ and $G_{12}$:

$$\frac{1}{E_x} = \frac{1}{E_1}\cos^4\theta + \left(\frac{1}{G_{12}} - \frac{2\upsilon_{12}}{E_1}\right)\sin^2\theta\cos^2\theta + \frac{\sin^4\theta}{E_2} \tag{1}$$

$$\nu_{xy} = \frac{\nu_{12}(\sin^4\theta + \cos^4\theta) - \left(1 + \frac{E_1}{E_2} - \frac{E_1}{G_{12}}\right)\sin^2\theta\cos^2\theta}{\cos^4\theta + \left(\frac{E_1}{G_{12}} - 2\nu_{12}\right)\sin^2\theta\cos^2\theta + \frac{E_1}{E_2}\sin^4\theta} \tag{2}$$

Strand properties were then compared against small, clear solid wood specimen values from the same vertical position and radial zone within the same sample trees that were previously tested (Langum et al 2009) to assess damage-induced reductions as a result of the flaking process.

## RESULTS AND DISCUSSION

### Tensile Properties of Strands

The overall average strand Young's modulus and rupture stress (ie ultimate tensile strength where failure in the specimen occurred within the extensometer gauge length) for the Douglas-fir trees were 6.44 GPa and 30.3 MPa, respectively. These values represent a 38% and 55% decrease when compared with values of small, clear specimens tested in tension (Langum 2007). The decrease in rupture strength can be attributed to damage from the stranding process. The overall average strand Young's modulus and rupture stress for the western hemlock trees were 6.03 GPa and 28.3 MPa, respectively. These values represent a 21% and 56% decrease in Young's modulus and rupture stress when compared with small, clear specimens tested in tension (Langum 2007). Compared with Douglas-fir, western hemlock strand modulus did not reduce at the same level indicating a lesser degree of damage during strand production; however, the reduction in strength was similar.

Strands were grouped by their grain angles (grain angle ranged from 0-10°) into three categories for each of the species to apply transformation equations effectively in estimating average material direction properties, $E_2$, and $G_{12}$. Measured, as well as computed, properties are summarized in Table 1. Properties measured for strands with average grain angle of zero were

Table 1. Measured and computed properties of strands.[a]

| Avg. grain angle (degrees) | Avg. $E_x$ (GPa) | COV (%) | Avg. $\nu_{xy}$ | COV (%) | Avg. computed $G_{12}$ (GPa) | Avg. computed $E_2$ (GPa) | Avg. UTS (MPa) | COV (%) |
|---|---|---|---|---|---|---|---|---|
| Douglas-fir | | | | | | | | |
| 0 | 7.70 | 34.7 | 0.54 | 35.4 | 0.09 | 0.18 | 32.3 | 36.7 |
| 2.7 | 5.66 | 35.9 | 0.52 | 29.7 | — | — | 29.9 | 31.0 |
| 4.9 | 4.88 | 34.8 | 0.51 | 35.9 | — | — | 24.8 | 31.8 |
| Western hemlock | | | | | | | | |
| 0 | 6.70 | 22.1 | 0.51 | 38.2 | 0.23 | 0.24 | 31.2 | 27.9 |
| 2.8 | 5.97 | 24.9 | 0.49 | 41.9 | — | — | 25.8 | 36.4 |
| 5.3 | 5.46 | 31.2 | 0.41 | 41.0 | — | — | 26.5 | 34.3 |

[a] Note that $E_x = E_1$ and $\nu_{xy} = \nu_{12}$ when grain angle is zero.
UTS, ultimate tensile strength.

assumed to be material direction properties, $E_1$ and $\nu_{12}$, respectively. Due to greater differences in elastic properties of strands with a larger difference in grain angle, experimental values obtained for strands with grain angles greater than 4° were used to estimate values of $G_{12}$ and $E_2$ using transformation equations (Eqs 1 and 2). The transformation equation accurately models the change in Young's modulus with increasing grain angle for both species (Figs 2 and 3).

Variations in measured strand properties were examined as a function of tree height (vertical position) and diameter (radial zone) for Douglas-fir and western hemlock (Table 2). Similar to clear specimen properties of Douglas-fir (Langum et al 2009), the midbolts yielded strands with the highest Young's modulus values, while the strands from the bottom bolts had the highest rupture strength. In the radial direction, unlike the clear specimens, Young's modulus and rupture stress of the strands from the outer zone, adjacent to the bark, yielded the lowest values.

Unlike clear specimen properties in western hemlock (Langum et al 2009), strands from the top bolts yielded the highest values for Young's modulus followed by the midbolts. As for ultimate strength, strands from the bottom bolt, like the small, clear specimens, yielded higher values while those from the top bolt were the lowest. When radial zone was considered, Young's modulus distributions remained basically the same as clear specimen properties. Strands from regions near the pith and intermediate rings had very similar moduli, while those from the region adjacent to the bark had significantly lower modulus values. Unlike Douglas-fir, western hemlock strand modulus increased

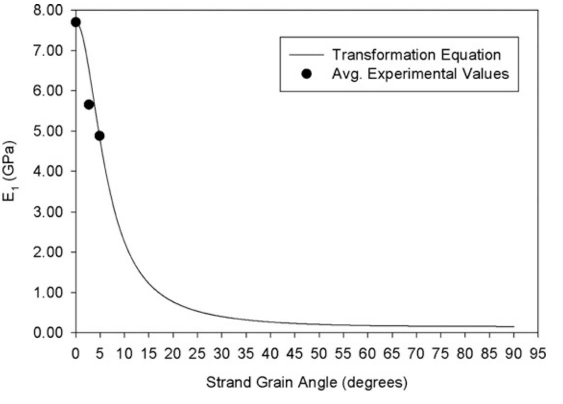


Figure 2. Douglas-fir strand Young's modulus vs grain angle.

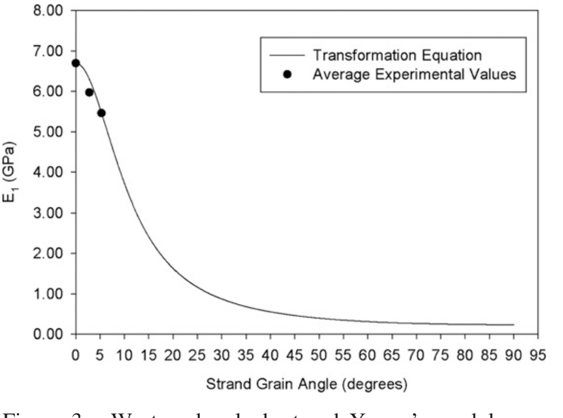


Figure 3. Western hemlock strand Young's modulus vs grain angle.

Table 2. Douglas-fir and western hemlock strand properties as influenced by their location within a tree.

| Location | | $E_x$ (GPa) | COV (%) | $\nu_{xy}$ | COV (%) | UTS (MPa) | COV (%) |
|---|---|---|---|---|---|---|---|
| Douglas-fir | Tree avg. | 6.44 | 42.1 | 0.53 | 34.2 | 30.4 | 14.1 |
| | Vertical position | | | | | | |
| | Bottom | 5.75 | 34.0 | 0.49 | 31.2 | 33.0 | 17.7 |
| | Middle | 7.10 | 47.4 | 0.52 | 36.6 | 29.2 | 8.0 |
| | Top | 6.48 | 29.9 | 0.60 | 31.9 | 28.0 | 12.7 |
| | Radial zone | | | | | | |
| | Pith | 5.95 | 33.8 | 0.52 | 34.9 | 30.0 | 14.5 |
| | Intermediate | 7.35 | 46.3 | 0.56 | 31.6 | 32.9 | 14.2 |
| | Bark | 5.81 | 37.9 | 0.49 | 36.1 | 26.7 | 0.1 |
| Western hemlock | Tree avg. | 6.03 | 26.4 | 0.47 | 40.7 | 28.3 | 13.3 |
| | Vertical position | | | | | | |
| | Bottom | 5.72 | 25.6 | 0.49 | 40.3 | 30.9 | 11.4 |
| | Middle | 6.21 | 22.9 | 0.44 | 41.4 | 27.0 | 1.6 |
| | Top | 6.30 | 29.6 | 0.47 | 40.5 | 25.8 | 19.2 |
| | Radial zone | | | | | | |
| | Pith | 6.21 | 24.9 | 0.46 | 41.4 | 29.2 | 6.3 |
| | Intermediate | 5.99 | 24.8 | 0.51 | 35.5 | 25.4 | 10.8 |
| | Bark | 5.59 | 35.2 | 0.37 | 45.4 | 34.4 | — |

UTS, ultimate tensile strength.

Table 3. Kolmogorov-Smirnov (K-S) *p*-values comparing distributions of strand properties by tree height for Douglas-fir and western hemlock (values in bold imply statistically no significant difference between the corresponding distributions).

| Vertical position | | Young's modulus | | | Ultimate tensile strength | | |
|---|---|---|---|---|---|---|---|
| | | Bottom | Middle | Top | Bottom | Middle | Top |
| Douglas-fir | Bottom | 1.000 | — | — | 1.000 | — | — |
| | Middle | **0.057** | 1.000 | — | **0.191** | 1.000 | — |
| | Top | **0.050** | **0.206** | 1.000 | **0.176** | **0.880** | 1.000 |
| Western hemlock | Bottom | 1.000 | — | — | 1.000 | — | — |
| | Middle | **0.149** | 1.000 | — | **0.073** | 1.000 | — |
| | Top | **0.106** | **0.635** | 1.000 | 0.021 | **0.635** | 1.000 |

while strength decreased with increasing height, while both properties increased for strands as they were taken from zones closer to the pith.

Strand properties by vertical position and radial zone were compared to examine the significance of location effects. *p*-values from the two-sample Kolmogorov-Smirnov (K-S) goodness-of-fit test were compared (Tables 3 and 4). Distributions are considered similar if the *p*-values is greater than the critical value of $\alpha = 0.05$. K-S testing indicated no significant variation between the distributions with respect to the vertical position (height) of the tree for both species (bold numbers indicate no significant difference). For both species, distance from the pith, however, did indicate significant variation in both strength and Young's modulus with the strands from the inner (closest to pith) and the bark (closest to the bark) zones being significantly less stiff than the strands from the intermediate zone. Strand modulus in the bark zone (closer to the bark) was in general lower than the other two regions.

## Comparison of Properties From Strand Testing to Small Clear Specimen Testing

Three-parameter Weibull and lognormal probability density functions were fit to data from strand testing to describe the property distributions (Table 5), and the chi-square goodness-of-fit test was conducted to determine how well the

Table 4. Kolmogorov-Smirnov (K-S) *p*-values comparing distributions of strand properties across tree diameter for Douglas-fir and western hemlock (values in bold imply statistically no significant difference between the corresponding distributions).

| | | Young's modulus | | | Ultimate tensile strength | | |
|---|---|---|---|---|---|---|---|
| Radial position | | Pith | Intermediate | Bark | Pith | Intermediate | Bark |
| Douglas-fir | Pith | 1.000 | — | — | 1.000 | — | — |
| | Intermediate | 0.022 | 1.000 | — | **0.491** | 1.000 | — |
| | Bark | **0.473** | **0.073** | 1.000 | 0.008 | 0.011 | 1.000 |
| Western hemlock | Pith | 1.000 | — | — | 1.000 | — | — |
| | Intermediate | **0.491** | 1.000 | — | 0.013 | 1.000 | — |
| | Bark | 0.001 | 0.004 | 1.000 | **0.177** | 0.002 | 1.000 |

Table 5. Probability density function parameters and *p*-values of strand properties.

| | Weibull parameters | | | Lognormal parameters | | |
|---|---|---|---|---|---|---|
| Probability density function tensile property | Location | Shape | Scale | Location | Shape | Scale |
| Douglas-fir | | | | | | |
| Young's modulus (GPa) | 1.73 | 1.88 | 5.2 | 0.33 | 0.39 | 1.72 |
| Ultimate strength (MPa) | 11.3 | 1.7 | 20.1 | 1.97 | 0.39 | 3.23 |
| Western hemlock | | | | | | |
| Young's modulus (GPa) | 0.93 | 2.58 | 6.01 | −2 | 0.23 | 2.09 |
| Ultimate strength (MPa) | 5.33 | 2.64 | 25.4 | −27 | 0.17 | 3.99 |

probability density function described the experimental distribution. Although goodness–of-fit tests indicated a poor fit (*p*-values $\approx$0.001) between the density functions and the experimental data in all cases except western hemlock tensile strength, visual inspection indicated that the density functions with given parameters were a good fit in all cases for both species. Probability density functions fit the ultimate strand strength data better than the Young's modulus for both species. It is well accepted that Weibull and log normal distributions describe experimentally derived wood properties well (Suddarth and Bender 1995). Derived distribution parameters can be used to generate strand properties for these species in modeling properties of wood–strand composites.

To establish reduction factors for strand properties with respect to small, clear solid wood specimen properties due to damage caused by the stranding process, cumulative distributions of strand tensile properties were compared with the experimental cumulative distributions of previously determined flexure and tensile properties of small, clear solid wood specimens taken from similar locations within the sampled trees (Figs 4 and 5). Tables 6 and 7 summarize mean values of strength and modulus for strands and clear, small specimens, as well as the reduction factors (ratio of strand property to corresponding clear specimen property, such as S/F and S/T which represent respective "strand" modulus or strength value divided by "flexural" or "tensile" modulus or strength). Examining the cumulative distribution plots reveals that there appears to be an almost parallel shift in strand property values, whether Young's modulus or strength, compared with corresponding values obtained from testing small, clear solid wood specimens in flexure. Reduction ratios given in Tables 6 and 7 can be used to estimate approximate property values of strands processed from the two species by multiplying them with the properties obtained by testing small, clear solid wood specimens in flexure or tension.

## CONCLUSIONS

Variation in mechanical properties within a tree in combination with damage induced to wood constituents during wood composite processing can impact final quality and properties of a composite product. Considering the shift to harvesting younger trees and using materials from production forestry treatments, we analyzed the effects of location within the tree and process-induced damage on tensile properties of strands processed from small-diameter Douglas-fir and western hemlock trees grown on the Washington coast. Induced damage was measured by correlating strand properties to previously examined small, clear solid wood specimen properties from the same set of trees (Langum et al 2009). These reductions can be assumed to be damage reduction factors which could help in understanding the expected reduction in tensile or flexure property values from testing solid wood specimens to estimate strand tensile properties.

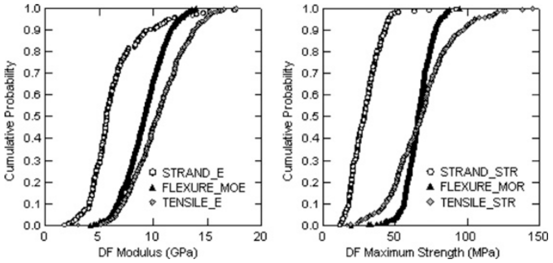


Figure 4. Comparison of cumulative distributions of Douglas-fir small clear specimens and strand properties.

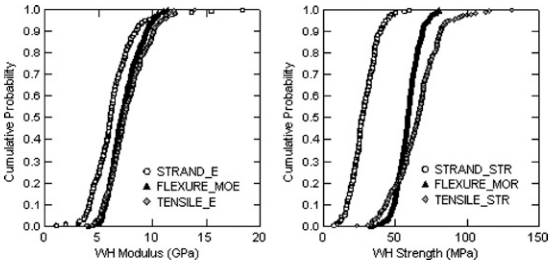


Figure 5. Comparison of cumulative distributions of western hemlock small clear specimens and strand properties.

Greatest variation in Young's modulus and UTS was found in the radial direction of both species. The strand property reduction factors ranged between 0.62 and 0.70 for Douglas-fir and 0.79 and 0.82 for western hemlock for the tensile modulus; whereas they were about 0.46 for both Douglas-fir and western hemlock for strand tensile strength properties relative to strength determined using small, clear solid wood flexure tests. The authors recommend using properties derived from flexure testing of solid wood specimens for estimating strand properties as there is a parallel shift in cumulative distributions.

Table 6. Mean modulus values and associated reduction factors for Douglas-fir and western hemlock strand modulus.

| | Location | Strand Young's modulus (GPa) | Clear specimen flexure MOE (GPa) | Clear specimen tensile Young's modulus (GPa) | Modulus damage reduction ratio | |
|---|---|---|---|---|---|---|
| | | | | | S/F | S/T |
| Douglas-fir | Species average | 6.44 | 9.17 | 10.41 | 0.70 | 0.62 |
| | Vertical position | | | | | |
| | Top | 6.48 | 8.41 | 9.67 | 0.77 | 0.67 |
| | Middle | 7.10 | 9.44 | 10.55 | 0.75 | 0.67 |
| | Bottom | 5.75 | 9.20 | 10.28 | 0.63 | 0.56 |
| | Radial zone | | | | | |
| | Pith | 5.95 | 8.19 | 9.27 | 0.73 | 0.64 |
| | Intermediate | 7.35 | 9.75 | 10.82 | 0.75 | 0.68 |
| | Bark | 5.81 | 9.94 | 12.13 | 0.58 | 0.48 |
| Western hemlock | Species average | 6.03 | 7.31 | 7.65 | 0.82 | 0.79 |
| | Vertical position | | | | | |
| | Top | 6.30 | 6.89 | 7.61 | 0.91 | 0.83 |
| | Middle | 6.21 | 7.48 | 7.83 | 0.83 | 0.79 |
| | Bottom | 5.72 | 7.47 | 7.31 | 0.77 | 0.78 |
| | Radial zone | | | | | |
| | Pith | 6.21 | 6.77 | 7.07 | 0.92 | 0.88 |
| | Intermediate | 5.99 | 7.72 | 8.29 | 0.78 | 0.72 |
| | Bark | 5.59 | 8.51 | 6.94 | 0.66 | 0.81 |

MOE, modulus of elasticity.

Table 7. Mean strength values and associated reduction factors for Douglas-fir and western hemlock strand strength.

| | Location | Strand strength (MPa) | Clear specimen flexure strength (MPa) | Clear specimen tensile strength (MPa) | Strength damage reduction ratio S/F[a] | S/T[b] |
|---|---|---|---|---|---|---|
| Douglas-fir | Species average | 30.4 | 66.0 | 68.2 | 0.46 | 0.45 |
| | Vertical position | | | | | |
| | Top | 28.0 | 60.5 | 60.0 | 0.46 | 0.47 |
| | Middle | 29.2 | 65.4 | 63.3 | 0.45 | 0.46 |
| | Bottom | 33.0 | 69.5 | 73.8 | 0.48 | 0.45 |
| | Radial zone | | | | | |
| | Pith | 30.3 | 63.9 | 63.2 | 0.47 | 0.48 |
| | Intermediate | 32.9 | 66.4 | 67.7 | 0.50 | 0.49 |
| | Bark | 26.7 | 68.1 | 72.6 | 0.39 | 0.37 |
| Western hemlock | Species average | 28.3 | 58.6 | 64.7 | 0.48 | 0.44 |
| | Vertical position | | | | | |
| | Top | 25.8 | 54.8 | 59.3 | 0.47 | 0.43 |
| | Middle | 27.0 | 57.9 | 64.4 | 0.47 | 0.42 |
| | Bottom | 30.9 | 62.6 | 67.6 | 0.49 | 0.46 |
| | Radial zone | | | | | |
| | Pith | 29.2 | 59.1 | 65.0 | 0.49 | 0.45 |
| | Intermediate | 25.4 | 58.1 | 65.2 | 0.44 | 0.39 |
| | Bark | 34.4 | 62.9 | 53.6 | 0.55 | 0.64 |

[a] S/F = ratio of strand modulus to flexural modulus.
[b] S/T = ratio of strand modulus to tensile modulus.

Measured and calculated strand properties, based on transformation equations, will provide needed values for constructing constitutive relationships when modeling strand-based composites.

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