CHARACTERIZATION OF PACIFIC NORTHWEST SOFTWOODS

FOR WOOD COMPOSITES PRODUCTION

By

CHRISTOPHER E. LANGUM

A thesis submitted in partial fulfillment of
the requirements for the degree of

MASTERS OF SCIENCE IN CIVIL ENGINEERING

WASHINGTON STATE UNIVERSITY
Department of Civil and Environmental Engineering

MAY 2007

To the Faculty of Washington State University:

The members of the Committee appointed to examine the thesis of CHRISTOPHER E. LANGUM find it satisfactory and recommend that it be accepted.

Chair

Acknowledgment

I would like to express a very special thanks to my wife, Abby, who sacrificed countless nights and weekends during my graduate school career, for her support and understanding.

My advisor, Dr. Vikram Yadama and my committee, Dr. David Pollock and Dr. William Cofer provided valuable input and support through the thesis writing and researching experience. Thank you for your time and patience.

Dr. David McLean granted me valuable opportunities at WSU both as an intern with the Pacific Earthquake Engineering Research Center and with an assistantship. For this and other help along the way, I am very thankful.

Also of significant help during my graduate school career are my fellow grad students and friends: Andy Schildmeyer, Ryan Musgrove, Tom Hervillard, Blandine Valle, Steve Nelson, Jesse Chase, Matt Snook, and Eliot Bonvalot, all who made the experience more enjoyable.

Bob Duncan and Scott Lewis's experience and know-how were invaluable during the preparation and testing phases of the research. Also, thank you for the company during the endless hours of testing.

My parents provided endless support and encouragement during both my undergraduate and graduate studies. With out their help, my college experience would have not been possible.

Finally, this project was partially funded through an agreement with the Pacific Northwest Research Station, Portland, OR. Raw materials, including harvesting and transportation, were provided by the Stand Management Cooperative, University of Washington.

CHARACTERIZATION OF PACIFIC NORTHWEST SOFTWOODS

FOR WOOD COMPOSITES PRODUCTION

Abstract

by Christopher E. Langum, M.S.
Washington State University
May 2007

Chair: Vikram Yadama

Forest management practices and the composition of forests are changing. Old growth trees that were once relied upon for timber production are becoming less available. Consequently, the forest industry has begun harvesting higher volumes of fast grown, small diameter trees. Due to the age of these trees, a larger percentage of juvenile timber is present, which in turn reduces physical and mechanical properties. It is critical to know and understand the characteristics of available wood resources for process and product optimization

The goal of this research is to characterize wood from small diameter trees to effectively utilize them in engineered wood composites. This research focused on evaluating and examining the variation in physical and mechanical properties of small-diameter Douglas-fir and western hemlock from the Olympic Peninsula of Washington State relevant to the production of wood-based composites. Testing was conducted in two stages. The first stage consisted of analyzing density profiles and conducting flexure, tension, and compression tests on clear specimens to determine respective

modulus and rupture stress values. These values were examined to determine the influence of location with respect to height and diameter. The second stage of testing involved further processing the material into furnish typically used in modern engineered wood composites. This furnish was then further evaluated to identify differences based on location; properties evaluated were wood flour particle size distribution, pH and buffering capacity, and tensile Young's modulus and rupture stress of typical OSB strands. Results from testing of clear specimens indicated the highest values of strength and modulus in tension, compression, and flexure could be expected from the bottom or mid-height region with further property increases as distance from the pith increased. Although some variation was encountered between species, the general trends remained the same. As for particle size distribution, analysis by location yielded very little variation with respect to location in both species; however, western hemlock did produce a greater overall percent of larger particles based on one particular processing technique. Similarly to the particle size distribution, analysis of pH and buffering capacity showed very little variation with respect to location in both species. Douglas-fir however, was considerably more acidic.

Finally, tensile testing of strands indicated density and grain angle of the specimen played a much larger role in the quality of the strand than location. Unlike clear specimen properties, when height was considered, little variation with respect to strength or modulus was encountered. However, average strength and modulus reductions of up to 50% should be expected when comparing strand properties to clear specimen properties due to processing induced damage.

Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

Introduction

Forest management practices and the composition of forests are changing. In the past, abundant forests were selectively harvested to produce only the best quality material. Now, due to past harvesting procedures and increased environmental pressures, old growth trees that were once relied upon for timber production are becoming less available. Additionally, legislation such as the Healthy Forest Restoration Act (HFRA) is providing additional incentives for those who utilize wood from thinning treatments and other forest biomass (HFRA 2003). Consequently, the timber industry has begun searching for ways to improve log recovery rates and more effectively utilize small diameter trees. Engineered wood composites allow manufacturers to produce high quality wood products by utilizing fast growing, small diameter trees. Because these products are tailored to meet a particular end use, a higher quality product can be manufactured from an otherwise under utilized resource, which makes engineered wood composites environmentally friendly as well. To continue the development of these innovative products, an understanding of the inherent properties of the raw materials used in production is imperative.

Typically, the small diameter tree stocks consist of subsequent-growth forests, plantations, and thinnings. Subsequent-growth forests are meant to model as well as possible the conditions similar to a never harvested forest, while plantations are manipulated through silviculture practices such as the use of fertilizers, irrigation, pruning, thinning, and genetics to produce the highest volume of valuable material. Timber from thinning treatments can come from any source where crowding is a problem. While the wood harvested from these sources is all suitable for wood composites manufacturing, their growth conditions are significantly different. Because the growth conditions are so different from those of old growth forests, the physical and mechanical properties of these trees are vastly different from their old growth counterparts. Silvicultural conditioning allow trees to reach sawmill size in only 15 to 25 years; however, due to the young age of these trees, they are composed of a large overall percentage of juvenile wood. Conversely, a sawmill size tree from a natural slow grown forest contains a very small overall percentage of juvenile wood. (Bendtsen 1978)

Juvenile timber is formed around the tree's pith and advances up the tree with the crown as the tree ages (Figure 1.1). The crown is affected by activity in the apical meristem which influences the cambial region that produces secondary xylem. A gradual transition between juvenile and mature timber occurs as the cambium continues to cause an increase in diameter. Increased distance from the apical meristem reduces its influence and allows wood to mature.

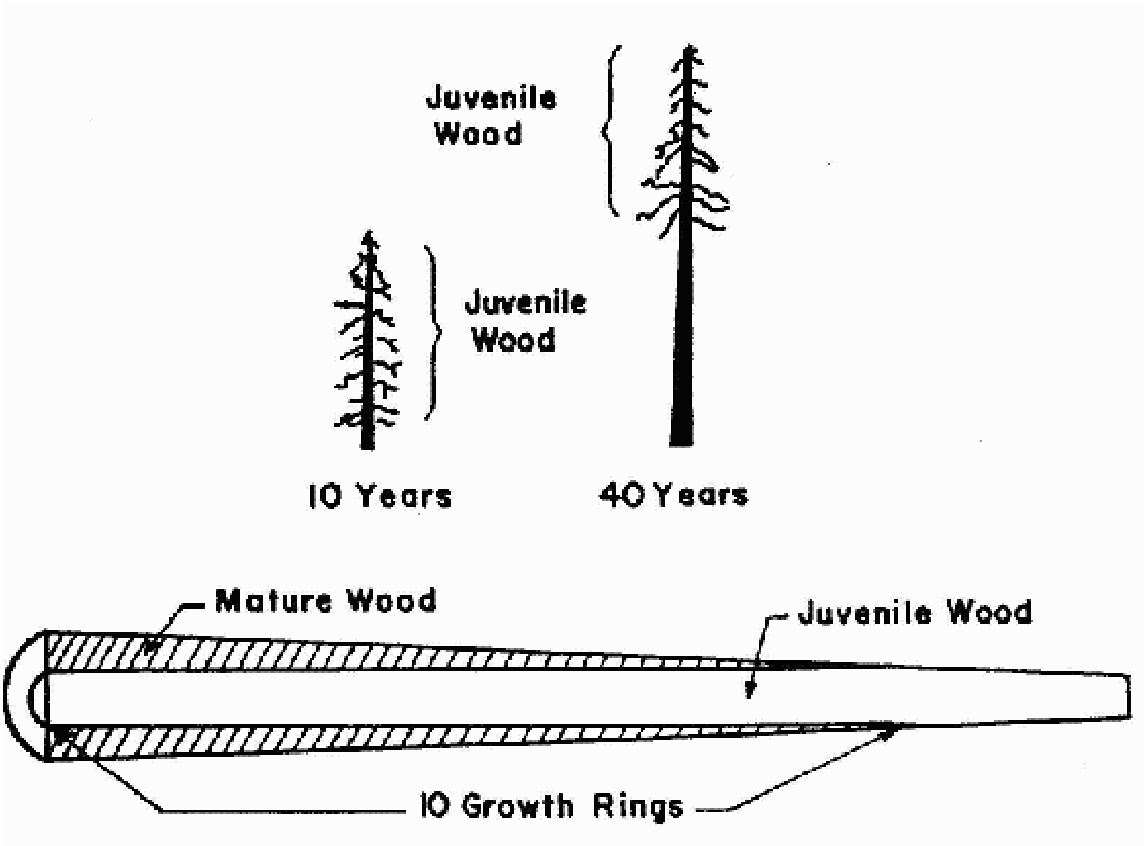

Figure 1.1. Juvenile wood growth area (Johnson 1987).

Juvenile timber is known to exhibit lesser strength qualities than mature wood. These reduced properties have been noted in a number of studies including those by Barrett and Kellogg (1989), Bendtsen (1978), Gerhards (1979), and MacPeak et al. (1990). This is in large part due to lower specific gravity, shorter cell lengths, thinner cell walls, higher microfibril angles, and greater moisture content which result in lower strength and increased longitudinal shrinkage (Figure 1.2) (Bendtsen 1978).

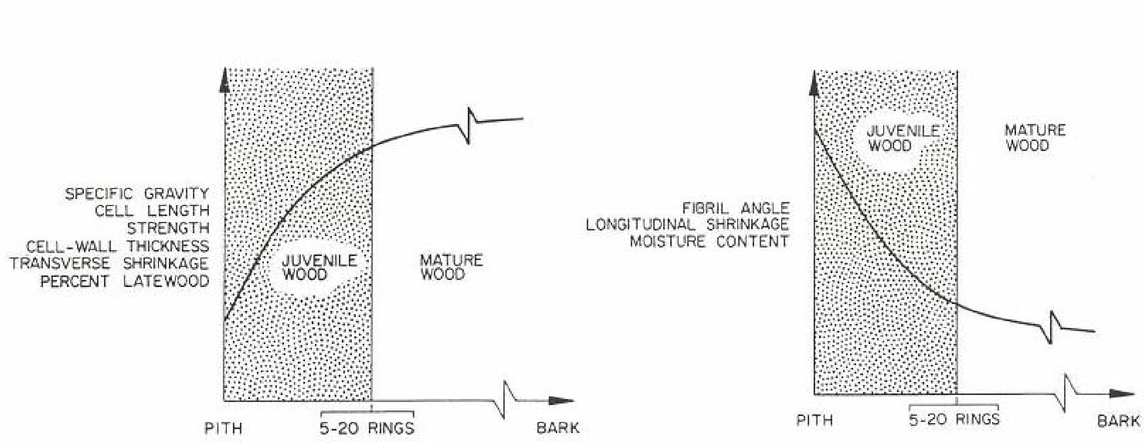

Figure 1.2. Gradual change in properties from juvenile to mature wood (Bendtsen 1978).

Additionally, properties vary further within a tree from butt to crown. Patterns of variation within stems vary from species to species and are further complicated by site location and growth characteristics (Cown and Parker 1978). These variations significantly affect overall utilization of the timber and alter processing characteristics.

Timber entrepreneurs are constantly searching for ways to reduce production costs, increase yields, and improve overall product quality (Wasniewski 1991, Sauter 1995). An understanding of the variation of wood properties within a tree is critical to maximize value recovery. It is possible to categorize zones of a tree with respect to logs which may be cut from the stem and regions from pith to bark (Burdon et al. 2004). Understanding variation in properties as a function of tree length could then help in segregating bolts from different sections of the same tree for different applications, such as oriented strand composite, fiberboard, or wood-plastic composite. The goal of this research is to better understand the variations in physical and mechanical properties along the height and across the diameter within fast growing softwood species from the Pacific

Northwest coast, specifically, the Olympic Peninsula in Washington State. This characterization could then be used to more effectively utilize timber.

Objectives

The primary goal of this research is to characterize the variation in small clear specimens and wood furnish for composite production from small diameter, fast grown Douglas-fir and western hemlock trees as a function of location within the tree. To achieve this goal, the following tasks were undertaken.

1) Test small clear Douglas-fir and western hemlock specimens taken from different locations along the height and diameter of the trees to investigate variation in physical and mechanical properties.

2) Characterize the attributes of furnish prepared from Douglas-fir and western hemlock relevant to wood-based composite manufacturing and describe property variation within the trees.

Rationale and Significance

Softwoods have been the species of choice for timber construction on the West Coast for many years. Because of previously mentioned small diameter tree sources, engineered wood composites such as oriented strand board (OSB) and wood plastic composites (WPC) have become popular replacement products for solid sawn lumber and plywood. According to the fifth Resources Planning Act, OSB is predicted to overtake softwood plywood production. Additionally, even though markets for small diameter logs will get better, prices will continue to be weak (Haynes and Skog 2002). The key to long-term stability and sustained profit margins is effective use of available timber resources and efficient utilization. For example, Schuler (2003) states that processing logs for lumber and plywood results in a conversion efficiency of only 50%; however, significantly smaller logs may not be suitable for production of either lumber or plywood. When used for OSB production, it is reported that conversion efficiency of approximately 71% can be obtained in a typical OSB manufacturing plant (Kline 2005). Highly engineered wood composites such as OSB and WPC can utilize wood from small diameter, fast grown trees to create uniform products which are not subject to the shortfalls of juvenile timber such as poor dimensional stability and strength. Additionally, higher yields equate to less waste and lower manufacturing costs, which in turn, increase revenues. To accomplish this, a sound understanding of these small diameter timber resources is essential.

Background

The current research was conducted under an agreement with the U.S. Department of Agriculture's Pacific Northwest Research Station in Portland, Oregon. Twelve Douglas-fir (*Pseudotsuga menziesii*) and twelve western hemlock (*Tsuga heterophylla*) trees were harvested from the American Mill site (Installation No. 727) during the fall of 2004. The trees all appeared to be of good health and free from growth defects. During harvesting, age of 15-20 years was the main selection criteria. The diameter at breast-height of the Douglas-fir trees ranged from 7.5 in. – 11.5 in. while the western hemlock trees ranged from 6.3 in. to 11.2 in.. All logs were processed at the Wood Materials and Engineering Laboratory of Washington State University.

Thesis Organization

The research presented in this thesis is divided into three chapters. The first chapter introduces the project objectives and consists of an overview of the current state of wood composite production. The second and third chapters are written as stand alone papers with a review of associated literature respective to each chapter. Due to the research objectives, the third chapter references results from the second. Chapter two consists of the clear specimen portion of testing. It includes flexural, compressive, and tensile test results as well as density profiles. The third chapter contains tests associated with wood composites manufacturing. It also provides a transformation equation for tensile Young's modulus of strands based on grain angle.

References

Barrett, J.D. and Kellogg, R.M. 1991. Bending strength and stiffness of second-growth Douglas-fir dimension lumber. Forest Products Journal. 41(10):35-43

Bendtsen, B.A. 1978. Properties of wood from improved and intensely managed trees. Forest Products Journal. 28(10):61-78

Burdon, R.D., Kibblewhite, R.P., Walker, J., Megraw, R.A., et al. 2004. Juvenile Versus Mature Wood: A New Concept, Orthogonal to Corewood Versus Outerwood, with Special Reference to Pinus radiate and P. taeda. Forest Science 50(4):399-415

Cown, D.J. and Parker, M.L. 1978. Comparisons of annual ring density profiles in hardwoods and softwoods by x-ray densitometry. Can. J. For. Res. 8:442-449

Gerhards, C.C. 1979. Effects of high temperature drying on tensile strength of Douglas fir 2 by 4's. Forest Products Journal. 29(3):39-46

Haynes, W. and Skog, K.E. 2002. The fifth resources planning act timber assessment: A critical tool for sound stewardship. Journal of Forestry. March.

Healthy Forest Restoration Act of 2003. Act of Congress.

Johnson, N.E. 1987. Concerns of the forest manager in managing the changing forest resource. Proceedings 47379, Managing and Marketing the Changing Timber Resource. For. Prod. Research Society. Madison, WI. Pp. 84-90

Kline, D.E. 2005. Gate-to-gate life-cycle inventory of oriented strandboard production. Wood and Fiber Science. 37(12):74-84

MacPeak, M.D., Burkhart, L.F., and Weldon, D. 1990. Comparison of grade, yield, and mechanical properties of lumber produced from young fast-grown and older slower-grown planted slash pine. For. Prod. J. 40(1):11-14

Sauter, S.L. 1995. Developing high-quality composites from waste wood and wheat straw using urea-formaldehyde resin. Master's Thesis. Washington State University. Pullman, WA.

Wasniewski, J.L. 1991. Evaluation of juvenile wood and its effects on Douglas-fir structural panels. Master's Thesis. Washington State University. Pullman, WA.

Chapter 2: Physical and Mechanical Properties of Small Clear Specimens of Douglas-fir and Western Hemlock With Respect to Location

Introduction

Studies by Abdel-Gadir and Krahmer (1993), Burdon, et al. (2004), Evans, et al. (2000), and Passialis and Kiriazakos (2004) among others have documented physical and mechanical property differences between mature and juvenile timber. Density variations within the stems of Douglas-fir and western hemlock have been studied by many researchers in the past. Recently, DeBell et al. (2004) reviewed the state of young-growth western hemlock density research. They also determined through use of X-ray densitometry that western hemlock density is highest near the pith and steadily declines for the first 10 years. Following the initial decline, little change occurred until age 25, at which point a slow increase in density occurred until age 40, at which point, density remained nearly uniform. This general trend was further reinforced by articles from Jozsa and Middleton (1994) and Jozsa et al. (1998) (Figure 2.1). A typical Douglas-fir density profile is illustrated in Figure 2.1. Abdel-Gadir and Krahmer (1993) published a similar article about Douglas-fir that further described previous work done with the species to estimate the juvenile/mature demarcation age. This article utilized previous X-ray densitometry work by Abdel-Gadir et al. (1993) to create piecewise linear regression models that estimated the age of transition between juvenile and mature wood. Abdel-Gadir and Krahmer (1993) estimated the demarcation age of Douglas-fir to be about 30 years and noted this change to be gradual and varying for all characteristics. Further description about the X-ray densitometry procedure are explained by Hoag and McKimmy (1988) and Hoag and Krahmer (1991).

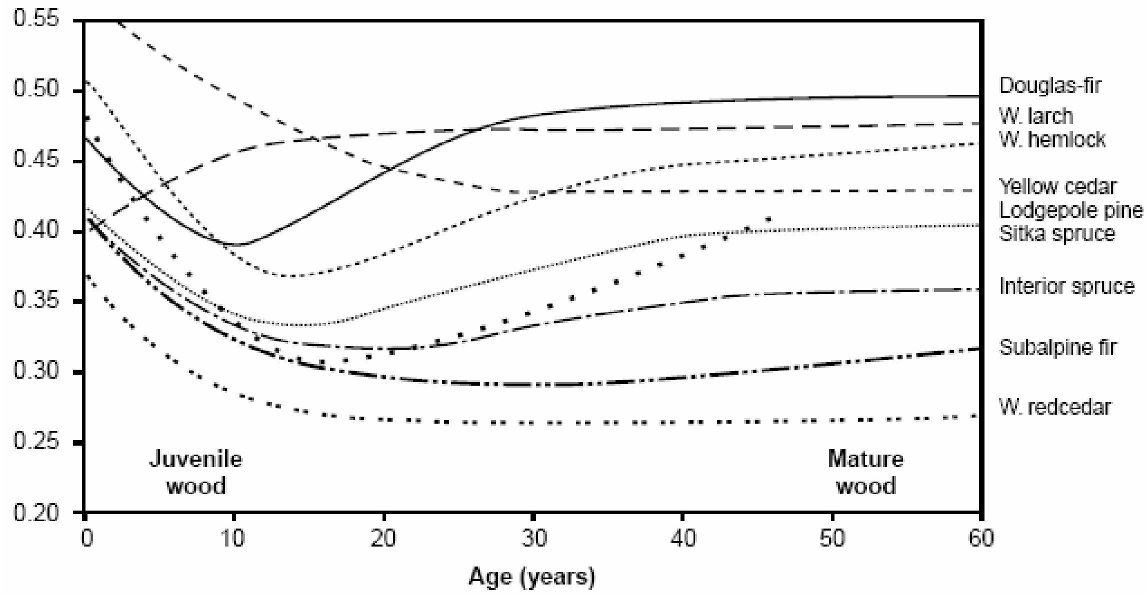

Figure 2.1. Average density at breast height from pith to bark of nine species (Jozsa et. al 1998).

Mechanical properties of Douglas-fir and western hemlock have also been the subject of much research in the past. Ifju and Kennedy (1962) observed a direct correlation between the high fibril angles associated with juvenile timber and reduced tensile strength. They also noticed typical failure trends in spring and summer wood, with spring wood tending to fail in tension across cell walls while summer wood tended to fail between cells in longitudinal shear. Testing of specimens from three trees indicated summerwood to springwood tensile strength ratio of 3.2 could be expected while the respective specific gravity ratio was lower at 2.5. Gerhards (1979) studied the effect of high-temperature drying on Douglas-fir and although his research did not focus on juvenile timber, reduced tensile and flexural properties were noted when specimens containing the pith were compared to those which did not contain pith. Kretschmann and Bendtsen (1992) also considered the effects of juvenile timber on 4 grades of 2 by 4 lumber. The study, which focused on fast-grown plantation loblolly pine found ultimate tensile stress and modulus values for pieces composed of juvenile timber were 45 to 63% lower than those pieces containing only mature wood. A similar study by Barrett and Kellogg (1991) examined changes in bending strength and modulus of second-growth Douglas-fir 2 by 4 lumber based on visual grade, log position, and percent juvenile timber. They found MOE and MOR decreased with increasing height in the tree and increasing overall percentage of juvenile timber

A more recent study by Green et al. (2005) determined that in the case of one stand of suppressed Douglas-fir trees, small diameter (< 10 in.) did not produce poor flexural properties. Instead, the 70 to 90 year-old trees produced 2 by 4 lumber of which 68% qualified as select structural for light framing and 89% passed as stud grade. Diameter alone can not be used to indicate a high overall percentage of juvenile timber.

Biblis (1969) looked specifically at differences between tensile properties of early and latewood loblolly pine according to ASTM standard D 103. He concluded that specific stress and specific modulus of latewood was 50% and 63% higher than earlywood respectively. He also examined the effect of moisture content and determined its effect on earlywood and latewood was approximately the same. Bendtsen (1978) addressed many issues associated with intensively managed trees. His literature review covered a wide range of species and indicated that accelerated growth rates were responsible for earlier harvesting of young trees due to their size, resulting in these trees possessing a high percentage of juvenile timber.

Many of the previously mentioned studies examined 2 by 4 lumber and determined the overall percentage of juvenile wood contained in the specimen. The goal of this study is to understand the variation in physical and mechanical properties by location within two of the Pacific Northwest (Olympic Peninsula, WA) small diameter softwood species which would then be correlated in the next chapter to furnish properties prepared for wood composite manufacturing.

Objectives

Close proximity to the apical meristem has been shown to negatively affect timber properties. It is therefore hypothesized that as distance from the apical meristem increases, wood strength and modulus will also increase. Because this zone extends up the tree, radial distance from the pith is expected to contribute the most to increases in mechanical properties, while height is expected to have less of an effect. A study was conducted to test this hypothesis where the primary objective is to characterize the physical and mechanical properties of small clear specimens from small diameter, fast grown Douglas-fir and western hemlock trees and relate these properties to vertical and radial location within the tree. The specific tasks to achieve this objective include:

1) Determine physical properties of small diameter, fast grown Douglas-fir and western hemlock specimens through X-ray densitometry to examine zones where changes in mechanical properties may be encountered.

2) Test small clear specimens of Douglas-fir and western hemlock in tension parallel to grain, compression parallel to grain, and flexure by zones established in objective one to determine the extent of variation in mechanical properties with respect to tree height and diameter.

Materials

Twelve Douglas-fir (*Pseudotsuga menziesii*) and twelve western hemlock (*Tsuga heterophylla*) trees were harvested from the American Mill site (Installation No. 727) during the fall of 2004. Immediately following harvesting of the trees, 6 ft. bolts were cut and labeled. Freshly cut ends were sealed with Anchor Seal to prevent drying. The specimens were then transported to Washington State University's Wood Materials and Engineering Laboratory (WMEL) where they were further reduced to a 2 in. thick x diameter disk, a 1 in. thick x diameter disk, an approximately 5 ft. x diameter log, a 1 in. thick x diameter disk, and a 2 in. thick x diameter disk (Figure 2.2). The process was repeated up the height of the tree. The roughly 4 ft.-5 ft. logs were then ripped into nominal 1 ½ in. x 1 ½ in. x 4 ft.-5 ft. sticks. All of the specimens were then conditioned at approximately 70^{o}F and 65% relative humidity for several months to equilibrate to approximately 12% moisture content.

Finally, the 4 ft.-5 ft. sticks were broken down to lengths of 18 in., 16 in., and 4 in. for tension, bending, and compression tests respectively per ASTM D 143 (ASTM 1994). Every stick was optimized for exclusion of knots or cracks. Since the specimens were rough cut to approximately 1 ½ in. square, they had to be further reduced to 1 in. x 1 in. using a table saw.

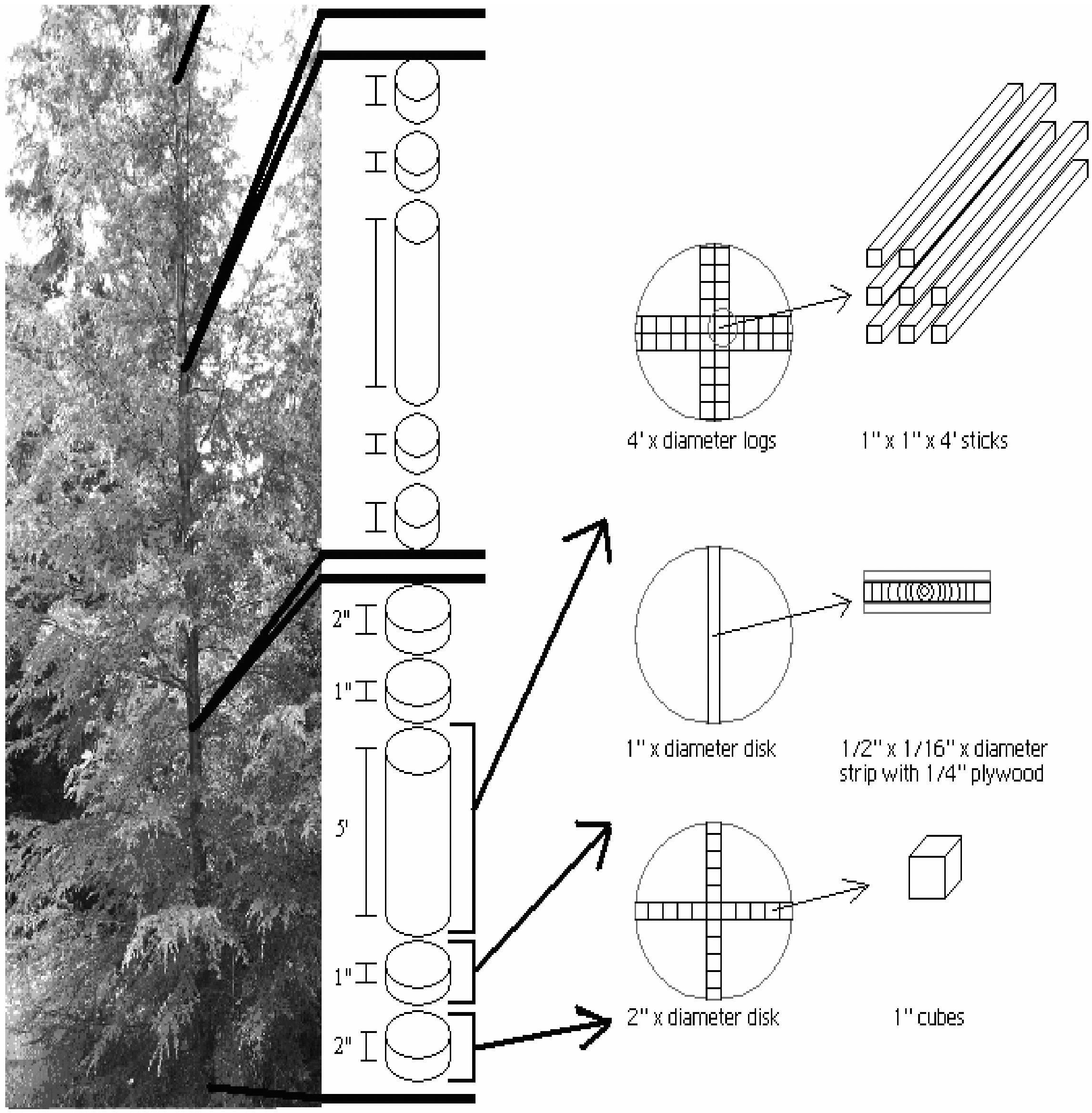

Figure 2.2. Bolt location along tree length and specimen extraction per experimental plan from each bolt.

Methodology

Physical Property Evaluation

X-Ray Density Profiling

X-ray density profiles were determined using the Quintek Measurement Systems, Inc. (QMS) Tree Ring Analyzer (Model QTRS-01X) at the University of Idaho's Forest Products Laboratory. Randomly oriented 1/2 in. x diameter strips were removed from 1 in. disks described above (Figure 2.2). Immediately following removal of the strips, 1/4 in. plywood was bonded to each vertical face of the specimen using the polyurethane adhesive Gorilla Glue®. Once the adhesive had fully cured, a 1/16 in. strip was removed from the center of the specimen. The radial strips were then allowed to air-dry to equilibrium moisture content and scanned with the x-ray density profiler to map changes in density from pith to bark on each end of the test bolts.

Mechanical Property Evaluation

Compression

Compression parallel to grain testing was followed the guidelines of ASTM D 143-94, Standard Test Methods for Small Clear Specimens of Timber (ASTM 1994). Due to the size of the specimens, the secondary method was followed. Clear 1 in. x 1 in. x 4 in. specimens were tested at a rate of 0.012 in/min using a 30 kip universal electromechanical test machine (Instron 4400 R). Strain was recorded using a 2 in. axial extensometer (Epsilon Model 3542). Properties calculated include Young's modulus and rupture stress. Following the destructive testing of the specimen, a 1 in. cube was removed from near the failure and used to calculate moisture content.

Tension

Tension parallel to grain was performed according to ASTM D 143-94, Standard Test Methods for Small Clear Specimens of Timber (ASTM 1994). Due to the size of the specimens, the secondary method was followed. Clear 1 in. x 1 in. x 18 in. specimens were reduced to the dog bone shape specified in ASTM D 143. A 2 kip universal electromechanical test machine (Instron 4466 R) applied a continuous rate of motion of 0.05 in/min. Strain was recorded using a 2 in. axial extensometer (Epsilon Model 3542). Properties calculated include Young's modulus and rupture stress. Following the destructive testing of the specimen, an approximately 3 in. length was removed from near the failure and used to calculate moisture content.

Flexure

Static bending was performed according to ASTM D 143-94, Standard Test Methods for Small Clear Specimens of Timber (ASTM 1994). Due to the size of the specimens, the secondary method was followed. Clear 1 in. x 1 in. x 16 in. specimens were measured with calipers to verify actual dimensions. Span length was determined according to the secondary method to be 14 in.. A continuous rate of deflection of 0.05 in/min was applied using a 2 kip universal electromechanical test machine (Instron 4466 R). Strain was recorded using an Electronic Instrument Research, Ltd. (EIR) Model LE-05 laser extensometer. Deflections were recorded over a gage length of 2 in.. Properties calculated include modulus of elasticity and modulus of rupture. Following the destructive testing of the specimen, a 1 in. cube was removed from near the failure and used to calculate moisture content.

Zones of Property Evaluation

For the purpose of testing and evaluation of physical and mechanical properties, each tree was divided into nine regions based on location along the height and across the diameter. In the field, each tree was subdivided into three bolts as stated earlier. Each of these sections represents one unique location with respect to height. Locations were further divided based on radial distance from the pith. According to the secondary method of ASTM D 103-94 (ASTM 1994), the required cross-sectional specimen size for tension parallel to grain, compression parallel to grain, and static flexure is 1 in. x 1 in.. Radial zones were selected with this requirement in mind as well as an allowance for saw blade kerf and final trimming. On occasion, the pith would deviate from its original position during rough specimen cutting. This resulted in the two typical specimen orientations noted in Figure 2.3. To maximize the number of unique zones and also accommodate some variation in growth patterns, three radial zones were selected (Figure 2.3.).

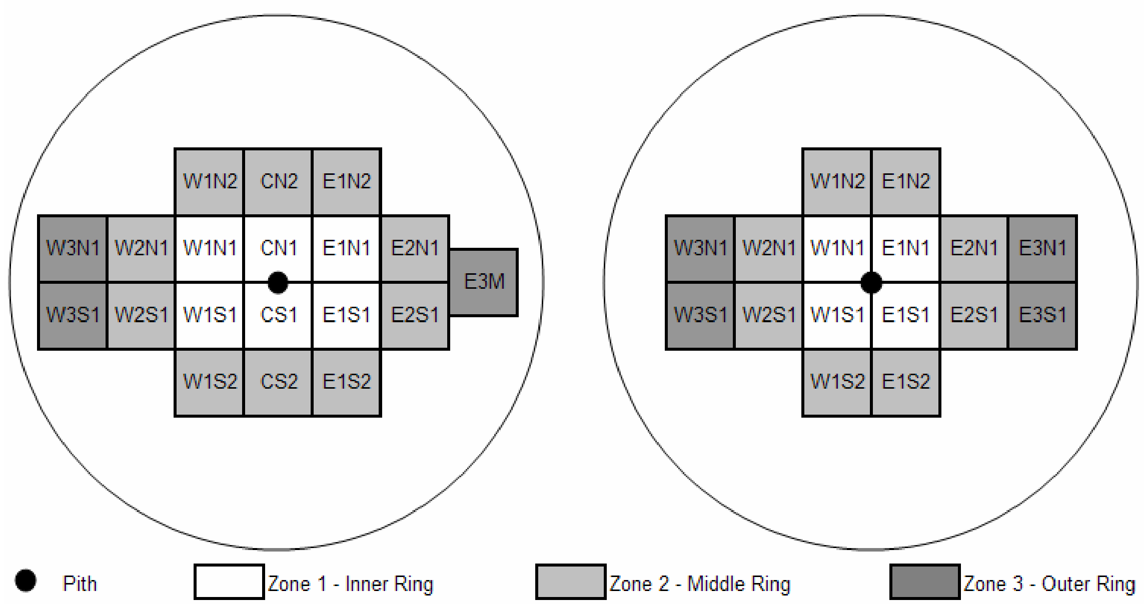

Figure 2.3. Radial location of specimens.

Statistical Evaluation

Distributions of all mechanical properties evaluated were statistically analyzed and parameters of the best fit probability density functions were estimated. This information assisted with stochastic models and served to compare with strand properties determined in the second part of the study. In this way, an understanding of the reduction in properties as a result of damage done during the stranding process can be gained. Chi-squared and Kolmogorov-Smirnov goodness of fit tests were conducted to judge if a chosen distribution fit the experimental data well. Further analysis was conducted to evaluate the differences in mechanical properties and the variation thereof. In many cases, due to the natural variation in tree size, uneven sample sizes were utilized which resulted in some zones having adequate numbers of samples while others were less than adequate. Because each sample does not represent an individual replicate, samples from similar locations were averaged to create one mean observation per each area, per each tree. This effectively created one unique set of mechanical properties for each zone in each tree which was then used in combination with t-tests; and in the case of flexural testing modified means, accounting for the covariate effects, were compared to determine significant differences with respect to location within the trees.

Results and Discussion

Physical Property Evaluation

Density Variations

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.

<u>Douglas-fir</u>

Typical trends in average ring width, earlywood and latewood relative densities, and ring specific gravity of the twelve Douglas-fir trees are shown in Figure 2.4. Variation in specific gravity within the earlywood, latewood, and tree ring as a whole, with respect to location within the tree is summarized in Table 2.1. The average specific gravity considering all of the Douglas-fir specimens was 0.46, 2% higher then the 0.45 reported in the Wood Handbook (1999). It should be noted however, the Wood Hand density values are calculated based on a mass and volume basis while this studies values were calculated through X-ray densitometry. The trends displayed in these graphs closely match trends published in Wood and Fiber Science by Abdel-Gadir and Krahmer (1993). Their article, which focused on estimation of the demarcation age of Douglas-fir, noted no apparent demarcation line in this species, but rather a general trend towards maturation which occurred between the ages of 27 and 37 years. Based on this and the general trends in density shown on Figure 2.4, it is rather apparent the trees are composed of nearly all juvenile timber.

Even though the trees are composed of mostly juvenile timber, there are well defined zones of increasing or decreasing densities across the radius of the trees. The data indicates it may be reasonable to expect large variations in strength and modulus based on these zones which correspond well with those described in the previous section (indicated by thick vertical lines in Figure 2.4). Also of interest is the decreasing trend in density with increasing height until the top log, which shows a slight increase in specific gravity (Table 2.1). This increase in density is most likely due to the influence of the crown; however, beyond the specific gravity measurement at the stump, height does not appear to have a large effect on density.

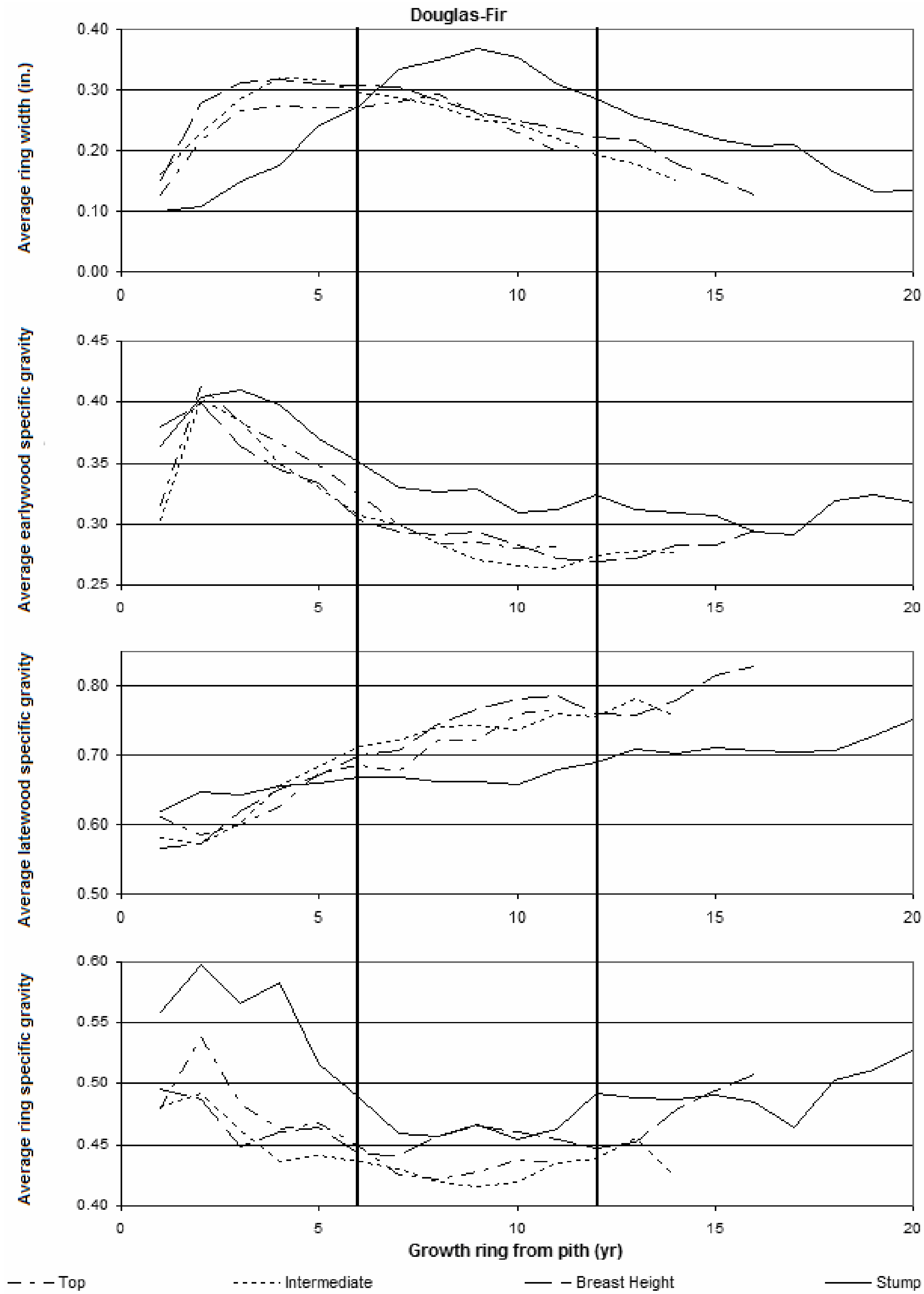

Figure 2.4. Average Douglas-fir specific gravity profile data.

Table 2.1. Douglas-fir ring specific gravity variation based on height.

Location	Earlywood		Latewood		Ring		n
	Mean	COV (%)	Mean	COV (%)	Mean	COV (%)	
Tree	0.31	16.6	0.70	13.9	0.46	15.7	1174
Stump	0.33	13.7	0.68	10.8	0.50	14.6	257
Breast Height	0.31	15.4	0.72	14.6	0.46	13.2	403
Intermediate	0.30	18.0	0.70	14.3	0.44	14.5	360
Top	0.32	18.1	0.68	14.2	0.45	20.8	154

Western hemlock

Western hemlock ring specific gravity was slightly higher than Douglas-fir; however, the density trends were very similar (Figures 2.4 and 2.5). Unlike Douglas-fir, western hemlocks average tree density (0.49) was considerably higher then the Wood Handbook value of 0.45 (1999). This discrepancy is most likely due to the different methods of calculation as previously mentioned. With the exception of higher density values, the similar trends could be expected based on Jozsa's et. al work (1998) . He showed 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, the western hemlock's average ring specific gravity (0.49) was much larger than the value of 0.41 for young-growth western hemlock published by DeBell, et. al (2004) (Table 2.2). As with the trees in this study, he did note the highest specific gravity at the pith and that the value quickly decreased and remained relatively constant after that point. Again in a trend similar to that of Douglas-fir, the average specific gravity decreased with height with the exception of the uppermost measurement of the top log. In both cases, the top measurement also had the highest coefficient of variation.

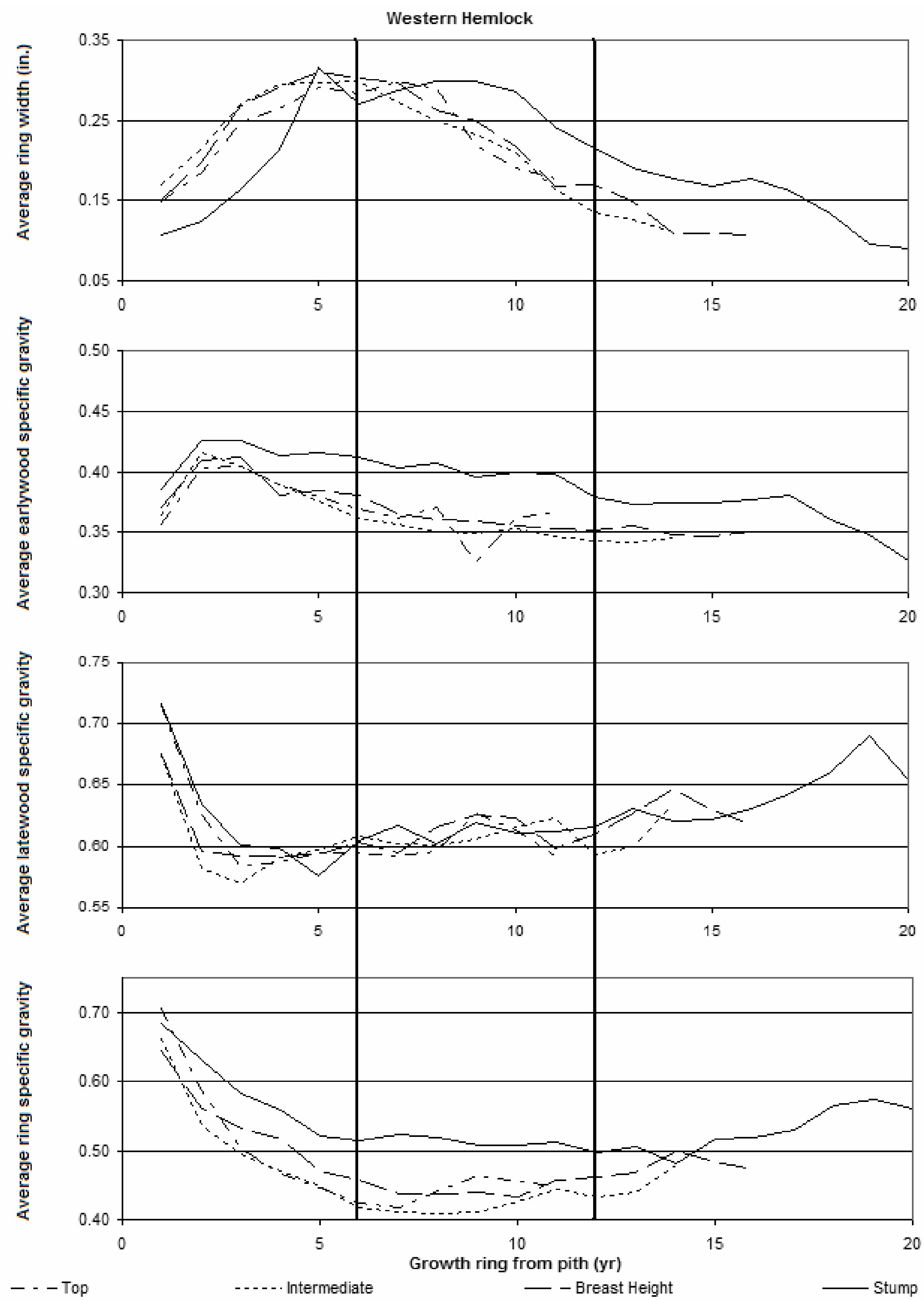

Figure 2.5. Average western hemlock specific gravity profile data.

Table 2.2. Western hemlock ring specific gravity variation based on height.

Location	Earlywood		Latewood		Ring		n
	Mean	COV (%)	Mean	COV (%)	Mean	COV (%)	
Tree	0.37	12.7	0.62	9.0	0.49	19.0	1008
Stump	0.39	14.3	0.63	8.5	0.54	14.3	234
Breast Height	0.37	11.9	0.62	8.8	0.49	18.7	352
Intermediate	0.36	10.3	0.61	9.0	0.46	18.7	302
Top	0.37	14.4	0.61	10.0	0.49	22.8	120

Mechanical Property Evaluation

Flexure

The first step in identifying clear specimen properties was determination of mean modulus of elasticity (MOE) and modulus of rupture (MOR) values through flexural testing. Results based on location within the tree are summarized for Douglas-fir and western hemlock respectively in Tables 2.3-2.12. In both cases, testing resulted in COVs which were less than the expected COVs listed in the Wood Handbook of 22% for modulus of elasticity and 16% for modulus of rupture (Wood Handbook 1999). The lower COVs should be expected however, as these trees came from one location while values used in the Wood Handbook come from trees of various locations.   Analysis of variance confirmed for both species, variation due to location and density was significant (p-values < 0.0001). Therefore, Duncan's comparison of means analysis was carried out to examine the differences and similarities between properties by location. Means that are not significantly different are indicated in the tables by specimen locations which have black dots (•) in the same columns.

Douglas-fir

The overall tree mean MOE and MOR calculated through flexural testing of 463 specimens was 1.33 x 10^6 psi and 9,570 psi with COVs of 20.7% and 14.2% respectively. According to the Wood Handbook (1999), values of 1.95 x 10^6 psi (greater by 47%) and 12,400 psi (greater by 30%) are expected MOE and MOR values for Coastal Douglas-fir at 12% moisture content. Wood Handbook values are based on mature wood physical and mechanical properties and the effect of juvenile timber is evident in the large difference in flexural properties.

MOE and MOR varied further when location within the tree was considered (Tables 2.3 and 2.4). Strength and modulus values were lowest at the top of the trees when only height was considered. This is almost certainly due to the influence of the crown, where the percent juvenile wood is known to be relatively higher. Statistical analysis indicated that MOE of middle and bottom bolts were similar; but, MOR was found to significantly decrease with increased tree height (Table 2.5). Specific gravity in these three areas ranged from 0.47-0.50 and appeared to affect MOR more so than MOE. The effect density had on MOE is not readily apparent because while the bottom and middle bolts were considered similar, there was a 6% difference in specific gravity. It is realized that other differences not evaluated in this study, such as microfibril angle, would also influence the properties.

__Table 2.3. Douglas-fir flexural property variation with respect to radial and vertical location.__
(Dots, read only down a column, indicate regions with a corresponding property that is not statistically significant at a significance level of 0.05)

Douglas-fir	Specific Gravity		MOE				MOR					Trees Tested
	Mean	COV (%)	Mean (psi)	COV (%)	t Grouping		Mean (psi)	COV (%)	t Grouping			
By Elevation												
Top	0.47	8.6	1219807	14.0		●	8780	8.4			●	23
Middle	0.47	6.5	1368515	13.8	●		9476	8.4		●		27
Bottom	0.50	5.0	1334923	19.1	●		10080	8.9	●			28
By Radial Distance												
Pith	0.48	6.1	1188325	13.1	●		9271	8.2		●		36
Intermediate	0.48	8.2	1413796	13.6		●	9626	9.7	●	●		34
Bark	0.49	8.1	1441815	18.8		●	9878	16.6	●			8

As expected, flexural properties increased with distance from the pith towards the outer regions closer to the bark. Distance from the pith had the greatest effect on MOE, which decreased 16%-17% in modulus as proximity of the pith decreased. MOR followed a similar trend with a steady increase from pith to bark; however, comparison of means test indicated the center and intermediate regions were similar as well as the intermediate and outer regions.

Table 2.4. Douglas-fir flexural property variation within the trees.
(Dots, read only down a column, indicate regions with a corresponding property that is not statistically significant at a significance level of 0.05)

Douglas-fir	Specific Gravity		MOE									MOR						Trees Tested
	Mean	COV (%)	Mean (psi)	COV (%)	t Grouping							Mean (psi)	COV (%)	t Grouping				
Top-Bark	0.53	N/A	949069	N/A							●	7540	N/A				●	1
Top-Intermediate	0.45	9.2	1311822	11.3			●		●	●		8805	6.3	●				10
Top-Pith	0.48	7.5	1165689	12.8	●				●			8863	9.3	●				12
Middle-Bark	0.46	7.2	1380449	14.6		●	●			●		9302	16.7	●				3
Middle-Intermediate	0.47	7.3	1480475	12.1		●		●				9578	8.5	●		●		12
Middle-Pith	0.47	5.9	1253571	10.4	●				●	●		9419	6.6	●				12
Bottom-Bark	0.51	6.4	1611025	9.1				●				10895	9.8		●			4
Bottom-Intermediate	0.50	5.3	1432096	14.9		●	●					10357	6.8		●	●		12
Bottom-Pith	0.49	4.1	1145715	15.4	●							9532	7.5	●				12

Finally, Table 2.4 shows variation in MOE and MOR across the nine specific locations within the trees. The wide range of MOEs which can be expected within a tree is apparent in Table 2.4. MOR however, was not subject to as much variation when location was considered. Interesting trends which should be noted from this table include:

1. Near the pith, strength and modulus remained constant through the height of the trees.

2. The highest average MOE came from the outer rings near the base of the trees. These values did not begin to decrease until beyond midheight.

3. The lowest MOE and MOR values were found in the outer rings of the upper level (it should be noted, however, that this is based on small sample sizes)

<u>Western hemlock</u>

Mean MOE and MOR values from flexure tests on western hemlock yielded overall tree mean values of 1.06 x 10^6 psi and 8,500 psi with COVs of 19.7% and 13.7% respectively. Compared to the published values in the Wood Handbook (1999), MOE and MOR of small-diameter western hemlock tested in this study were significantly lower, 35% in the case of MOE and 25% with respect to MOR. Once again this indicates a larger percentage of juvenile wood in these study trees from the Olympic Peninsula.

Interestingly, MOE and MOR variation with respect to height was exactly the same as Douglas-fir (Table 2.3 and 2.5). Variation with respect to distance from the pith differed some, but MOR values indicated no significant change from the pith to intermediate range. Again, strength and modulus values were lowest at the top of the trees when only height was considered. Specific gravity in the western hemlock trees varied as much as the Douglas-fir trees, however, the values were slightly lower (0.45-0.48). The 0.48 specific gravity values measured near the pith is one possible explanation for the significantly higher MOR values near the center of the bolts. A decreasing trend in properties, both MOE and MOR, is apparent going from outer regions towards the pith and from the bottom log to the top long.

Table 2.5. Western hemlock flexural property variation with respect to radial and vertical location. *(Dots, read only down a column, indicate regions with a corresponding property that is not statistically significant at a significance level of 0.05)*

Western hemlock	Specific Gravity		MOE					MOR					Trees Tested
	Mean	COV (%)	Mean (psi)	COV (%)	t Grouping			Mean (psi)	COV (%)	t Grouping			
By Elevation													
Top	0.45	8.7	999626	11.8			●	7945	10.7			●	18
Middle	0.46	7.0	1085032	14.2	●			8396	7.5		●		23
Bottom	0.48	8.8	1084017	9.8	●			9082	10.8	●			29
By Radial Distance													
Pith	0.48	7.5	982009	11.8			●	8567	8.8	●			35
Intermediate	0.45	8.4	1120443	15.0		●		8422	12.5	●			28
Bark	0.45	8.6	1234687	16.2	●			9120	15.0		●		7

Table 2.6 shows MOE and MOR variation with respect to the eight specific test locations within the western hemlock trees. Originally, nine test locations were planned; however, there was not sufficient material for specimens remaining at the upper-bark location after processing. As is evident by Table 2.6, significantly less variation existed within the western hemlock specimens. Statistical analysis indicates MOE remained relatively consistent throughout the trees, and the outer regions in the bottom and middle logs had properties that were not significantly different. Even though MOE analysis indicated no significant difference with increasing height in the tree, there was a decreasing trend in modulus with height and radial distance from the pith. The following observations are noteworthy based on the statistical analysis:

1. MOE was lowest at the base of the tree and closer to the tree center.

2. MOE remained relatively constant through the intermediate and outer rings in the lower two bolts of the trees.

3. Specimens located near the center demonstrated significantly lower MOE.

4. With the exception of the outer regions of the butt log, MOR decreased with height and distance from the pith.

Table 2.6. Western hemlock flexural property variation throughout the trees
(Dots, read only down a column, indicate regions with a corresponding property that is not statistically significant at a significance level of 0.05)

Western hemlock	Specific Gravity		MOE					MOR							Trees Tested
	Mean	COV (%)	Mean (psi)	COV (%)	t Grouping			Mean (psi)	COV (%)	t Grouping					
Top-Intermediate	0.42	3.6	1047863	12.7		●	●	7804	10.1					●	7
Top-Pith	0.46	8.9	975508	10.9			●	8015	11.2				●	●	11
Middle-Bark	0.43	-	1221464	-	●			8312	-			●	●	●	1
Middle-Intermediate	0.45	7.1	1164025	14.6	●			8355	9.8		●	●			10
Middle-Pith	0.47	6.0	1007835	9.8			●	8436	5.7		●	●	●		12
Bottom-Bark	0.45	9.0	1236890	17.7	●			9255	15.6	●					6
Bottom-Intermediate	0.47	8.3	1136152	15.9	●	●		9003	11.6	●	●	●	●		11
Bottom-Pith	0.50	7.1	959790	14.5			●	9068	7.8	●	●				12

Compression

The results from clear specimen compression testing of Young's modulus and rupture stress are shown in Tables 2.7-2.10. The Wood Handbook (1999) lists an average COV of 18% for compression testing. For both species, testing resulted in Young's modulus COVs which were higher than 18% and rupture stress COVs which were lower than expected.

Douglas-fir

The overall tree mean Young's modulus and rupture stress calculated through compression testing was 1.42 x 10^6 psi and 4,840 psi with COVs of 20.9% and 11.4% respectively. The Wood Handbook notes that Young's modulus can be approximated by increasing the modulus of elasticity by 10% (1999). By increasing MOE by 10%, Young's modulus can be approximated as 2.15 x 10^6 psi, while the Wood Handbook lists rupture stress in compression along the longitudinal axis as 7,230 psi. The values calculated in this study are comparatively 34% and 33% lower than Wood Handbook values respectively (1999).

Surprisingly, statistical analysis of the compressive data showed that compressive rupture stress values do not vary by location significantly through the whole tree (Table 2.7). Analysis of variation of Young's modulus also showed a low degree of variation with respect to location; in general, however, regions closer to the pith and bottom log yielded significantly lower values. A higher percentage of juvenile wood closer to the pith and greater grain angle deviations in bottom logs could have contributed to this trend. Additionally, compression data analysis also indicates the middle log possessed the greatest modulus.

Table 2.7. ***Douglas-fir compressive property variation with respect to radial and vertical location.*** *(Dots, read only down a column, indicate regions with a corresponding property that is not statistically significant at a significance level of 0.05)*

Douglas-fir	Young's Modulus				Rupture Stess			Trees Tested
	Mean (psi)	COV (%)	t Grouping		Mean (psi)	COV (%)	t Grouping	
By Elevation								
Top	1445644	17.7	●	●	4734	7.7	●	22
Middle	1502172	18.0		●	4966	18.0	●	23
Bottom	1358465	21.4	●		4939	9.5	●	26
By Radial Distance								
Pith	1262882	18.1	●		4789	6.5	●	31
Intermediate	1578830	16.3		●	4995	16.5	●	32
Bark	1500290	8.4		●	4813	10.7	●	8

Table 2.8 shows how the previously mentioned compressive properties differed throughout nine specific locations within the trees. The narrower range of values is unexpected after noting the wide range of MOEs calculated through flexural testing. This is significant because the Wood Handbook notes that compressive Young’s modulus can be estimated as a 10% increase in MOE (1999); however, the actual increase in MOE from flexural testing to compression testing was closer to 7%.

Despite the fact that Young’s modulus and MOE do not compare well, compressive rupture stress and modulus of rupture do compare quite well with only a few values which were significantly different than the majority when MOR was considered (Table 2.4 and 2.8).

Table 2.8. Douglas-fir compressive property variation throughout the trees.
(Dots, read only down a column, indicate regions with a corresponding property that is not statistically significant at a significance level of 0.05)

Douglas-fir	Young's Modulus					Rupture Stress			Trees Tested
	Mean (psi)	COV (%)	t Grouping			Mean (psi)	COV (%)	t Grouping	
Top-Bark	1489972	-		●	●	4883	-	●	1
Top-Intermediate	1581409	12.3		●	●	4623	9.6	●	9
Top-Pith	1340126	19.7	●		●	4806	6.2	●	12
Middle-Bark	1499016	11.0		●	●	4483	10.2	●	3
Middle-Intermediate	1648421	16.0		●		5144	23.1	●	12
Middle-Pith	1283980	11.7	●		●	4882	5.3	●	8
Bottom-Bark	1503825	9.1		●	●	5043	10.9	●	4
Bottom-Intermediate	1500801	19.7		●	●	5137	9.0	●	11
Bottom-Pith	1163272	18.4	●			4702	7.7	●	11

The following trends can be observed from compression testing of Douglas-fir:

1. Rupture stress in compression did not seem to be influenced by location.

2. Other than low Young's modulus values near the pith, Young's modulus in compression had very little variation through the trees. It should be noted, however, that compression modulus in the regions closer to the pith generally yielded lower values.

Western hemlock

Testing of western hemlock compression specimens yielded overall tree mean Young's modulus and rupture stress values of 1.04×10^6 psi and 4,010 psi with COVs of 22.5% end 12.1% respectively. The Wood Handbook's method of increasing flexural MOE by 10% approximates Young's modulus at 1.79×10^6 psi while rupture stress is listed at 7,200 psi at 12% moisture content (1999). Compared to the published values in the Wood Handbook (1999), MOE and MOR of small-diameter western hemlock tested in this study were significantly lower, 42% in the case of MOE and 44% with respect to MOR.

Young's modulus and rupture stress did not vary significantly with respect to location when regional groups were considered (Table 2.9). Radial distance from pith appeared to affect modulus while height influenced compressive rupture stress. As with Douglas-fir, the lowest values again occurred around the pith and at the top logs of the trees.

Table 2.9. Western hemlock compressive property variation with respect to radial and vertical location. *(Dots, read only down a column, indicate regions with a corresponding property that is not statistically significant at a significance level of 0.05)*

Western hemlock	Young's Modulus				Rupture Stess				Trees Tested
	Mean (psi)	COV (%)	t Grouping		Mean (psi)	COV (%)	t Grouping		
By Elevation									
Top	1026172	19.9	●		3884	8.2		●	15
Middle	1099849	19.1	●		4020	11.7		●	21
Bottom	1043730	23.1	●		4214	12.4	●		28
By Radial Distance									
Pith	977714	18.1		●	4103	18.0	●		33
Intermediate	1138788	18.7	●		4055	12.1	●		25
Bark	1163267	29.0	●		4082	10.5	●		6

Variation with respect to the nine individual zones is shown in Table 2.10. Comparison of means analysis revealed much more variation than when only radial location or height was considered. As expected, the outer rings of the bottom and mid bolts had similar properties. Unlike Douglas-fir compressive properties, modulus and strength were not significantly lower than the intermediate zone in the radial direction.

Compressive analysis also showed modulus remained somewhat constant with increased height in the tree. A few significant points to note from the analysis of compression properties are:

1. Young's modulus was lowest at the center of the top bolts as opposed to the bottom bolt of Douglas-fir trees.

2. Compressive modulus increased with height and distance from the pith.

3. Strength decreased with both increased height and distance from the pith.

Table 2.10. Western hemlock compressive property variation throughout the trees.
(Dots, read only down a column, indicate regions with a corresponding property that is not statistically significant at a significance level of 0.05)

Western hemlock	Young's Modulus						Rupture Stress					Trees Tested
	Mean (psi)	COV (%)	t Grouping				Mean (psi)	COV (%)	t Grouping			
Top-Intermediate	1221326	8.5			●	●	3803	7.2			●	6
Top-Pith	896070	15.2		●			3938	8.9	●	●	●	9
Middle-Bark	1283223	-				●	3908	-		●	●	1
Middle-Intermediate	1171393	20.4	●		●	●	4054	14.1	●	●	●	8
Middle-Pith	1036872	17.6	●	●	●		4007	11.0	●	●	●	12
Bottom-Bark	1139276	32.7	●		●	●	4142	19.8	●	●		5
Bottom-Intermediate	1070055	21.5	●	●	●	●	4193	12.0	●	●		11
Bottom-Pith	979789	19.1	●	●			4265	10.3	●			12

Tension

Results based on location within the tree are summarized for Douglas-fir and western hemlock respectively in Tables 2.11-2.14. The Wood Handbook notes that little data for parallel to grain tensile property evaluation is available. It lists values for green lumber of selected species and indicates that 12% moisture content data can be approximated by increasing green values by 13%. Expected COVs of 25% are listed for tension parallel to grain testing. In this study, COVs lower than 25% were calculated for Young's modulus and rupture stress in Douglas-fir and western hemlock with the exception of a few locations for rupture stress in Douglas-fir.

<u>Douglas-fir</u>

The overall tree mean tensile Young's modulus and rupture stress was 1.51×10^6 psi and 9,890 psi with COVs of 24.1% and 31.6% respectively. While the Wood Handbook lists Young's modulus values for axial stress, it references only compression. If interior north Douglas-fir green values are increased by 13% to account for moisture content, rupture stress can be approximated at 17,630 psi. The rupture stress calculated in this study represents a decrease in expected values of 44% when compared to the Wood Handbook (1999).

Young's modulus and rupture stress varied with location within the trees (Tables 2.11 and 2.12). Young's modulus was not significantly affected by height within the tree; however, rupture stress did decrease with increasing tree height, especially with respect to the bottom bolt.

Table 2.11. Douglas-fir tensile property variation with respect to radial and vertical location. *(Dots, read only down a column, indicate regions with a corresponding property that is not statistically significant at a significance level of 0.05)*

Douglas-fir	Young's Modulus					Rupture Stess				Trees Tested
	Mean (psi)	COV (%)	t Grouping			Mean (psi)	COV (%)	t Grouping		
By Elevation										
Top	1402103	16.6	●			8695	22.2		●	21
Middle	1530656	11.8	●			9179	16.9		●	26
Bottom	1490710	19.5	●			10706	19.3	●		25
By Radial Distance										
Pith	1345202	15.5			●	9163	18.2		●	34
Intermediate	1569246	11.4		●		9817	19.4	●	●	32
Bark	1759368	15.0	●			10532	36.2	●		6

Strength and modulus values increased significantly with distance from the pith. T-tests showed significant increase in Young's modulus through each arbitrary radial location. In the case of maximum tensile stress, values from regions around the pith were significantly lower than the outer regions near the bark.

Tables 2.12a and 2.12b summarize variation in Young's modulus and rupture stress through the nine different locations within the Douglas-fir trees. The apparent wide variation in t-grouping of compressive properties is similar to that of the flexural property distribution. To alleviate some confusion caused by small sample sizes in the outer region, Table 2.12b was generated without this data. Table 2.12b more clearly illustrates some of the following trends:

1. Young's modulus and rupture stress in regions surrounding the pith remained constant along the height of the trees with the exception of the center portion of the top bolt having a slightly lower rupture stress.

2. Radial location rather than height appeared to have more effect on tensile properties; tensile Young's modulus and rupture stress increased with distance from the pith.

Table 2.12a. Douglas-fir tensile property variation throughout the trees.
(Dots, read only down a column, indicate regions with a corresponding property that is not statistically significant at a significance level of 0.05))

Douglas-fir	Young's Modulus						Rupture Stress							Trees Tested
	Mean (psi)	COV (%)	t Grouping				Mean (psi)	COV (%)	t Grouping					
Top-Bark	1761067	-			●	●	10448	-	●	●				1
Top-Intermediate	1475049	15.1	●	●			8676	21.5		●	●		●	9
Top-Pith	1309786	15.6	●				8550	24.3			●		●	11
Middle-Bark	1597526	14.6		●		●	7210	7.5					●	2
Middle-Intermediate	1623594	8.0		●	●	●	9494	15.9	●	●	●			12
Middle-Pith	1426572	12.2	●	●			9191	16.7		●	●			12
Bottom-Bark	1866697	17.2			●		12776	32.8				●		3
Bottom-Intermediate	1587029	10.8		●		●	11102	15.1	●			●		11
Bottom-Pith	1291851	18.4	●				9744	12.3	●	●	●			11

Table 2.12b. Douglas-fir tensile property variation throughout the trees (modified).
(Dots, read only down a column, indicate regions with a corresponding property that is not statistically significant at a significance level of 0.05)

Douglas-fir	Young's Modulus					Rupture Stress					Trees Tested
	Mean (psi)	COV (%)	t Grouping			Mean (psi)	COV (%)	t Grouping			
Top-Intermediate	1475049	15.1		●	●	8676	21.5			●	9
Top-Pith	1309786	15.6	●			8550	24.3			●	11
Middle-Intermediate	1623594	8.0		●		9494	15.9	●		●	12
Middle-Pith	1426572	12.2	●		●	9191	16.7	●		●	12
Bottom-Intermediate	1587029	10.8		●		11102	15.1		●		11
Bottom-Pith	1291851	18.4	●			9744	12.3	●			11

Western hemlock

The overall mean tree Young's modulus and rupture stress calculated through tensile testing was 1.11×10^6 psi and 9,380 psi with COVs of 23.1% and 24.5% respectively. The Wood Handbook notes that tensile rupture stress can be approximated at 14,690 psi by increasing green values by 13% (1999). The decrease associated with the value calculated in this study was less than that of Douglas-fir, at 36%.

Statistical analysis indicated no significant variation in Young's modulus along the height; however, the middle bolt possessed slightly higher modulus. Rupture stress also decreased with each level of height above the butt log, but statistical analysis indicated significant strength reduction from the butt log to the top log (Table 2.13). With respect to radial location, beyond the intermediate ring, Young's modulus appeared to decrease with increased distance from the pith. Rupture stress also decreased slightly, but the decrease was not statistically significant until the bark ring.

Table 2.13. Western hemlock tensile property variation with respect to radial and vertical location. *(Dots, read only down a column, indicate regions with a corresponding property that is not statistically significant at a significance level of 0.05)*

Western hemlock	Young's Modulus				Rupture Stess				Trees Tested
	Mean (psi)	COV (%)	t Grouping		Mean (psi)	COV (%)	t Grouping		
By Elevation									
Top	1103688	18.7	●		8605	21.2		●	18
Middle	1136012	17.8	●		9344	16.1	●	●	23
Bottom	1060009	22.3	●		9795	25.5	●		26
By Radial Distance									
Pith	1025147	16.5	●		9434	17.0	●		34
Intermediate	1202298	19.2		●	9457	25.6	●		28
Bark	1007105	21.6	●		7782	29.8		●	5

Table 2.14 illustrates how the tensile properties differed throughout the eight specific locations within the trees. The lowest Young's modulus values again appeared near the pith even though clear trends are not apparent. Rupture stress, however, showed an increasing trend with increased tree height and radial distance from the pith.

Table 2.14. Western hemlock tensile property variation throughout the trees.
(Dots, read only down a column, indicate regions with a corresponding property that is not statistically significant at a significance level of 0.05)

Western hemlock	Young's Modulus				Rupture Stress					Trees Tested
	Mean (psi)	COV (%)	t Grouping		Mean (psi)	COV (%)	t Grouping			
Top-Intermediate	1219133	13.8		●	8236	18.1		●	●	7
Top-Pith	1030223	19.4	●	●	8840	23.2	●	●	●	11
Middle-Bark	1095745	-	●	●	8339	-		●	●	1
Middle-Intermediate	1236392	20.1		●	8964	21.0	●	●	●	10
Middle-Pith	1055717	11.7	●	●	9744	11.5	●	●		12
Bottom-Bark	984945	24.8	●		7643	34.8			●	4
Bottom-Intermediate	1160591	22.4	●	●	10682	27.1	●			11
Bottom-Pith	986722	18.9	●		9691	15.9	●	●		11

Statistical Distributions of Properties

Probability density functions (PDF) were fit to the data to describe the property distributions for both species. This information will be useful to understand the variations in mechanical properties of these small-diameter Douglas-fir and western hemlock to efficiently utilize them. Normal and Weibull probability density functions (PDF) were found to describe the data distributions adequately. Lognormal distribution was also explored; however, it did not fit the data as well as Weibull or normal distributions and therefore is not presented. Suddarth and Bender (1995) note these PDFs are 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, which is not possible for strength or modulus properties. The probability density functions are given as:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$ Normal Probability Density Function [2.1]

$$f(x) = \alpha\beta^{-\alpha} x^{\alpha-1} e^{\left(x/\beta \right)^{\alpha}}$$ Weibull Probability Density Function [2.2]

where μ is the mean and σ is the standard deviation in the case of normal PDF, and α and β are shape and scale parameters respectively in the Weibull PDF. Typical normal and Weibull distribution fits are shown in Figures 2.6 and 2.7 respectively.

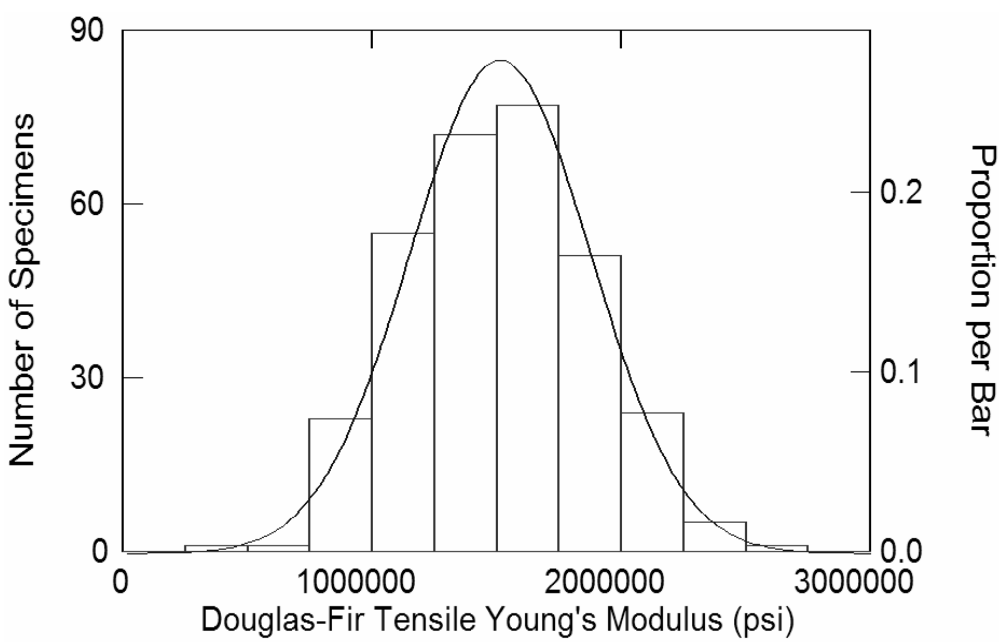

Figure 2.6: A typical normal PDF describing tensile Young's modulus of Douglas-fir.

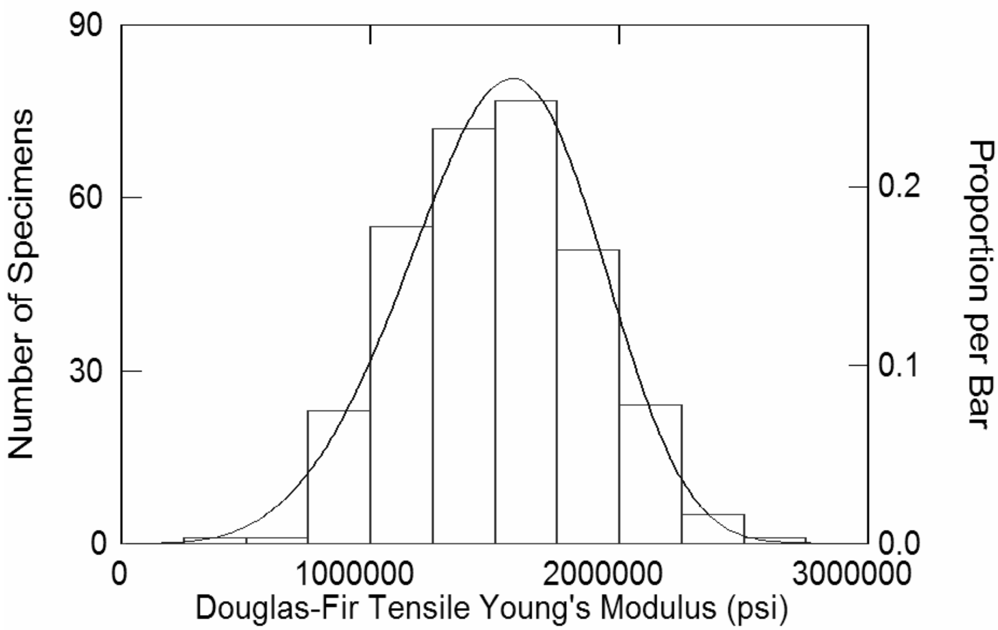

Figure 2.7: A typical Weibull PDF describing tensile Young's Modulus of Douglas-fir.

Chi-squared and Kolmogorov-Smirnov goodness of fit tests were performed to evaluate how well the PDFs fit the experimental data distributions. Results of these tests along with distribution parameters are summarized in Table 2.15. P-values greater than 0.05 are indicated by bold letters indicating a good fit. Visual inspection also verified that Weibull PDFs generally fit the experimental distributions better.

Table 2.15. Probability density function parameters and p-values of clear specimen data

Physical Property \ Probability Density Function	Normal μ	Normal σ	Normal Chi-Squared p-value	Weibull α	Weibull β	Weibull Kolmogorov-Smirnov p-value
Dougals-Fir						
Flexure						
Modulus of Elasticity (psi)	1,327,640	274,217	**0.459**	5.350	1,438,958	**0.767**
Rupture Stress (psi)	9,570	1,353	**0.664**	7.847	10,142	**0.056**
Tension						
Young's Modulus (psi)	1,415,265	295,094	**0.594**	5.279	1,535,081	**0.838**
Rupture Stress (psi)	4,839	552	0.037	6.351	5,095	0.000
Compressoin						
Young's Modulus (psi)	1,513,914	363,603	**0.204**	4.574	1,656,281	**0.714**
Rupture Stress (psi)	9,888	3,115	0.032	3.372	10,992	**0.191**
Western Hemlock						
Flexure						
Modulus of Elasticity (psi)	1,061,568	208,286	0.000	5.323	1,148,696	0.022
Rupture Stress (psi)	8,496	1,166	**0.650**	7.796	9,003	**0.127**
Tension						
Young's Modulus (psi)	1,040,928	233,570	0.037	4.757	1,134,979	**0.384**
Rupture Stress (psi)	4,010	485	**0.173**	8.723	4,229	0.013
Compressoin						
Young's Modulus (psi)	1,108,920	255,554	0.002	4.543	1,211,242	**0.085**
Rupture Stress (psi)	9,379	2,292	**0.112**	4.247	10,262	**0.198**

To examine the differences in mechanical properties, namely strength and modulus, derived using three different test methods, flexure, compression, and tension, the cumulative distribution functions were compared (Figures 2.8-2.11). The modulus properties of both species were similar with tension having the highest average values and the highest probability of yielding high values. Flexure yielded the lowest modulus values and less deviation from the mean occurred (Figures 2.8 and 2.10). Cumulative strength trends were considerably different than their modulus counterparts. With respect to both species, compression strength was much lower and less variable than flexure or tension. Mean flexure and tension values were similar; however, bending was less variable than tension, which displayed a wide range of possible values (Figures 2.9 and 2.11).

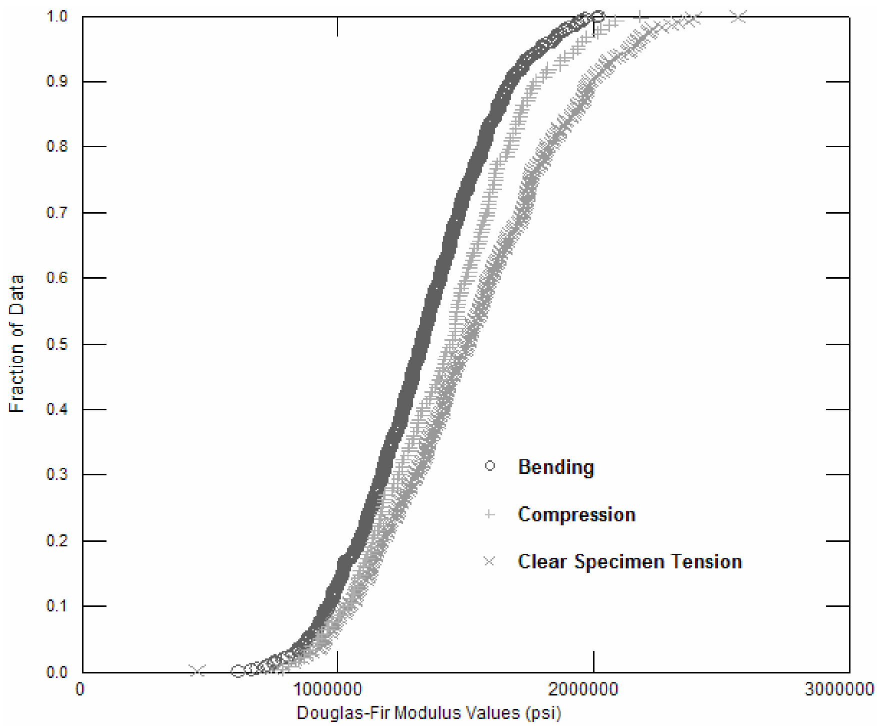

Figure 2.8. Experimental Cumulative distributions of Douglas-fir modulus properties.

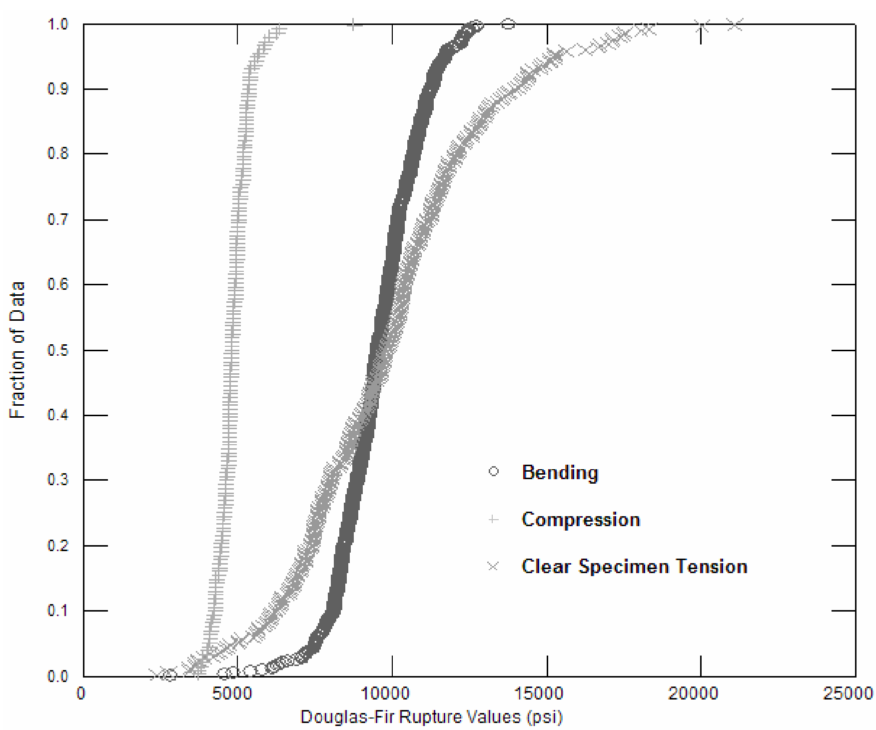

Figure 2.9. Experimental Cumulative distributions of Douglas-fir strength properties.

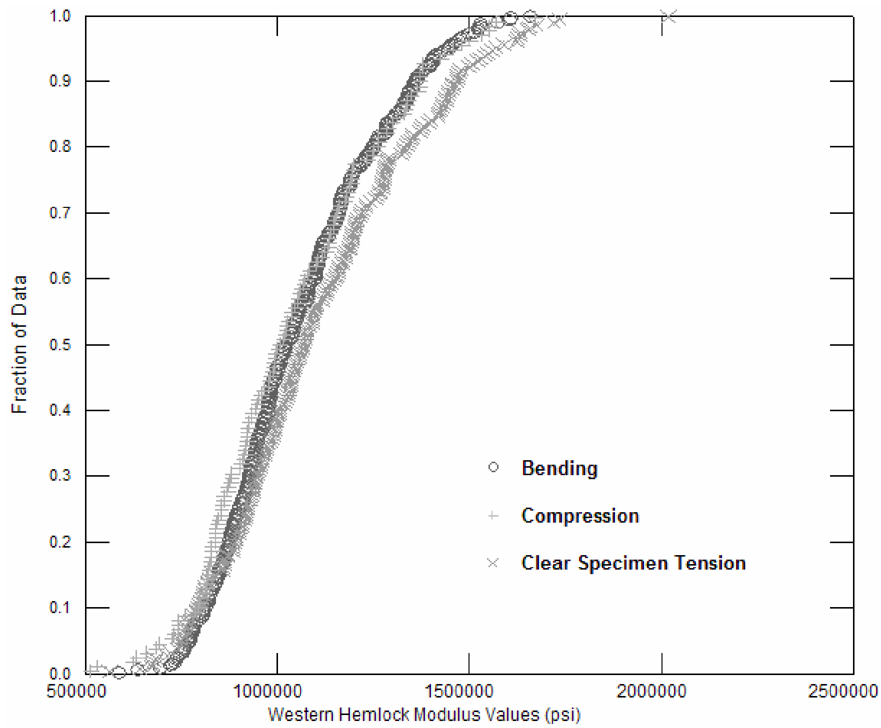

Figure 2.10. Experimental Cumulative distributions of western hemlock modulus properties.

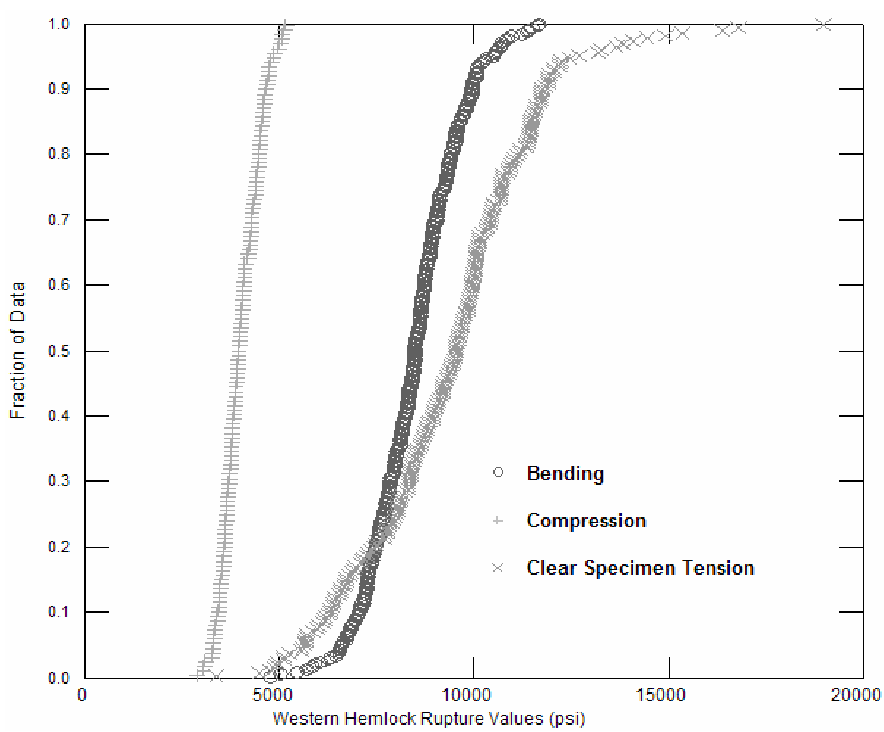

Figure 2.11. Experimental Cumulative distributions of western hemlock strength properties.

Comparison of Clear Specimen Properties

The results of the flexural, compressive, and tensile tests are compared in Table 2.15 for Douglas-fir and western hemlock. The objective of this portion is to identify trends between mechanical properties and zones of increased or decreased strength and modulus. While the magnitudes are not necessarily the same, clear trends can be found between the two species when mechanical properties are compared with one another. These trends, shown in Table 2.15, do not appear to be affected by location of interest as height, radial location, or species average values do not vary by more than a few percent in most cases. Of most interest in these tables is the variation between strength and modulus within flexural, compressive, or tensile testing. Notice the ratios of flexural to tensile modulus (F/T) are of the same magnitude as those of flexural to tensile strength. This trend does not extend to the flexural to compressive (F/C) or compressive to tensile (C/T) ratios. In fact, quite the opposite occurs, showing while flexural and compressive modulus may be equivalent, compressive strength should be expected to be nearly double that of flexural strength. Likewise, C/T moduli are comparable while compressive strength was nearly half of the tensile strength in both species. The large difference in tensile to compressive strength can be attributed to the cells reaction to axial load. If the cell structure is though of as a bundle of straws, when tension is applied, all of the straws act as one unit to resist the force. When a compressive force is applied however, adjacent straws do not act in a way to brace each other and buckling occurs at a much lower force.

Table 2.16. Summary of clear specimen testing by height and radius.

	Flexural Modulus of Elasticity (psi)	Tensile Young's Modulus (psi)	Compressive Young's Modulus (psi)	Ratio of F/T	Ratio of F/C	Ratio of C/T	Flexural Modulus of Rupture (psi)	Tensile Rupture Stress (psi)	Compressive Rupture Stress (psi)	Ratio of F/T	Ratio of F/C	Ratio of C/T
Douglas-Fir												
Species Average	1,330,000	1,510,000	1,420,000	0.88	0.94	0.94	9,570	9,890	4,840	0.97	1.98	0.49
By Elevation												
Top	1,219,800	1,402,100	1,445,600	0.87	0.84	1.03	8,780	8,700	4,730	1.01	1.86	0.54
Middle	1,368,500	1,530,700	1,502,200	0.89	0.91	0.98	9,480	9,180	4,966	1.03	1.91	0.54
Bottom	1,334,900	1,490,700	1,358,500	0.90	0.98	0.91	10,080	10,710	4,940	0.94	2.04	0.46
By Radial Location												
Pith	1,188,300	1,345,200	1,262,900	0.88	0.94	0.94	9,270	9,160	4,790	1.01	1.94	0.52
Intermediate	1,413,800	1,569,200	1,578,800	0.90	0.90	1.01	9,630	9,820	5,000	0.98	1.93	0.51
Bark	1,441,800	1,759,400	1,500,300	0.82	0.96	0.85	9,880	10,530	4,810	0.94	2.05	0.46
Western Hemlock												
Species Average	1,060,000	1,110,000	1,040,000	0.95	1.02	0.94	8,500	9,380	4,010	0.91	2.12	0.43
By Elevation												
Top	999,600	1,103,700	1,026,200	0.91	0.97	0.93	7,950	8,600	3,880	0.92	2.05	0.45
Middle	1,085,000	1,136,000	1,099,800	0.96	0.99	0.97	8,400	9,340	4,020	0.90	2.09	0.43
Bottom	1,084,000	1,060,000	1,043,700	1.02	1.04	0.98	9,080	9,800	4,210	0.93	2.16	0.43
By Radial Location												
Pith	982,000	1,025,100	977,700	0.96	1.00	0.95	8,570	9,430	4,100	0.91	2.09	0.43
Intermediate	1,120,400	1,202,300	1,138,800	0.93	0.98	0.95	8,420	9,460	4,060	0.89	2.07	0.43
Bark	1,234,700	1,007,100	1,163,300	1.23	1.06	1.16	9,120	7,780	4,080	1.17	2.24	0.52

Recall the density analysis and Figures 2.4 and 2.5 which show the highest densities near the center of the tree regardless of height. Table 2.16 illustrates that high density does not necessarily imply high strength or modulus. Notice when radial location is considered, of all the properties considered, only once is the highest value located at the pith.

Conclusions

The main objective of this portion of the study was to characterize clear specimen material properties and their variation within Douglas-fir and western hemlock trees with the ultimate end goal being a better understanding of small diameter, fast grown trees for use in more manufacturing of engineered wood composites. As 25% to 35% of total wood composite (such as particleboard, MDF, and OSB) manufacturing costs are associated with wood raw material, an understanding of material properties and their variations could assist in optimizing the manufacturing process and maximizing efficiency of wood raw material usage and profits.

Density profiling illustrated variations in specific gravity with respect to location. The profiles created in this study match closely other trends published in the past. Furthermore, the specific gravity of the Douglas-fir specimens also match closely values published by others; however, the western hemlock specimens were higher than published values.

Flexure

Flexural testing indicated decreases in modulus should be expected with increased height in the tree. Douglas-fir (maximum reduction of 11%) and western hemlock (maximum reduction of 8%) both exhibited a statistically significant decrease in modulus from the bottom to top log within a tree. Strength trends were also similar between the two species (Douglas-fir maximum reduction of 13%, western hemlock maximum reduction of 12%). T-tests indicated significant strength decreases in each testing zone as height in the trees was increased.

With respect to radial location, both species showed increasing modulus from the pith to the bark. Douglas-fir (maximum reduction of 18%) indicated lower modulus should only be expected at the center of the bolts while western hemlock showed significant modulus increases in each zone from the pith to the bark (maximum reduction of 20%). With respect to strength, both species exhibited the highest MORs at the outer ring while the inner and middle rings remained significantly lower (Douglas-fir maximum reduction of 6%, western hemlock maximum reduction of 8%).

When compared to mean values listed in the Wood Handbook, a decrease of 32% and 23% for MOE and MOR respectively was calculated for Douglas-fir while western hemlock displayed slightly larger reductions at 35% and 25% respectively (1999).

Compression

Compression testing of the Douglas-fir specimens indicated no significant change in rupture stress regardless of testing height within the trees. Western hemlock was similar; however, the bottom bolt possessed significantly higher strength values than the middle and top bolts (maximum reduction of 8%). Modulus results were slightly more convoluted. The general trend here indicated the highest modulus for Douglas-fir could be expected in the mid-height bolt (maximum reduction of 10% from the bottom log). Western hemlock, on the other hand, indicated no significant changes through the height of the trees. When radial location was considered, no variation in strength was found with respect to location in Douglas-fir or western hemlock. Young's modulus was found to be significantly lower in the center than the intermediate and outer rings in both species (Douglas-fir maximum reduction of 20%, western hemlock maximum reduction of 16%).

The compressive values were again significantly lower for both species when compared to the Wood Handbook (1999). Douglas-fir reductions for strength and modulus were 33% and 34% respectively while western hemlock reductions were again larger at 44% and 42%.

Tension

Tensile testing of both species showed similar trends with respect to Young's modulus and rupture stress when height was considered. The bottom bolts of both species possessed the largest rupture strength while the middle and top bolts were shown to be similar (Douglas-fir maximum reduction of 15%, western hemlock maximum reduction of 12%). Statistical analysis also showed no significant variation with respect to modulus through the height of either species.

In a trend uncharacteristic of the flexural and compressive tests, the rupture strength of western hemlock was found to be significantly higher in the pith and intermediate zone than the outer zone (maximum reduction of 18%). Douglas-fir did not follow this trend, showing instead a significant increase in rupture stress in each zone from the center to the bark (maximum reduction of 13%). Western hemlock was also atypical with respect to Young's modulus, showing the center and outer test zones to be similar and significantly lower than the intermediate zone (maximum reduction of 16%). Douglas-fir did not follow this trend and its modulus again increased significantly in each zone from the center to the bark (maximum reduction of 24%).

According to values listed for tensile rupture stress in the Wood Handbook, Douglas-fir strength was 44% lower than that of mature wood while western hemlock was 36% lower.

Recommendations

While the data may appear confusing at first glance, definite trends with respect to individual properties exist. This project only serves as a launching point for further research to fine tune any given area listed above. Possible further refinement opportunities include:

1. Increased zone separation based on preliminary density testing.
2. Comparison of these results to the same species from other geographic locations.
3. Comparison of this data to other related processing parameters.

Recommendation three is a lead-in to chapter three where wood furnish properties will be characterized and related to other aspects such as location within the tree and the clear specimen mechanical properties discussed in this chapter.

References

Abdel-Gadir, A.Y. and Krahmer, R.L. 1993. Estimating the age of demarcation of juvenile and mature wood in Douglas-fir. Wood and Fiber Science. 25(3):243-249

Abdel-Gadir, A.Y., Krahmer, R.L., and McKimmy, M.D. 1993. Intra-ring variations in mature Douglas-fir trees from provenance plantations. Wood and Fiber Science. 25(2):170-181

ASTM D143-94 (1994), "Standard methods of testing small clear specimens of timber." ASTM International

Barrett, J.D. and Kellogg, R.M. 1991. Bending strength and stiffness of second-growth Douglas-fir dimension lumber. Forest Products Journal. 41(10):35-43

Bendtsen, B.A. 1978. Properties of wood from improved and intensely managed trees. Forest Products Journal. 28(10):61-78

Biblis, E.J. 1969. Tensile properties of loblolly pine growth zones. Wood and Fiber. 1(1):18-28

Burdon, R.D., Kibblewhite, R.P., Walker, J.C., Megraw, R.A., Evans, R., and Cown, D.J. 2004. Juvenile versus mature wood: A new concept, orthogonal to corewood versus Outerwood, with special reference to Pinus radiate and P. taeda. Forest Science. 50(8):399-415

DeBell, D.S., Singleton, R., Gartner, B.L., and Marshall, D.D. 2004. Wood density of young-growth western hemlock: relation to ring age, radial growth, stand density, and site quality. Canadian Journal of Forest Research. December.

Evans, J.W., Senft, J.F., and Green, D.W. 2000. Juvenile wood effect in red alder: Analysis of physical and mechanical data to delineate juvenile and mature wood zones. Forest Products Journal. 50(7/8):75:87

Gerhards, C.C. 1979. Effect of high-temperature drying on tensile strength of Douglas-fir 2 by 4's. Forest Products Journal. 29(3):39-46

Green, D.W., Lowell, E.C., and Hernandez, R. 2005. Structural lumber from dense stands of small-diameter Douglas-fir trees. Forest Products Journal. 55(7/8):42-50

Hoag, M.L. and Krahmer, R.L. 1991. Polychromatic X-ray attenuation characteristics and wood density applications. Wood and Fiber Science. 23(1):23-31

Hoag, M.L. and McKimmy, M.D. 1988. Direct scanning X-ray densitometry of thin wood sections. Forest Products Journal. 38(1):23-26

Ifju, G. and Kennedy, R.W. 1962. Some variables affecting microtensile strength of Douglas-fir. Forest Products Journal. 12(5):213-217

Josza, L.A. and Middleton, G.R. 1994. A discussion of wood quality attributes and their practical implications. Forintek Canada Corporation, Vancouver, B.C. Special Publication SP-34.

Josza, L.A., Munro, B.D., and Gordon, J.R. 1998. Basic wood properties of second-growth western hemlock. Victoria. Ministry of Forestry, B.C., Forest Practices Branch. Special Publication SP-38.

Kretschmann, D.E. and Bendtsen, B.A. 1992. Ultimate tensile stress and modulus of elasticity of fast-grown plantation loblolly pine lumber. Wood and Fiber Science. 24(2):189-203

Passialis, C. and Kiriazakos, A. 2004. Juvenile and mature wood properties of naturally-grown fir trees. Springer-Verlag. 62(11):476-478

Suddarth, S.K. and Bender, D.A. 1995. Statistical fundamentals for wood engineering. Wood Design Focus. 6(1):3-18

Wood Handbook: wood as an engineering material. 1999. Gen. Tech. Rep. FPL-GTR-113. U.S. Department of Agriculture. 463pp.

Chapter 3: Characterization of Wood Furnish From Young, Small-Diameter Trees Harvested From the Olympic Peninsula

Introduction

Properties of wood composites are dependent on their constituent properties, arrangement of these constituents, and the interaction between the constituents and other additives. To optimize and improve processing and the performance of the end product, it is critical to understand the characteristics of the raw material that is converted into feedstock for production of wood composites, structural or non-structural. Understanding properties of the available raw materials, for example, will enable a manufacturer to decide on an appropriate resin or resin characteristics to use, adjust manufacturing processes to accommodate the quality of the furnish, be more specific on type of raw material required to prepare the furnish, and have a better control on quality and consistency of the final product.

Perhaps of the highest importance to the wood composites industry due to widespread use of various thermoset and thermoplastic resins is the pH and buffering capacity of the wood furnish. Chemical companies spend considerable time formulating resin mixtures which suit the conditions of an individual manufacturing plant. Urea-formaldehyde, phenol-formaldehyde, and melamine-formaldehyde respectively are considered to be the most popular among synthetic resins used for composite panel manufacturing (Maloney 1993). Because each of these resins have unique curing conditions, furnish pH, buffering capacity, and product end use all play a large role in resin selection. Curing of urea-formaldehyde occurs at a pH of 5.0-5.5 or lower (Maloney 1993). Douglas-fir, for example, has a pH of about 4.2. Because of this, bond quality between Douglas-fir particles could be expected to be good. On the other hand, most phenolic resins require a base environment for proper curing (Ahmad 2000). If these interactions are not understood and respected, poor bond strength will lead to low quality products.

Many past studies have examined the effect of wood furnish pH on bond properties. Freeman (1959) studied 22 hardwood species to determine what effect pH, specific gravity, and wettability had on bond strength. Freeman determined that increased acidity led to weaker bonding in urea-formaldehyde resins and attributed this to reduced polymerization and wood/adhesive bonding. Johns and Niazi (1980) considered how gel time was effected by wood flour of ten hardwood and nine softwood species. They determined a strong correlation between the gel time of urea-formaldehyde and the pH and an inverse correlation between gel time and acid buffering capacity of water extracted from said species. Douglas-fir heartwood was more acidic than the sapwood, and the acid buffering capacity of the heartwood was higher than the acid buffering capacity of the sapwood.

In a study similar in form to the process involved with this study, Albert et al. (1999) examined variations in pH and buffering capacity with respect to distance from the pith on red-heartwood beach wood. They found a generally increasing trend in pH from the pith to sapwood with a slight decrease in pH from the pith to approximately 15th ring. Conversely, the buffering capacity of the beech wood tended to decrease with distance from the pith. In 2004, Xing et al. examined the effect of less desirable raw material such as bark, forest thinning, and tree tops acidity and catalyst on the gel time of urea-formaldehyde resin. They determined raw material pH had a strong effect on gel time at lower levels of catalyst. This effect diminished as higher levels of catalyst was used.

Olson (1996) performed a study similar in scope to the present one. His project consisted of fabricating particleboard and oriented strand board after studying the density, pH, and furnish characteristics of densely stocked, stagnant, small diameter lodgepole pine, western larch, and Dougals-fir. Olson created both types of panels with varying density. His research confirmed species significantly effected panel properties and all the furnish species were suitable for use in these engineered wood composites.

Another parameter of critical concern during the manufacture of engineered wood composites, specifically wood-plastic composites and particleboard, is particle size and its distribution. For example, lamination of particleboard is common procedure in today’s market. Smooth particleboard faces are critical for proper bonding between the board and veneer. To accomplish this, smaller particles are typically oriented towards panel faces. Additionally, Maloney (1970) found coarse particles required two to three times as much resin on a surface area basis than fine particles to achieve equivalent bonding properties. This is apparently due to the greater density obtained through use of smaller particles. Therefore, proper particle size distribution is critical to panel quality.

Particle size distributions are equally important when manufacturing wood plastic composites. Because the interaction between wood flour and the thermoplastic resin in wood plastic composites is influenced by mechanical interaction between these two materials, an understanding of the effects of particle size is critical. Stark and Berger (1997) in particular studied the effect of particle size in polypropylene wood composites. Their investigation involved wood flours of four different species of uniform sizes. In general, they found increasing particle size lead to among others, increases in melt index, tensile elongation, and modulus and strength in tension and flexure.

Wood-strand composite behavior is influenced by the properties of its constituents, namely strands, and their arrangement. A few studies (Price 1976, Mahoney 1980, Jahan-Latibari 1982, Yadama 2002, Yadama 2006) have examined individual strand properties and noted that the modulus of elasticity 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). Geimer et al. (1985) specifically examined damage induced through heat and pressure during the hot-pressing process. Geimer (1985), Yadama (2002), and others have hypothesized this reduction in modulus may be due to processing induced damage. Of particular importance to this study is the effect of damage from pressing and flaking on strength properties of Douglas-fir flakes conducted by Geimer et al. (1985). After flaking, flakes were classified into two groups based on quality and tested in a control form and two hot-pressed forms. In general, flake properties were degraded by hot pressing with the average modulus of rupture lowered by 13% and the modulus of elasticity lowered by 34%.

Finally, Kelly (1977) in cooperation with the USDA Forest Products Laboratory published a comprehensive literature review of processing, furnish, and resin parameters effecting physical and mechanical properties of particleboard. This report covers in greater detail the wide variety of research performed on all aspects of composite panel manufacturing.

Objectives

The primary goal of this portion of the research is to characterize the wood furnish properties of small diameter, fast grown Douglas-fir and western hemlock trees and relate these properties to vertical and radial location within the tree. The specific objectives of the research are as follows:

1) Investigate the influence of wood furnish location relative to tree height and girth on particle size distribution when converted into wood flour for composites such as wood-plastic composites.

2) Examine pH and buffering capacities of wood and their variation as a function of location within a tree.

3) Evaluate mechanical properties of strands produced from wood taken from different locations within a tree and correlate these properties with small clear specimen properties discussed in chapter two.

Materials

Material remaining from the clear specimen property evaluation was used in this stage of testing to reinforce the correlation between clear specimen properties and furnish properties. The specimens were conditioned under identical conditions of approximately 70^{o}F and 65% relative humidity for several months to obtain approximately 12% moisture content.

Wood Flour Generation

Specimen material was reduced to chip size using a Sumner Iron Works chipper. A Prater Blue Streak hammermill was then used to reduce the chips to a size that passed an internal 0.25 in. screen. Once all the chips had been reduced in size, moisture content was determined and the particles were further reduced using a Bliss hammermill and 0.046 in. screen. To prevent cross contamination, all equipment was thoroughly cleaned after processing of material from each individual location. These locations, as described in chapter two (Langum 2007) were based on nine specific zones of interest within the trees with respect to height and radius.

The wood flour produced during this process was used for particle size distribution as well as pH and buffering capacity analysis.

Strand Generation

Clear specimen material (app. 1.5 in. x 1.5 in. x 6 in.) was immersed in water for approximately three weeks prior to stranding. Strands were generated with a CAE disk strander. Approximate strand dimension were 6 in. in length, 0.03 in. in thickness, and 1.25 in. in width; however, strands were individually measured before testing. Strand length was generally parallel to grain orientation; however, the transverse orientation was random with respect to the grain/knife orientation. Following processing of each batch, the strands were placed in an open air box dryer for approximately two hours. The strands were then conditioned to approximately 12% moisture content under approximately 70^{o}F and 65% relative humidity for several days. Following conditioning, strands were tested in tension to determine strand properties including Young's modulus, ultimate tensile strength or rupture stress, and Poisson's ratio.

Methods

Particle Size Distribution

Particle size distribution was determined by completing a series of screen analysis. This process consists of passing a given sample through a set of nested screens or “sieves”. The largest material is retained in the upper sieves while the smaller material passes though the apparatus until it is retained by a smaller sieve. When the process is complete, the weight retained by each sieve is reported as a percent of the overall weight. A Ro–Tap sieve shaker was used in combination with screen sizes of 20, 40, 60, 80, 100, and 120 mesh to calculate the overall percentage of material retained by each screen. The sieves had openings of 0.0331 in., 0.0165 in., 0.0098 in., 0.007 in., 0.0059 in., and 0.0049 in. respectively. The W.S. Tyler sieves used were in accordance with ASTM E-11, Standard Specification for Wire Cloth and Sieves for Testing Purposes (ASTM 2004).

Due to limited availability of remaining material, the twelve trees per species were combined based on location into the nine locations described in chapter two (Figures 2.2 and 2.3). In some cases, sufficient material was not available to perform analysis on certain locations. Wood flour was produced in batches based on the remaining locations. Analysis was then performed in a manner similar to the chapter two procedures where averages and variations were computed based on distance from the pith, distance from the butt, and the whole tree. Statistical analysis of particle size distributions was performed to examine differences in distributions as a function of location within a tree.

pH and Buffering Capacity

The process followed for determination of pH and buffering capacity was that described by Johns and Niazi (1980). The process consisted of removing particles which were too coarse or too fine; in this case, particles which passed the #40 screen and were retained by the #60 screen were used. The samples were collected immediately after the sieve analysis and stored in polyethylene bags until testing for pH and buffering capacity. Prior to testing, the specimens were dried at a temperature of $105^{o}C$ for 24 hours to remove moisture and uniformly dry the material. Then, 25 g of the dry wood material was refluxed with 250 g of distilled water for 20 minutes while being stirred continuously. After refluxing, the material was filtered using a #1 Whatman filter and an aspirator vacuum to remove any remaining wood particles. The samples were then allowed to cool to room temperature before testing continued.

Once the specimens cooled to room temperature, a pH meter (calibrated before every use) was used to record the pH of a 50 ml solution of the wood and the temperature at testing was recorded. The specimens were titrated to a pH of 3 using a 0.01 N solution of sulfuric acid (H_2SO_4) to calculate the acid buffering capacity and a pH of 7 using a 0.01 N solution of sodium hydroxide (NaOH) to calculate the base buffering capacity. This process consisted of recording the pH after an increment of 1 ml of sodium hydroxide or sulfuric acid was added to the solution. When the solution approached a pH of 3 or 7, smaller amounts of the buffers were added to ensure the pH would not exceed 3 or 7 during the test. The resulting total buffer added to the wood solution was then noted as the buffering capacity of a given solution.

Tensile Properties of Strands

Once the strands equilibrated to a nominal moisture content of 12%, testing was performed according to the method proposed by Yadama (2002, 2006). Strands of approximately 0.03 in. thickness were trimmed to approximately 1 in. width and 6 in. in length (actual strand dimensions were measured using a digital caliper). To obtain tensile properties, the strands were stressed until failure in a parallel to grain orientation using a 2-kip universal electromechanical test machine (Instron 4466 R). First, strands were positioned in self -aligning mechanical grips with a four inch gap between the grips. A ½ in. gage length axial extensometer (Epsilon Model 3442) was then installed mid section 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 calculate Poisson's ratio. The specimens were loaded at a uniform crosshead speed of 0.015 inches/minute until the Instron testing machine registered an axial force of 500 pounds. At this point, the strands were released and given sufficient time to relax and recover. Next, the strands were again loaded in the self aligning mechanical grips. This time, the ½ in. gage length axial extensometer was installed on the specimen to measure strain parallel to grain and the specimens were tested to failure.

Tensile testing of the strands with strains measured along the two principal axes allowed for the calculation of E_x and ν_{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 photo was then analyzed using Adobe Photoshop to accurately determine the grain angle of each strand within the gage length. Note that the grain angle was recorded, not the microfibril angle.

Strands with a grain angle of 1^o or less were used to calculate E_1 and ν_{12}. With approximated values of E_1 and $\nu_{12,}$ E_2 and G_{12} were estimated by simultaneously solving the following equations proposed by Jones (1999):

$$\frac{1}{E_x} = \frac{1}{E_1}\cos^4\theta + \left(\frac{1}{G_{12}} - \frac{2\upsilon_{12}}{E_1}\right)\sin^2\theta\cos^2\theta + \frac{\sin^4\theta}{E_2} \qquad [3.1]$$

$$\nu_{xy} = \frac{\nu_{12}(\sin^4\theta + \cos^4\theta) - \left(1 + \frac{E_1}{E_2} - \frac{E_1}{G_{12}}\right)\sin^2\theta\cos^2\theta}{\cos^4\theta + \left(\frac{E_1}{G_{12}} - 2\nu_{12}\right)\sin^2\theta\cos^2\theta + \frac{E_1}{E_2}\sin^4\theta} \qquad [3.2]$$

Mean values of E_x and ν_{xy}, for groups of strands categorized by grain angle were then used to simultaneously solve equations 3.1 and 3.2.

Results and Discussion

Furnish Property Evaluation

Particle Size Distribution

The results from sieve analysis of particles created through the hammermill procedure described previously are presented in Tables 3.1-3.4 and Figures 3.1-3.4. For both species, not enough material remained from the outer rings (near bark) to perform particle size distributions. Distribution analysis was performed on the six remaining locations per species (Figures 3.1-3.4). Moisture content analysis at the time of testing indicated that it was uniform for both species ranging between 10.3% - 11.1% (Table 3.1 and 3.3). Due to limited availability of remaining material, only one batch per area was used for wood flour generation and of that batch, one sieve analysis was performed.

<u>Douglas-fir</u>

The particle size distribution analysis of Douglas-fir is summarized in Table 3.1, which corresponds to Figures 3.1a and 3.1b. Average values based on location are represented in Table 3.2, which corresponds to Figures 3.2a and 3.2b. When particle size is considered based on location within the tree, very little variation appears to occur with the exception of the specimen located near the pith of the middle log. Larger percentages of wood flour were retained in screens 20 and 40 indicating a tendency for this material to produce larger particle sizes when processed by the hammermill. These characteristics are perhaps more appealing than the other zones that produced greater percentages of fines, which could potentially reduce composite properties and generate higher torques during processing of wood-plastic composites.

Table 3.1. Douglas-fir sieve analysis based on location within the trees.

Location	Bottom - Pith	Middle - Pith	Top - Pith	Bottom - Intermediate	Middle - Intermediate	Top - Intermediate
Moisture Content	10.54%	10.98%	10.88%	10.75%	11.07%	10.67%
Sieve Size						
0.0328*	0.6%	5.6%	0.9%	3.3%	0.4%	1.3%
0.0165*	14.0%	26.4%	11.3%	18.2%	9.9%	13.7%
0.0098*	35.1%	31.3%	29.5%	30.5%	33.8%	32.8%
0.0070*	18.8%	16.2%	18.2%	16.4%	20.7%	18.6%
0.0059*	7.3%	6.5%	7.6%	6.6%	8.4%	7.4%
0.0049*	5.3%	5.1%	6.5%	5.2%	6.8%	6.1%
<0.0049*	18.8%	8.9%	26.0%	19.9%	20.0%	20.1%

* Indicates sieve sizes of 20, 40, 60, 80, 100, 120, and pan respectively

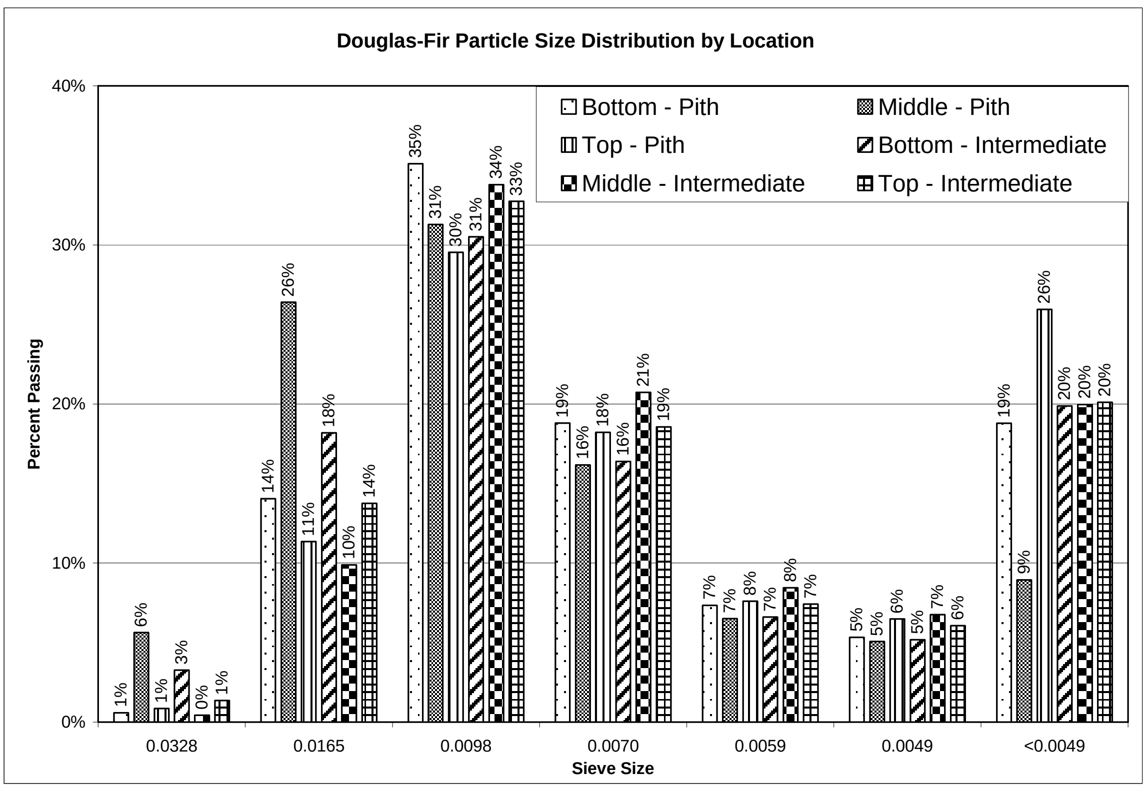

Figure 3.1a. Douglas-fir particle size distribution based on location within the trees.

Differences and similarities in these distributions can be better observed with the cumulative distributions shown in Figure 3.1b. The six locations of interest had similar trends with the exception of the middle-pith and top-pith locations. The middle-pith location exhibited higher retentions in the larger size sieves which resulted in less fine material being retained by the 0.049 and pan sieves. The top-pith cumulative curve consistently retained less material in the sieves with larger openings, which resulted in a larger percentage of fine material being retained in the pan.

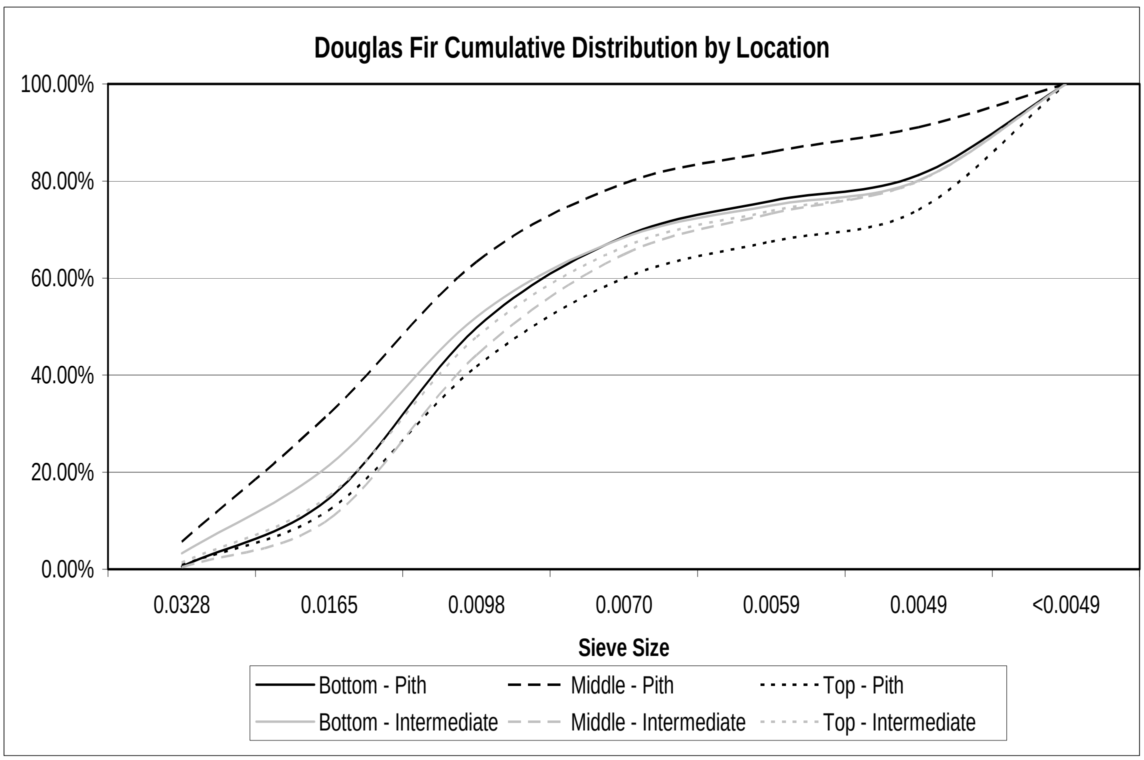

Figure 3.1b. Cumulative distributions of Douglas-fir particle size based on location within the trees.

When the six locations shown above were grouped based on distance from the pith, distance from the butt, and as an average whole tree, a higher degree of uniformity was observed (Table 3.2, Figure 3.2a, and Figure 3.2b). Because averaged zones with respect to differing height and radial location within the trees appeared nearly identical to the whole tree average, particle size distributions for Douglas-fir could be expected to vary very little within the tree.

Table 3.2. Douglas-fir sieve analysis based on grouping within the trees.

Location	Tree	Radius		Elevation		
	Average	Pith	Intermediate	Bottom	Middle	Top
Mositure Content	10.8%	10.8%	10.8%	10.6%	11.0%	10.8%
Sieve Size						
0.0328*	2.0%	2.4%	1.7%	1.9%	3.0%	1.1%
0.0165*	15.6%	17.3%	13.9%	16.1%	18.1%	12.5%
0.0098*	32.2%	32.0%	32.4%	32.8%	32.5%	31.1%
0.0070*	18.1%	17.7%	18.6%	17.6%	18.4%	18.4%
0.0059*	7.3%	7.1%	7.5%	7.0%	7.5%	7.5%
0.0049*	5.8%	5.6%	6.0%	5.2%	5.9%	6.3%
<0.0049*	18.9%	17.9%	20.0%	19.3%	14.4%	23.0%

* Indicates sieve sizes of 20, 40, 60, 80, 100, 120, and pan respectively

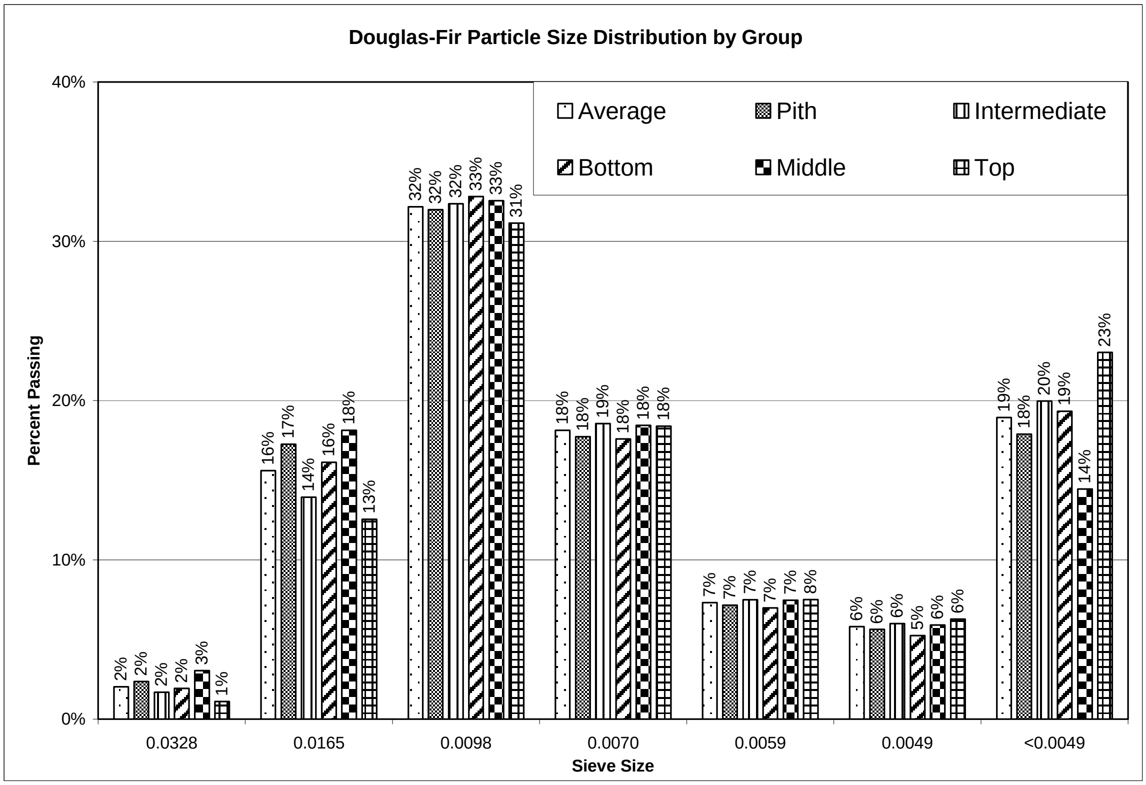

Figure 3.2a. Douglas-fir particle size distribution based on group within the trees.

Unlike the cumulative distribution graph based on location for Douglas-fir, Figure 3.2b shows little variation regardless of the grouping considered. If there is any significant variation, it is represented by the middle and top zones, which were the outliers when location was considered.

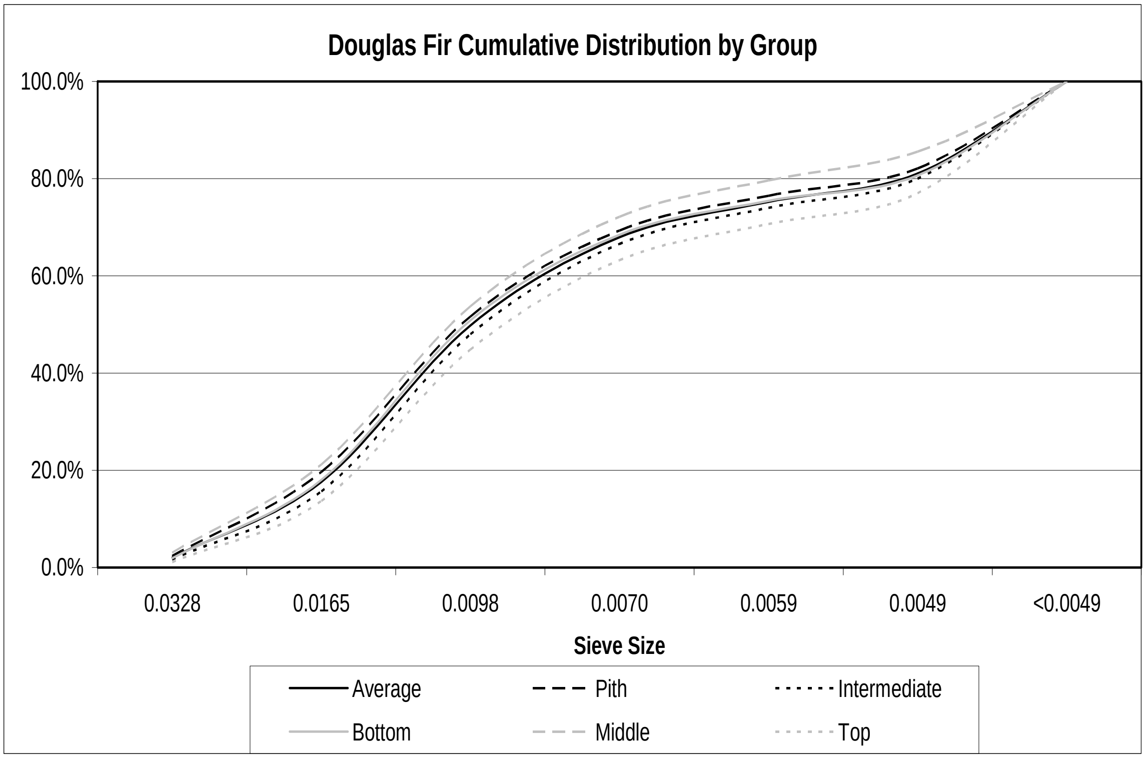

Figure 3.2b. Cumulative distributions of Douglas-fir particle size based on group within the trees.

<u>Western hemlock</u>

The particle size distribution analysis of the western hemlock trees is summarized in Table 3.3 and Figures 3.3a and 3.3b. Average values based on location are represented in Table 3.4 and Figures 3.4a and 3.4b. The western hemlock samples had moisture contents similar to Douglas-fir with a range of 10.3%-11.3%. Unlike Douglas-fir, more variation in the percent material retained in the first two pans occurred; however, the middle-pith location again had a greater percent retained in the first two pans which corresponded to the lowest overall percent being collected in the pan (Table 3.3). Although slightly more variation occurred in the western hemlock trees, the variation was limited to a range of 14% in the most severe case.

Table 3.3. Western hemlock sieve analysis based on location within the trees.

Location	Bottom - Pith	Middle - Pith	Top - Pith	Bottom - Intermediate	Middle - Intermediate	Top - Intermediate
Moisture Content	10.6%	11.1%	10.4%	10.9%	10.4%	10.3%
Sieve Size						
0.0328*	11.8%	16.3%	10.5%	2.0%	8.3%	5.5%
0.0165*	30.9%	34.1%	27.7%	22.9%	28.2%	30.4%
0.0098*	26.4%	23.4%	27.0%	32.9%	26.9%	30.5%
0.0070*	11.5%	9.6%	12.9%	16.2%	12.7%	13.7%
0.0059*	4.3%	3.7%	5.1%	6.2%	5.0%	5.2%
0.0049*	3.2%	2.8%	3.8%	4.4%	4.0%	3.9%
<0.0049*	11.8%	10.1%	13.0%	15.4%	14.8%	11.0%

* Indicates sieve sizes of 20, 40, 60, 80, 100, 120, and pan respectively

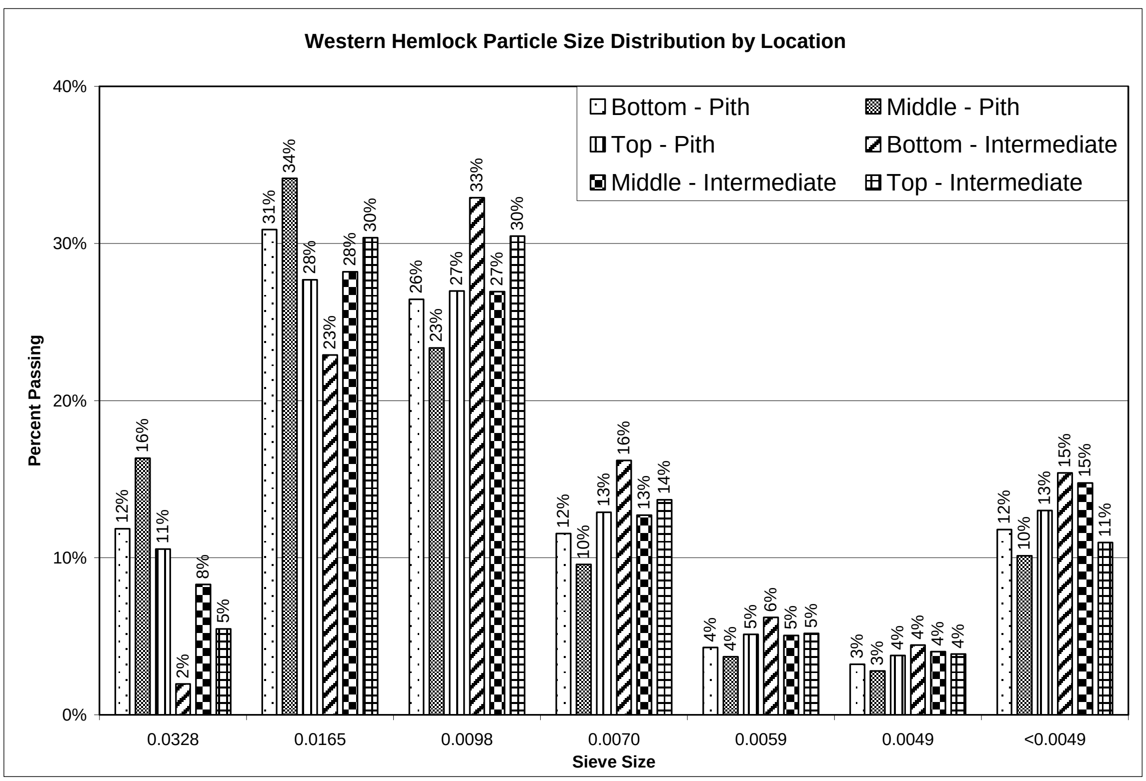

Figure 3.3a. Western hemlock particle size distribution based on location within the trees.

Unlike Douglas-fir, western hemlock exhibited more variation in the first three sieves when cumulative particle size distribution was considered (Figure 3.3b). The majority of this variation had disappeared by the last three sieve sizes resulting in uniform amounts of fines being produced.

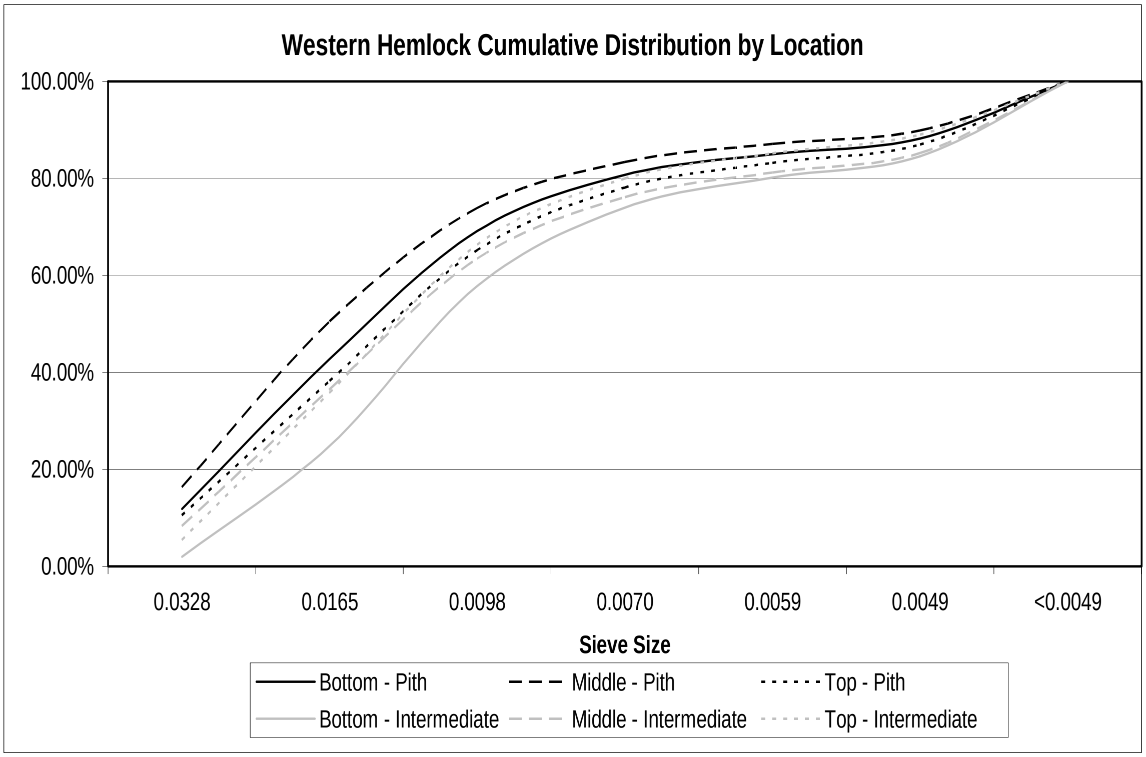

Figure 3.3b. Cumulative distributions of western hemlock particle size based on location within the trees.

Again, the six locations shown above were grouped based on distance from the pith, distance from the butt, and as an average whole tree. More variation in the average values based on location did result from the variation shown in the individual locations as expected (Table 3.4, Figure 3.4). This variation nearly disappears beyond the #60 screen size; however, depending on end use, should possibly be considered when larger particles are necessary for production.

Table 3.4. Western hemlock sieve analysis based on grouping within the trees.

Location	Tree	Radius		Elevation		
	Average	Pith	Intermediate	Bottom	Middle	Top
Mositure Content	10.6%	10.7%	10.5%	10.8%	10.8%	10.3%
Sieve Size						
0.0328*	9.1%	12.9%	5.2%	6.9%	12.3%	8.0%
0.0165*	29.0%	30.9%	27.2%	26.9%	31.2%	29.0%
0.0098*	27.8%	25.6%	30.1%	29.7%	25.1%	28.7%
0.0070*	12.8%	11.3%	14.2%	13.9%	11.1%	13.3%
0.0059*	4.9%	4.4%	5.5%	5.2%	4.4%	5.1%
0.0049*	3.7%	3.3%	4.1%	3.8%	3.4%	3.8%
<0.0049*	12.7%	11.6%	13.7%	13.6%	12.4%	12.0%

* Indicates sieve sizes of 20, 40, 60, 80, 100, 120, and pan respectively

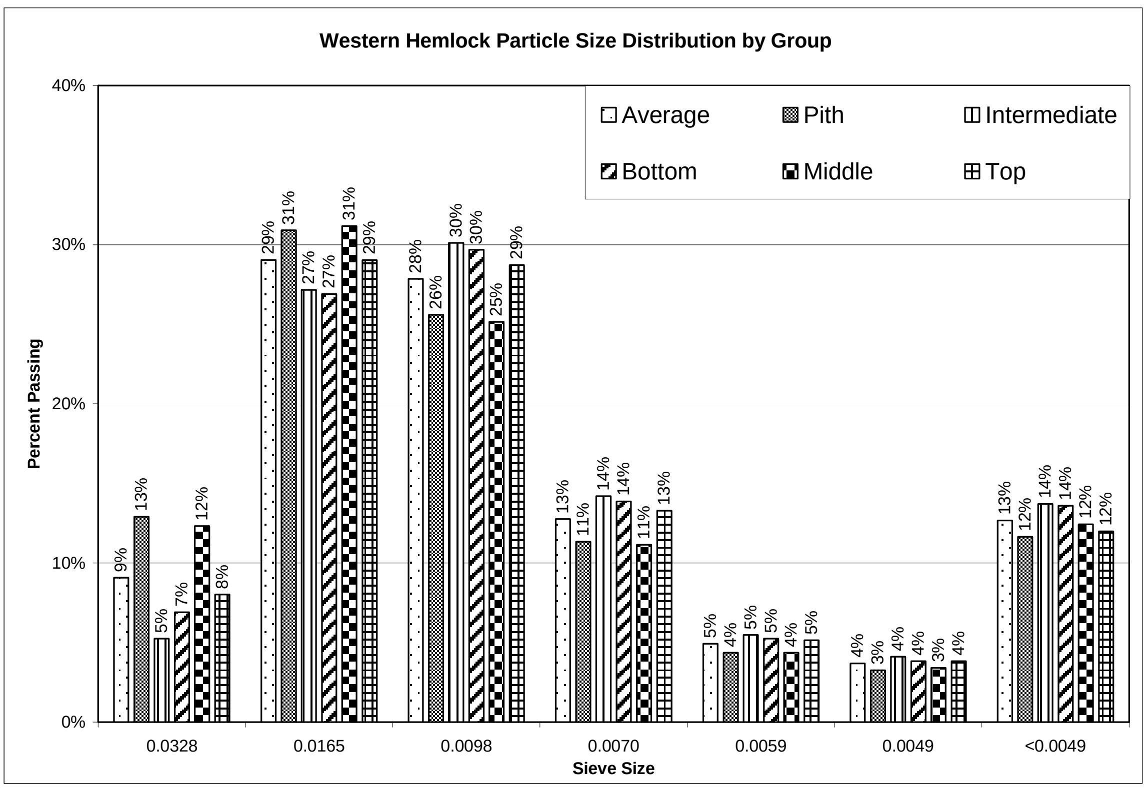

Figure 3.4a. Western hemlock particle size distribution based on group within the trees.

Variation in the first three sieves is apparent again when various cumulative groupings are considered (Figure 3.4b). As with the location specific cumulative distribution graph, this variation is nearly non-existent in the last four fine sieves.

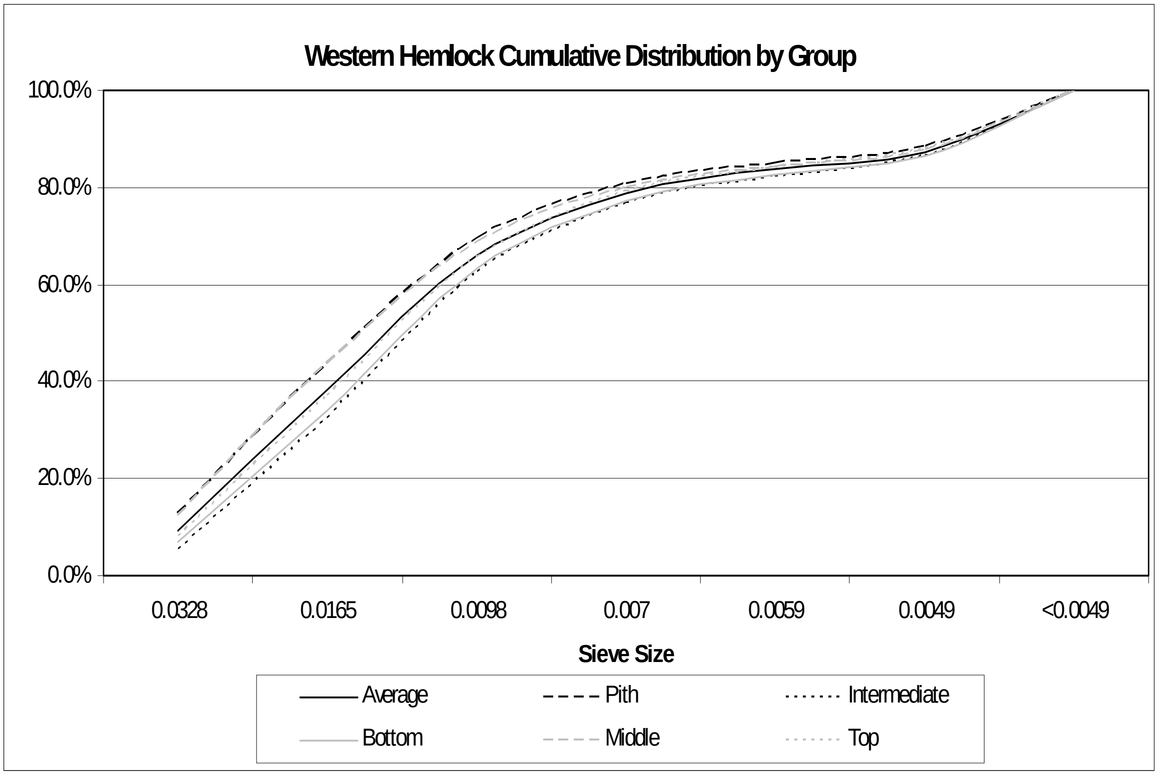

Figure 3.4b. Cumulative distributions of western hemlock particle size based on group within the trees.

Particle size distribution is a critical property when producing wood flour for wood-plastic composites. Generally it is preferred for the majority of the particles to fall within a desired size category with a minimum volume of fine dust. It is easier to feed an extruder with WPC feedstock that does not adhere to the walls of a feeder, and mechanical properties improve with consistent quality wood flour which contains a minimal amount of fine dust. An understanding of particle size distributions is important as it impacts the penetration of thermoplastic resin in the wood particles, thus contributing to the mechanical interlocking between wood and thermoplastic which is a primary mechanism of interaction between these two dissimilar materials (polar and non-polar). Particle size also has an effect on torque levels during the extrusion process.

Based on these principles and particle size alone, western hemlock appears to be the more appropriate furnish for WPCs. A larger overall fraction of material was produced in the larger sieve range while fines were kept to a minimum. Dougals-fir, however exhibited less variation by region. Additionally, Douglas-fir exhibited the largest overall percent of material being retained in the #60 sieve.

pH and Buffering Capacity

The results from the pH and buffering capacity analysis of particles generated by the hammermill procedure described previously are presented in Tables 3.5-3.6 and Figures 3.5-3.6. Because pH and buffering tests were performed on the same samples used for particle size analysis, only six locations per species were tested. One average tree titration curve was created per species by mixing equal parts of solution from each area. From this data, the mean pH for Douglas-fir was determined to be 4.38 while western hemlock was slightly higher at 4.98. The pH was slightly higher for western hemlock but the buffering capacities and titration curves of the two species differed greatly.

Douglas-fir

Titrations determined on average 13.1 ml of sodium hydroxide was required to raise the pH to 7.0, while 5.5 ml of sulfuric acid was required to lower the pH to 3.0 (Table 3.5). Testing also showed Douglas-fir was more susceptible to change in pH due to addition of an acidic substance (ΔpH/ml H_2SO_4 = 0.25) than it is to change in pH due to the addition of a basic substance (ΔpH/ml NaOH = 0.20) (Figure 3.5). Buffering capacity of Douglas-fir to pH of 7.0 was in general higher for bottom logs and in regions near the pith.

On a per location basis, pH varied from the most acidic (pH = 4.14) near the pith at the bottom of the tree to least acidic (pH = 4.55) at the highest outer ring tested. The titration curves did not appear to change significantly through the tree with respect to titration towards pH = 3; however, milliliters of NaOH required to titrate to a pH of 7 varied from 9.2-16.0. In general, the rings near the pith appeared to be more susceptible to NaOH and less susceptible to H_2SO_4 while the rings further from the pith behaved exactly the opposite (Figure 3.5).

Table 3.5. pH and buffering capacity of Douglas-fir particles.

Douglas-fir	Initial pH	Buffer Capacity to pH 7.0 (ml NaOH)	Buffer Capacity to pH 3.0 (ml H_2SO_4)
Average	4.38	13.1	5.5
Top-Intermediate	4.53	9.2	5.5
Top-Pith	4.33	14.2	5.2
Middle-Intermediate	4.55	8.9	6.0
Middle-Pith	4.33	13.8	5.0
Bottom-Intermediate	4.38	13.2	5.3
Bottom-Pith	4.14	16.0	4.5

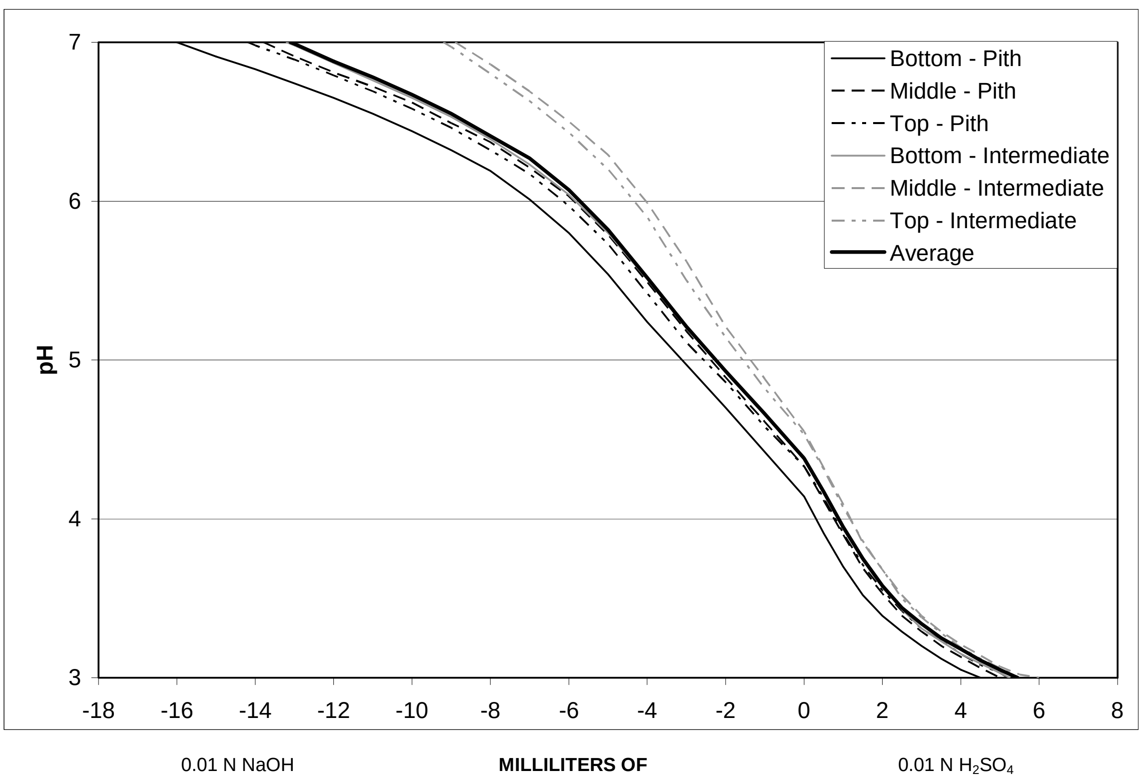

Figure 3.5. Titration curves base on location within Douglas-fir trees.

Western hemlock

Testing indicated the average pH of western hemlock was 4.98, slightly less acidic than the Douglas-fir tested (Table 3.6). Titrations determined on average 3.2 ml of sodium hydroxide was required to raise the pH to 7.0 while 8.0 ml of sulfuric acid was required to lower the pH to 3.0 (Table 3.6). Unlike Douglas-fir, titrations showed western hemlock was more susceptible to changes due to the addition of a basic substance (ΔpH/ml NaOH = 0.63) than it was to changes in pH due to the addition of an acid (ΔpH/ml H_2SO_4 = 0.25) (Figure 3.6).

Unlike Douglas-fir, pH variation within the tree was minimal. However, similarly to Douglas-fir, the most acidic regions were closer to the pith at all heights of the tree (Table 3.6). Very little variation with respect to the titration curves occurred with the exception of the bottom-pith location (Figure 3.6.). In both cases, this location was most resistant to change due to the addition of a base, but unlike the Douglas-fir specimen, this location was also the most resistant to change with the addition of an acid as well.

Table 3.6. pH and buffering capacity of western hemlock particles.

Western hemlock	Initial pH	Buffer Capacity to pH 7.0 (ml NaOH)	Buffer Capacity to pH 3.0 (ml H_2SO_4)
Average	4.98	3.2	8.0
Top-Intermediate	5.00	3.3	7.8
Top-Pith	4.94	3.0	8.1
Middle-Intermediate	5.08	2.4	7.2
Middle-Pith	5.00	2.6	7.4
Bottom-Intermediate	5.00	2.9	7.8
Bottom-Pith	4.93	4.5	9.6

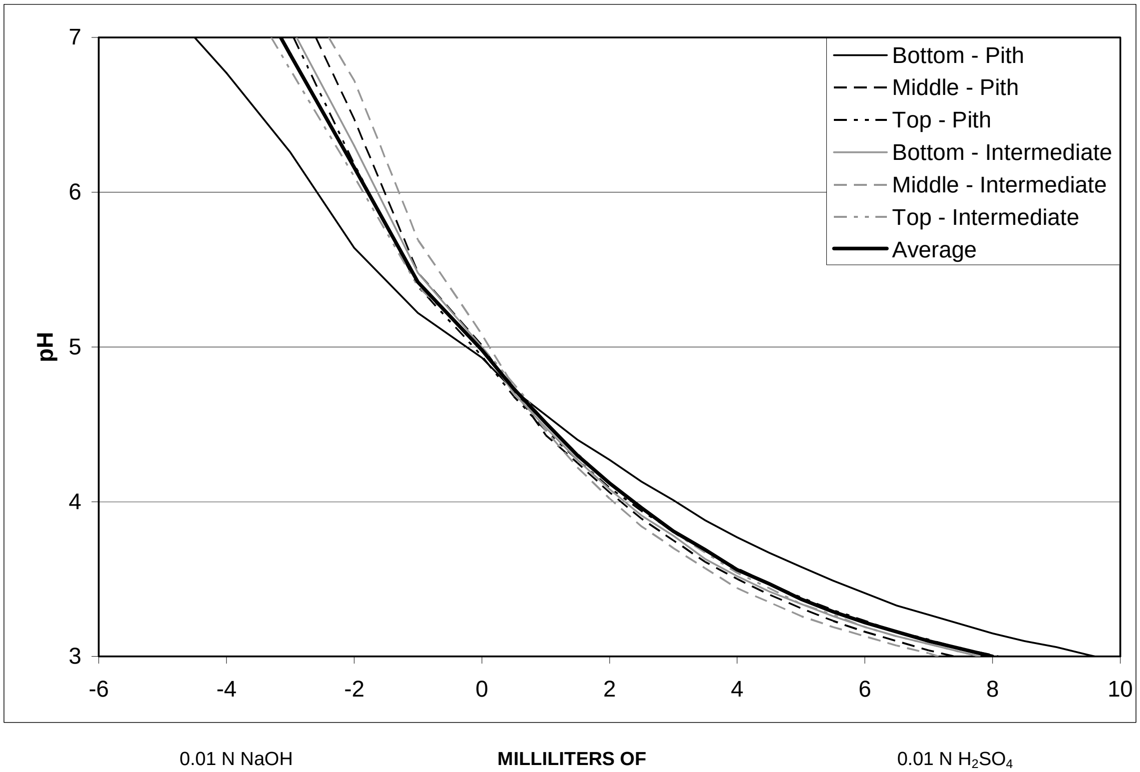

Figure 3.6. Titration curves based on location within western hemlock trees.

It is critical to know the pH of wood furnish when manufacturing composites as adhesive cure kinetics are influenced by wood pH. Efficiency of penetration, solubility, rate of hardening, and degree of hardening that is specific for each adhesive formulation is influenced by wood pH (Marra 1992, Maloney 1993). Very low pH wood could retard or even inhibit the curing of certain alkaline adhesives, such as resorcinolic adhesives; however, low wood pH could pose a problem with urea-based adhesives that cure rapidly on high-acid wood. Most wood has a pH ranging between 3 and 6. The small diameter Douglas-fir trees from the Olympic Peninsula in this study had an average pH of 4.38. Olson (1996) reported a pH of 4.15 for small Douglas-fir trees. The western hemlock trees yielded a higher pH at 4.98. Both species fell within the range expected for softwoods of 4.02-5.82 reported by Johns and Niazi (1980).

Tensile Properties of Strands

Strand analysis results are presented in Tables 3.7-3.20 and Figures 3.7-3.18. For both species, not enough material remained from the outer rings (near bark) of the top log to perform strand analysis. Remaining specimens were used to determine Young's modulus in tension, E_x, and Poisson's ratio, $\nu_{xy.}$ As these properties are correlated with the grain angle, grain deviations in these strands were determined to compute the material properties, E_1, ν_{12}, E_2, and G_{12} respectively, using the transformation equations. Variation in these properties was then examined as a function of tree height and diameter. Strands were grouped by their grain angles into categories of 2.0^o-3.9^o and greater then 4^o to apply transformation equations effectively in estimating average material direction properties.

In general, the variation in western hemlock strands was lower than Douglas-fir strands. Additionally, variation in E_x of the strands was greater than most variations encountered in the clear specimen testing phase of this research (flexural, tensile, and compressive testing of clear specimens); however rupture stress variation was generally lower then comparable clear specimen tensile variation.

Trends between species appeared to be very similar. Both Douglas-fir and western hemlock strand strengths were half or less-than-half of those calculated for clear specimens. As with clear specimens, strength decreased with increasing height in the trees; however, a clear trend was not apparent with respect to radial location.

Douglas-fir

The results of the Douglas-fir strand tests are summarized based on location within the tree in Table 3.7. The average strand Young's modulus and rupture stress for the Douglas-fir trees as a whole were 934,400 psi and 4,400 psi respectively. These values represent a 38% and 55% decrease when compared to values of small clear specimens tested in tension (Langum 2007). This decrease in rupture strength can be attributed to damage from the stranding process. As discussed previously, values of G_{12} and E_2 were calculated based on the average angle, E_x, and ν_{xy} of a given location along with the average species E_1 and ν_{12} calculated based on strands with a grain angle of less then 1^o (Table 3.8). Due to small grain angle measurements, there is a greater degree of error in determining G_{12} and E_2, and this is reflected in the differences in these two values estimated using the two measured group angles. Therefore, values calculated using strands with angles greater then four degrees were used as estimates of G_{12} and E_2 to obtain transformation equations.

When compared to clear specimen properties, the strength and modulus trends do not always directly correlate. Like the related clear specimen properties, again the mid logs possessed the highest Young's modulus values, while the strands from the region near the bark had the highest rupture strength. When Young's modulus and rupture stress were considered for two different location schemes, only rupture stress in the tree behaved exactly as its clear specimen counterpart when examined by height. In the radial direction, Young's modulus and rupture stress of small clear specimens were highest in the regions adjacent to the bark. Unlike the clear specimens; however, the strands from the region adjacent to the bark yielded the lowest Young's modulus and rupture stress values. This indicates the high degree of variability found in juvenile wood due to differences in microfibril angle and cell wall chemical composition.

Table 3.7. Strand properties of Douglas-fir based by location within the tree.

Douglas-Fir	E_x (psi)	COV (%)	ν_{xy} (psi)	COV (%)	Rupture Stress (psi)	COV (%)
Tree	934,410	42.1	0.530	34.2	4,403	14.1
By Height						
Bottom	834,685	34.0	0.496	31.2	4,790	17.7
Middle	1,030,423	47.4	0.521	36.6	4,240	8.0
Top	939,977	29.9	0.600	31.9	4,065	12.7
By Radius						
Pith	863,691	33.8	0.521	34.9	4,392	14.5
Intermediate	1,066,608	46.3	0.565	31.6	4,767	14.2
Bark	842,190	37.9	0.499	36.1	3,871	0.1

Table 3.8. Young's modulus and Poisson's ratio for Douglas-fir strands in the material direction.

Douglas-Fir	Average	COV (%)
E_1 (psi)	1,117,332	34.7
ν_{12}	0.535	35.4

As expected, Young's modulus and rupture stress decreased as grain angle increased (Figures 3.7 and 3.8) (each hollow dot represents an individual strand test). G_{12} and E_2 estimated from the two angle groupings as well as Figures 3.7 and 3.8 are summarized in Table 3.9. Because the values calculated from strands with grain angles greater than 4^o more accurately estimate values of G_{12} and E_2, 13,281 psi and 25,521 psi respectively were selected for calculation of the transformation equation [3.1] (represented by the heavy line shown in Figure 3.7a). Visual inspection of Figure 3.7a indicates the transformation equation accurately models trends in modulus of elasticity vs. grain angle. Figure 3.7b is an extension of the transformation equation to 90°. Similar to the analysis by location within the tree, Young's modulus again was subject to a large coefficient of variation (as indicated by standard deviation bars with the heavy black dots representing average values per respective angle increment). Surprisingly however, analysis by angle also resulted in the rupture stress COV increasing unlike its counterpart based on location.

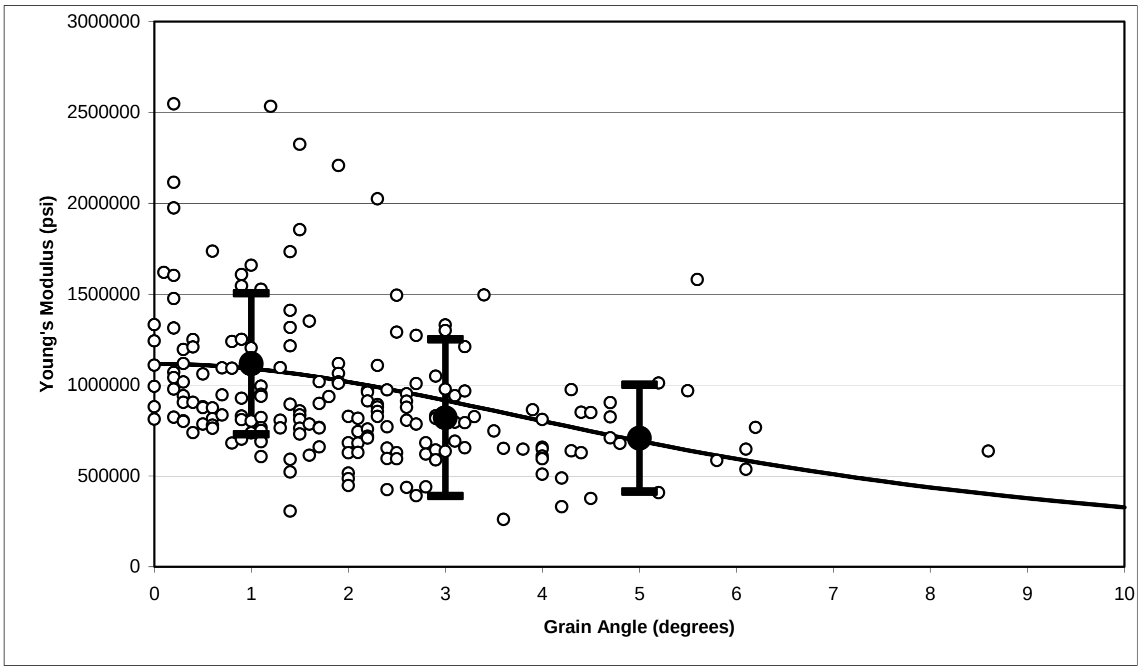

Figure 3.7a. Variation of strand Young's modulus in Douglas-fir with respect to grain angle.

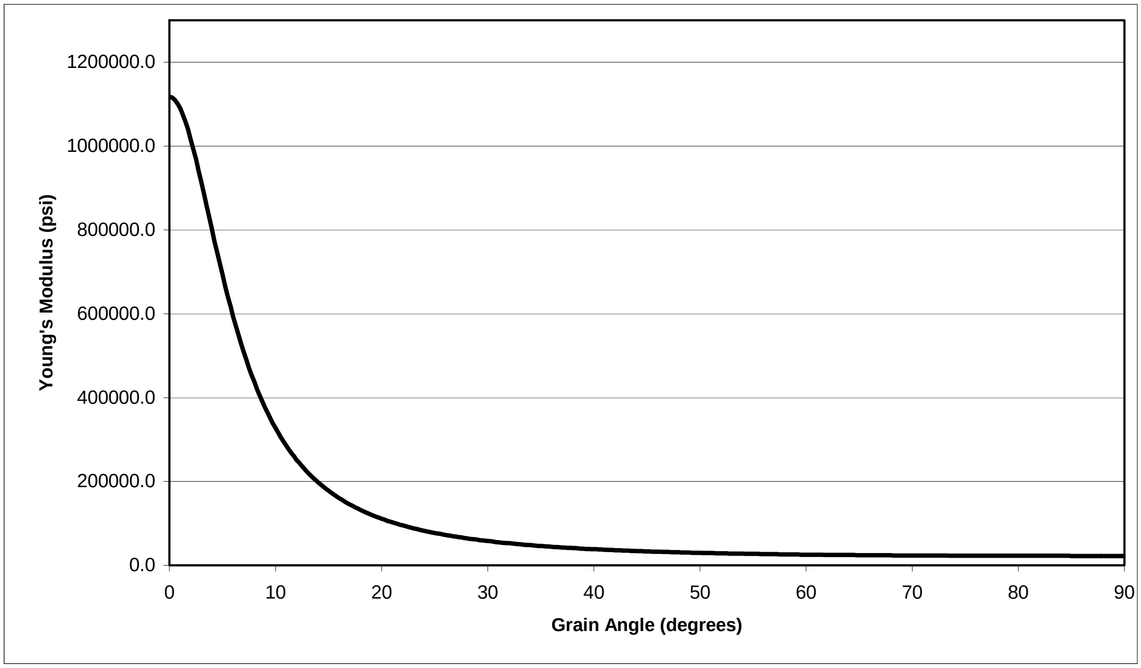

Figure 3.7b. Transformation equation: Douglas-fir strand Young's modulus vs. grain angle.

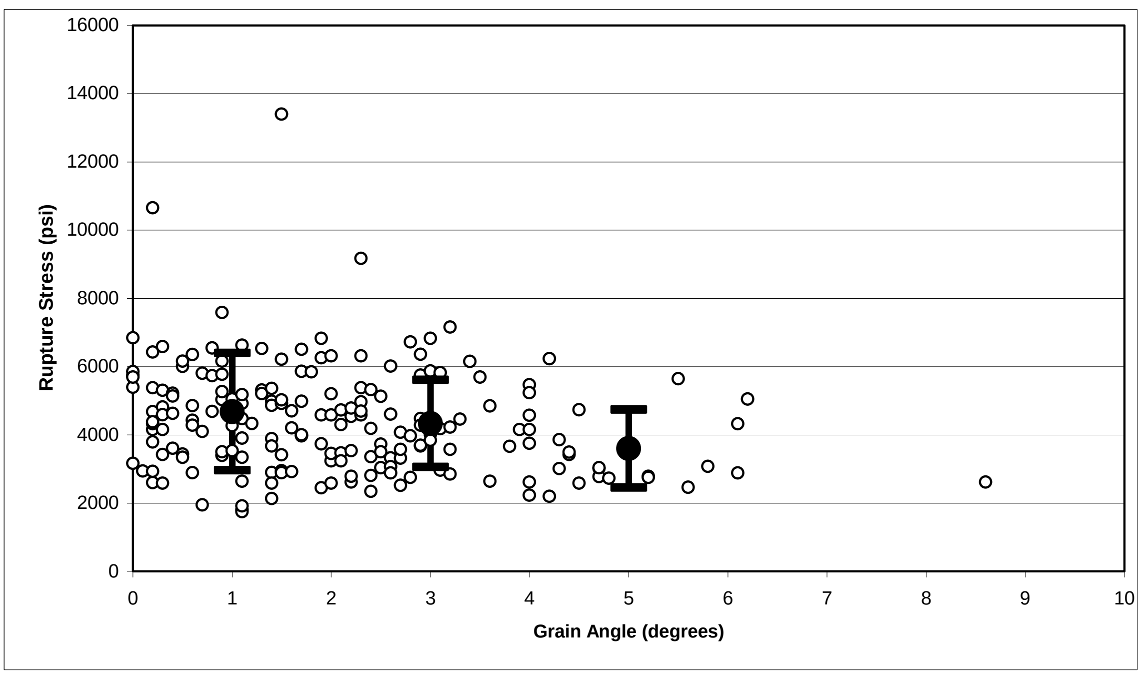

Figure 3.8. Variation of strand rupture stress in Douglas-fir with respect to grain angle.

Table 3.9. Strand properties of Douglas-fir based on grain angle.

Douglas-Fir	Average Angle (degrees)	E_x (psi)	COV (%)	ν_{xy} (psi)	COV (%)	G_{12} (psi)	E_2 (psi)	Rupture Stress (psi)	COV (%)
2-3.9 degrees	2.7	820,341	35.9	0.522	29.7	6,520	12,828	4,336	31.0
>4 degrees	4.9	707,532	34.8	0.511	35.9	13,281	25,521	3,597	31.8

Now variation in strand properties of Dougals-fir trees will be considered on a location basis. Variation between regions was visually inspected by comparing cumulative distribution curves (Figures 3.9–3.12). Since visual inspection only gives the reader a feel for expected variation, distributions were also compared using p-values from the two sample Kolmogorov-Smirnov (K-S) goodness of fit test (Tables 3.10-3.13). Distributions are considered similar if the p-values is greater than the critical value of α = 0.05.

Figures 3.9 and 3.10 illustrate Douglas-fir Young's modulus and ruptures stress cumulative distributions for three height and radial locations. The heavy black line is the cumulative distribution representing all specimens. This distribution only serves as a visual reference and was not considered for K-S testing. When height was considered as a variant affecting strength and modulus, K-S testing indicated no significant variation between the distributions (bold numbers indicate no significant difference) (Table 3.10). Distance from the pith, however, did indicate significant variation in both strength and modulus exists, with the strands from the pith being significantly less stiff than the strands from the intermediate zone (Table 3.11).

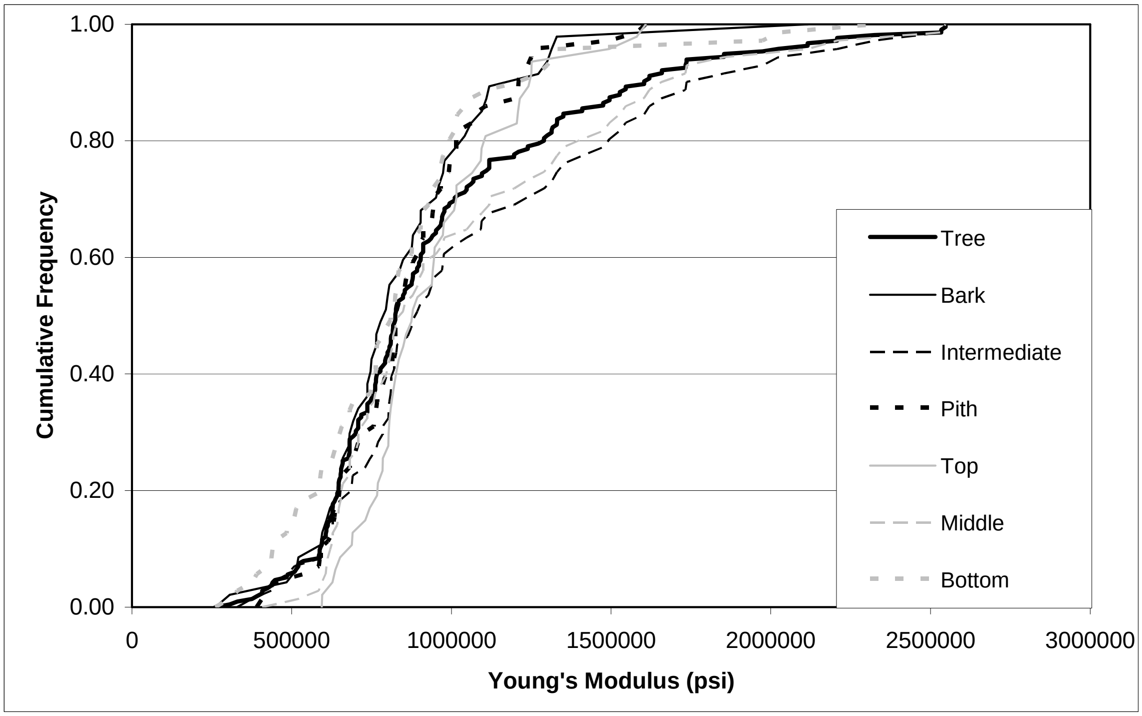

Figure 3.9. Cumulative distributions of Douglas-fir strand Young's modulus based on zone grouping.

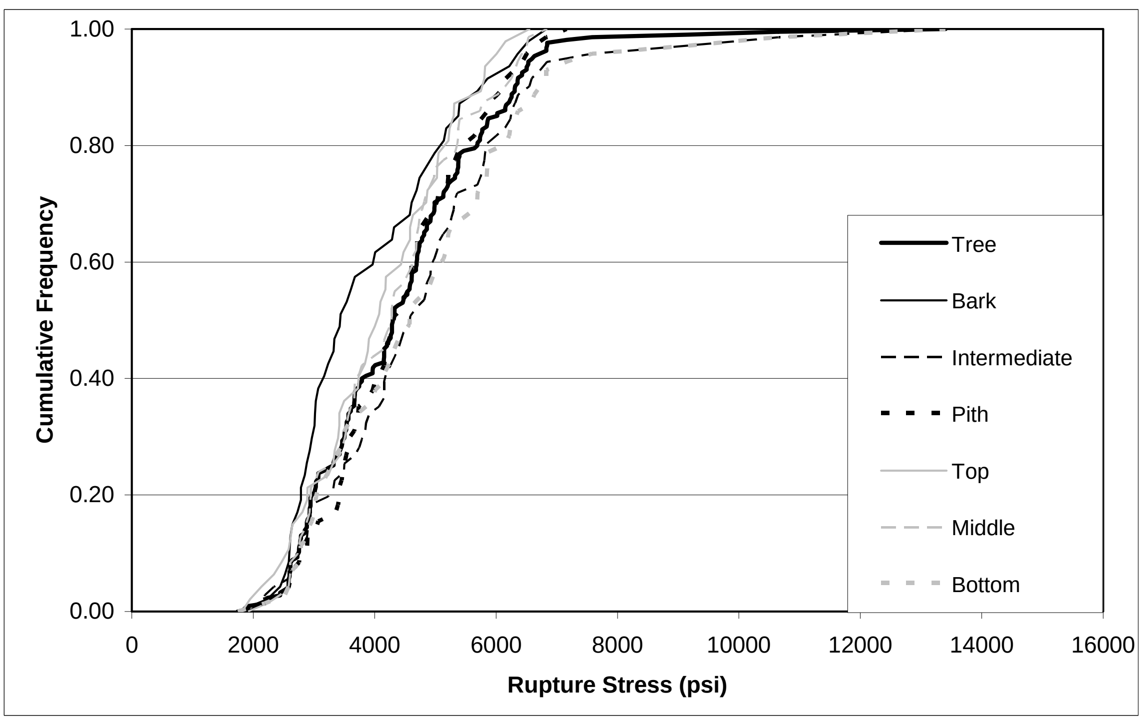

Figure 3.10. Cumulative distributions of Douglas-fir strand rupture stress based on zone grouping.

Table 3.10. Kolmogorov-Smirnov p-values for Douglas-fir strand properties based on height.

Douglas-Fir	Young's Modulus (psi)			Rupture Stress (psi)		
	B	M	T	B	M	T
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

Table 3.11. Kolmogorov-Smirnov p-values for Douglas-fir strand properties based on diameter

Douglas-Fir	Young's Modulus (psi)			Rupture Stress (psi)		
	P	I	B	P	I	B
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

When further refinement of the data based on the nine individual locations is performed, additional variation in distribution of strength and modulus properties becomes apparent. The nine locations of interest, described in chapter two (Langum 2007), for the most part are similar. However, Figure 3.11 indicates the middle-intermediate zone possesses significantly higher modulus. Unlike the cumulative distributions of modulus, the cumulative distribution of rupture stress (Figure 3.12) shows little variation. For this reason, it is necessary to further evaluate the data with the two value K-S goodness of fit test.

The two value K-S test confirms what is apparent in Figure 3.11. Bold values in Table 3.12 indicate two respective zones are similar with a probability of 95%. The table reaffirms the middle-intermediate zone possesses dissimilarly higher modulus. Additionally, the top-pith zone is shown to be dissimilar to the majority of the other specimens. When rupture stress is considered (Table 3.13), much less variation occurred, and it is reasonable to assume little variation occurs from zone to zone in the Douglas-fir trees.

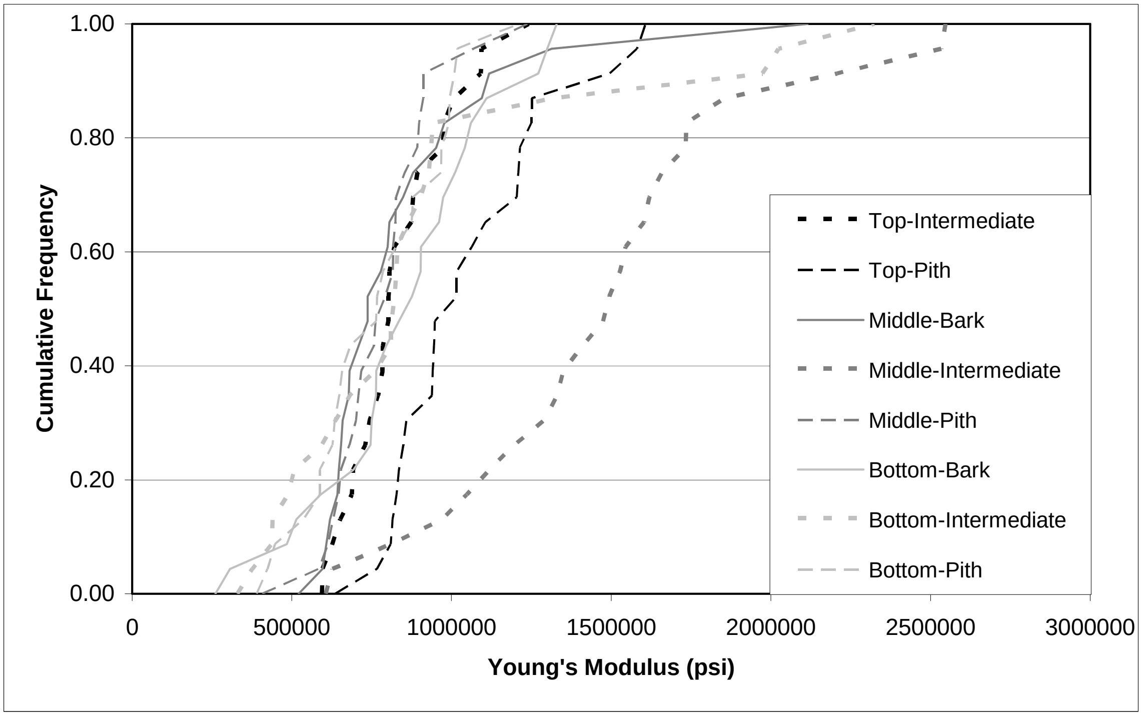

Figure 3.11. Cumulative distributions of Douglas-fir strand Young's modulus based on location.

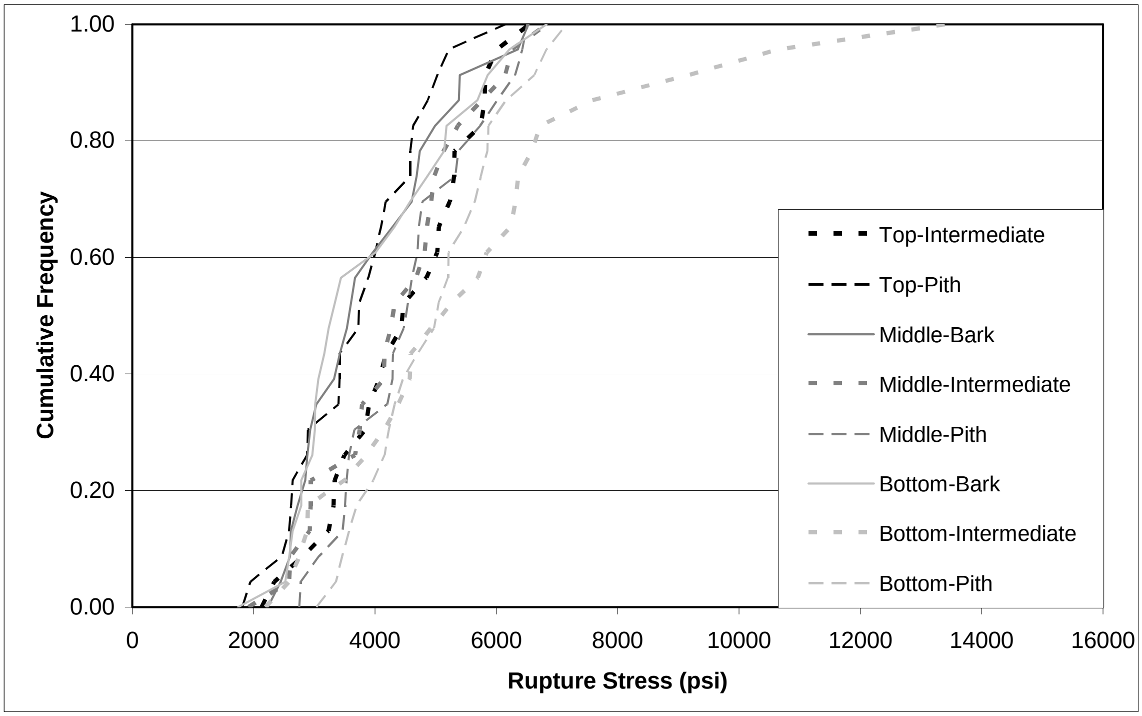

Figure 3.12. Cumulative distributions of Douglas-fir strand rupture stress based on location.

Table 3.12. Kolmogorov-Smirnov p-values for Douglas-fir strand Young's modulus based on location.

Douglas-Fir	Young's Modulus (psi)							
	T-I	T-P	M-B	M-I	M-P	B-B	B-I	B-P
Top-Intermediate	1.000	-	-	-	-	-	-	-
Top-Pith	0.003	1.000	-	-	-	-	-	-
Middle-Bark	**0.378**	0.000	1.000	-	-	-	-	-
Middle-Intermediate	0.000	0.000	0.000	1.000	-	-	-	-
Middle-Pith	**0.840**	0.000	**0.840**	0.000	1.000	-	-	-
Bottom-Bark	**0.604**	**0.050**	**0.231**	0.000	**0.213**	1.000	-	-
Bottom-Intermediate	**0.213**	0.008	**0.378**	0.000	**0.604**	**0.604**	1.000	-
Bottom-Pith	**0.213**	0.003	**0.604**	0.000	**0.604**	**0.378**	**0.840**	1.000

Table 3.13. Kolmogorov-Smirnov p-values for Douglas-fir strand rupture stress based on location.

Douglas-Fir	Rupture Stress (psi)							
	T-I	T-P	M-B	M-I	M-P	B-B	B-I	B-P
Top-Intermediate	1.000	-	-	-	-	-	-	-
Top-Pith	**0.213**	1.000	-	-	-	-	-	-
Middle-Bark	**0.213**	**0.980**	1.000	-	-	-	-	-
Middle-Intermediate	**0.840**	**0.213**	**0.213**	1.000	-	-	-	-
Middle-Pith	**0.840**	**0.050**	**0.109**	**0.840**	1.000	-	-	-
Bottom-Bark	**0.050**	**0.604**	**0.980**	**0.109**	0.008	1.000	-	-
Bottom-Intermediate	**0.109**	0.008	**0.050**	**0.213**	**0.378**	**0.050**	1.000	-
Bottom-Pith	**0.604**	0.021	0.021	**0.378**	**0.378**	0.003	**0.378**	1.000

Western hemlock

Results from testing of the western hemlock strands are summarized in Tables 3.14-3.20 and Figures 3.13-3.18. Overall, the western hemlock strands showed much less variability as evidenced by lower coefficients of variation. The average strand Young's modulus and rupture stress for the western hemlock trees as a whole were 874,300 psi and 4,100 psi respectively. These values represent a 21% and 56% decrease in Young's modulus and rupture stress respectively when compared to small clear specimens tested in tension (Langum 2007). When compared with the previous Douglas-fir results, strand modulus was not reduced as drastically as Douglas-fir strands (38%); however, the reduction in strength (55%) was almost identical.

As with the Douglas-fir strands, strength and modulus trends did not always directly correlate. Unlike clear specimen properties, strands in the top log yielded the highest values for Young's modulus followed by the mid logs (Table 3.14). As for ultimate strength, strands from the bottom log, like the small clear specimens, yielded higher values while those from the top logs were the lowest.

When radial location was considered, Young's modulus distributions remained basically the same as clear specimen properties. Regions near the pith and intermediate rings had very similar modulus while the near bark region was considerably lower. When rupture strength was considered, the zones of highest and lowest strength were reversed from their clear specimen counterparts while the pith remained as the median.

Table 3.14. Strand properties of western hemlock based on location within the tree

Western Hemlock	Ex (psi)	COV (%)	νξψ (psi)	COV (%)	Rupture Stress (psi)	COV (%)
Tree	874,332	26.4	0.476	40.7	4,108	13.3
By Height						
Bottom	830,045	25.6	0.497	40.3	4,481	11.4
Middle	901,154	22.9	0.445	41.4	3,916	1.6
Top	913,942	29.6	0.472	40.5	3,739	19.2
By Radius						
Pith	901,220	24.9	0.464	41.4	4,233	6.3
Intermediate	868,522	24.8	0.514	35.5	3,690	10.8
Bark	811,101	35.2	0.377	45.4	4,987	n=1

When the influence of grain angle on strand properties was investigated Young's modulus and rupture stress decreased as grain angle increased (Figures 3.13a, 3.13b, and 3.14). G_{12} (32,965 psi) and E_2 (34,145 psi) were calculated using values from the strands with grain angles greater than 4^o, as these values, when combined with the transformation equation [3.1], better modeled the modulus of elasticity vs. grain angle trend. As with the Douglas-fir strands, visual inspection of Figure 3.13 indicates the transformation equation (heavy line) accurately models trends in modulus of elasticity vs. grain angle. Similarly to the analysis by location within the tree, Young's modulus again was subject to a large coefficient of variation.

Table 3.15. Young's modulus and Poisson's ratio for western hemlock strands in the material direction.

Western Hemlock	Average	COV (%)
E_1 (psi)	971,529	22.1
ν_{12}	0.518	38.2

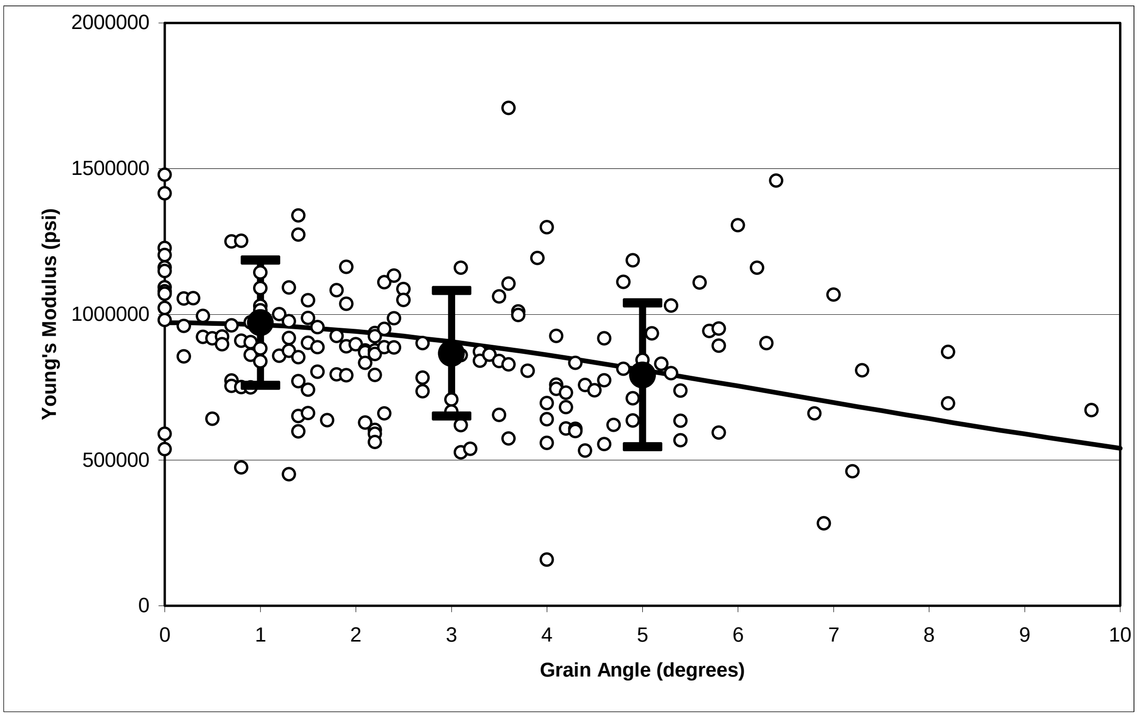

Figure 3.13a. Variation of strand Young's modulus in western hemlock strands with respect to grain angle.

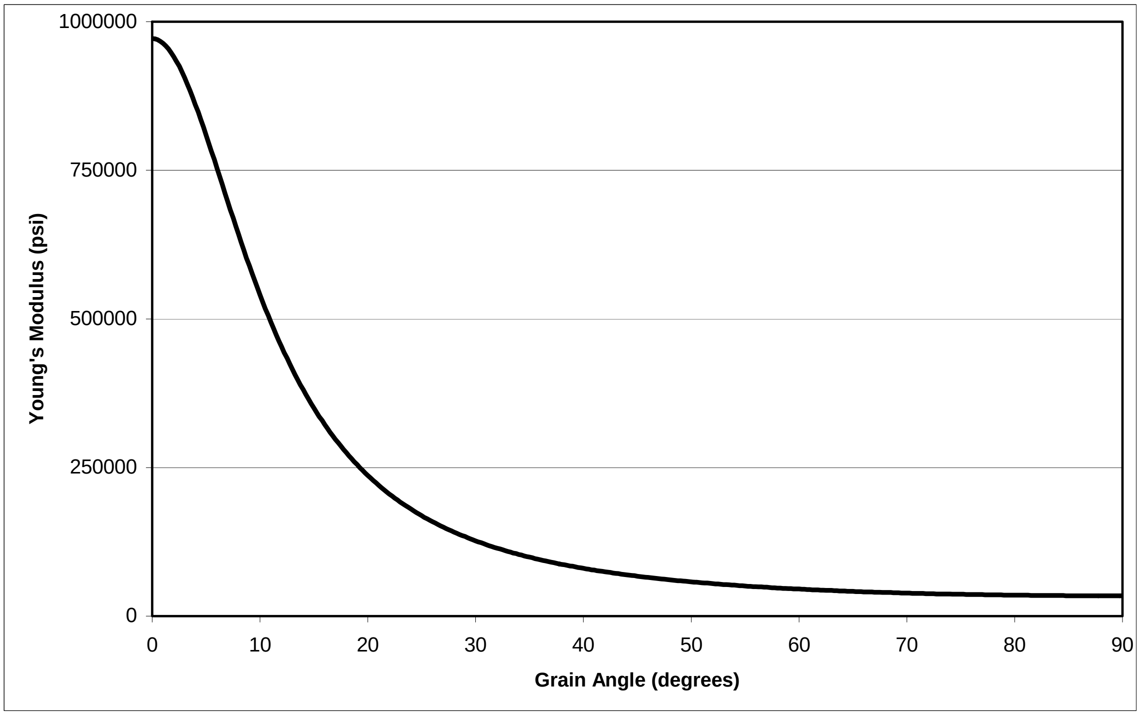

Figure 3.13b. Transformation equation: western hemlock strand Young's modulus vs. grain angle.

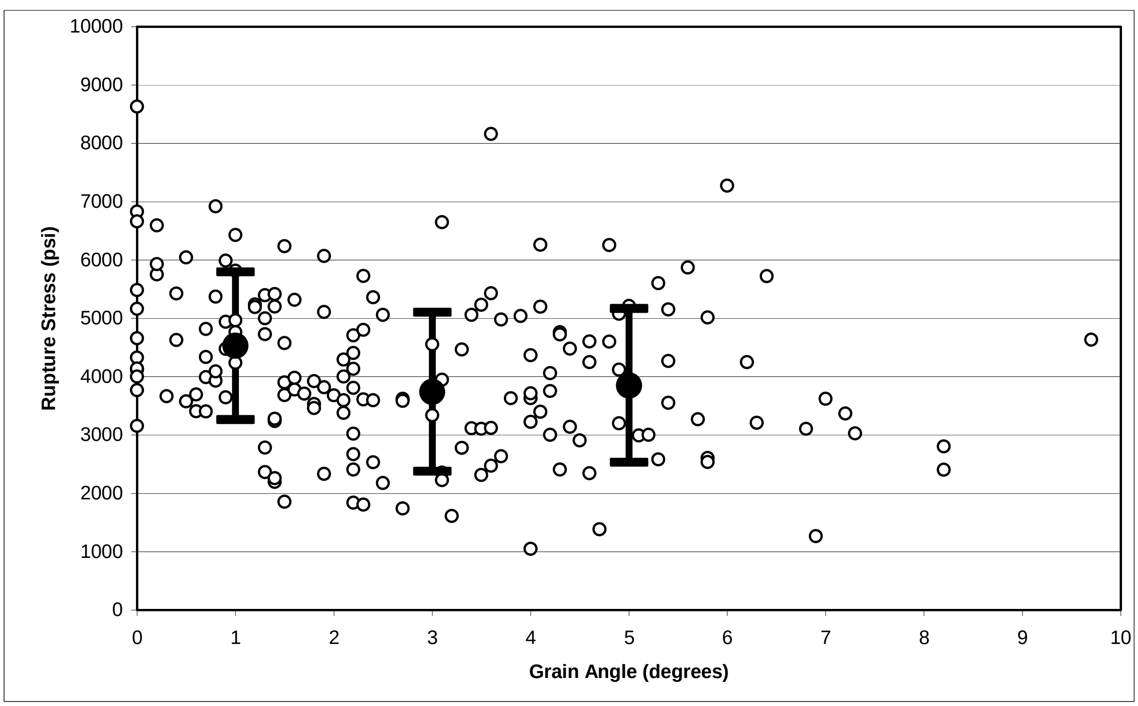

Figure 3.14. Variation of rupture stress in western hemlock strands with respect to grain angle.

Table 3.16. Strand properties of western hemlock passed on grain angle.

Western Hemlock	Average Angle (degrees)	E_x (psi)	COV (%)	ν_{xy} (psi)	COV (%)	G_{12} (psi)	E_2 (psi)	Rupture Stress (psi)	COV (%)
2-3.9 degrees	2.8	866,023	24.9	0.496	41.9	18,181	27,542	3,740	36.4
>4 degrees	5.3	792,028	31.2	0.415	41.0	32,965	34,145	3,848	34.3

Unlike Douglas-fir, western hemlock modulus tends to increase with height in the tree while strength decreases. When radial location is considered, properties appear to increase towards the pith, which is surprising. It must be noted, however, the test results from near bark location only consists of strands from the lowest height considered (hence strands were not available from the middle and top heights and n=1).

Figures 3.15 and 3.16 illustrate cumulative density functions for western hemlock Young's modulus and rupture stress distributions based on three levels of height and three locations at set distance from the pith. As was previously mentioned, the "Bark" region is based on only one location (bottom-bark). The large offset in this locations cumulative density curve is most likely explained by the small sample size (Figures 3.15 and 3.17). As with Douglas-fir, when height was considered as a variant affecting strength and modulus, K-S testing indicated very little significant variation between distributions, with the exception of rupture stress between bottom to top logs (Figures 3.15, 3.16, and Table 3.17). Unfortunately, this variation is most likely due to the small sample size available for the bark region. As with Douglas-fir, distance from the pith, did show significant variation with almost every possible combination, indicating that distance from the pith does significantly affect strength and modulus.

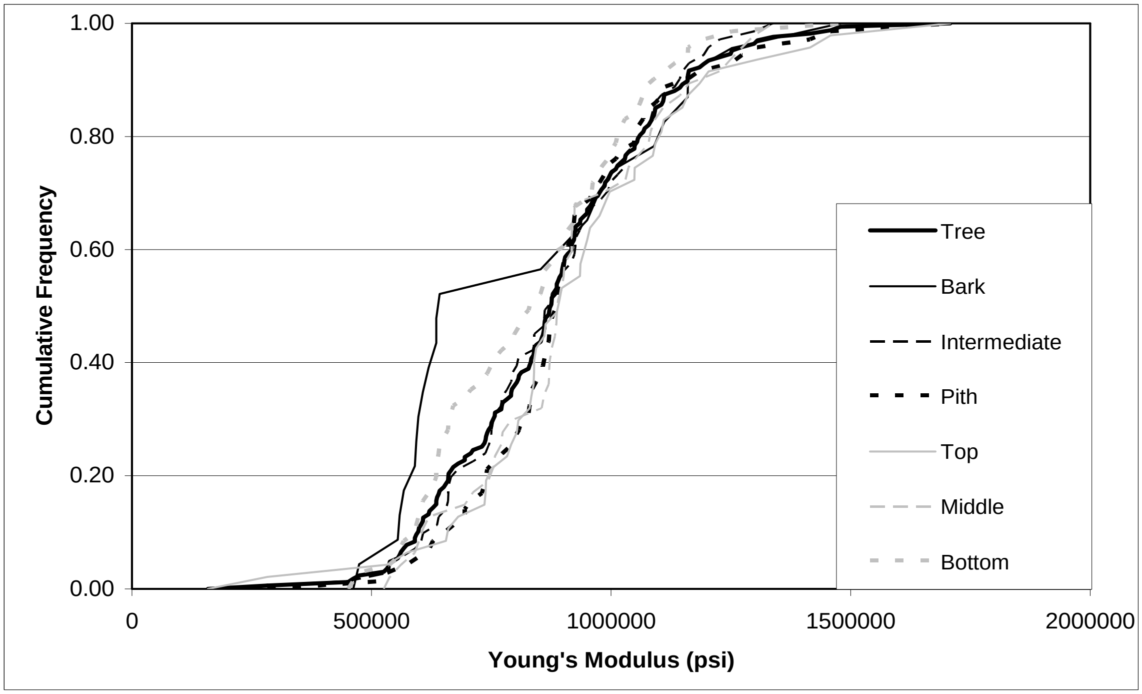

Figure 3.15. Cumulative distributions of western hemlock strand Young's modulus based on zone grouping.

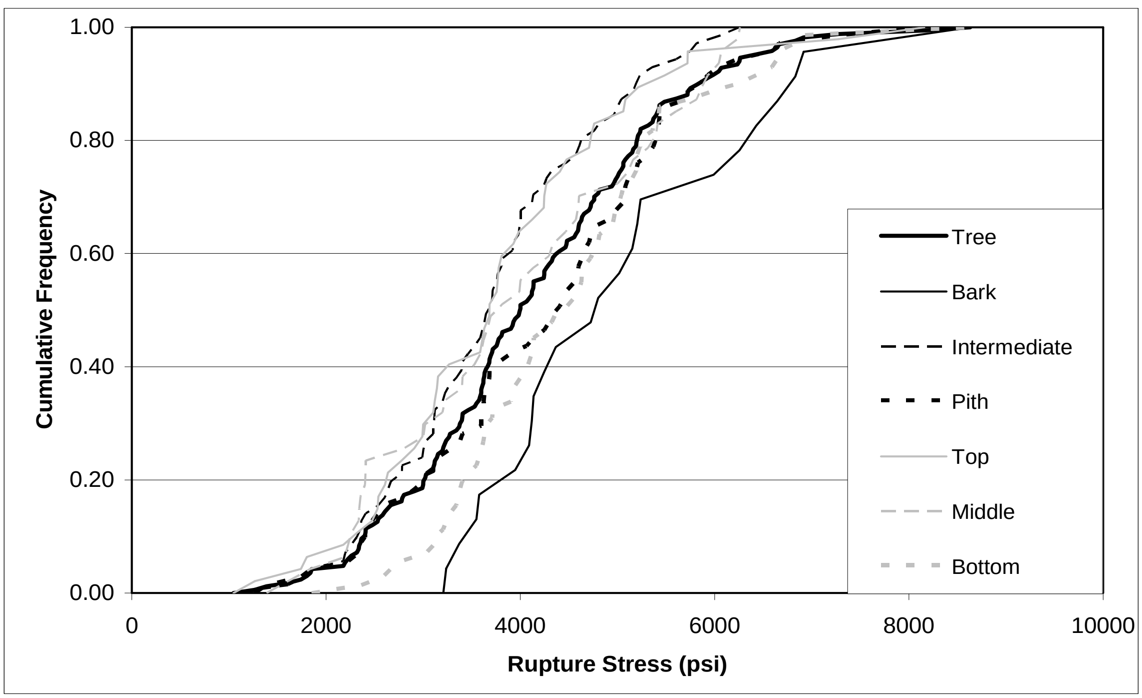

Figure 3.16. Cumulative distributions of western hemlock strand rupture stress based on zone grouping.

Table 3.17. Kolmogorov-Smirnov p-values for western hemlock strand properties based on height.

Western Hemlock	Young's Modulus (psi)			Rupture Stress (psi)		
	B	M	T	B	M	T
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

Table 3.18. Kolmogorov-Smirnov p-values for western hemlock strand properties based on diameter.

Western Hemlock	Young's Modulus (psi)			Rupture Stress (psi)		
	P	I	B	P	I	B
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

Unlike Douglas-fir, when the eight specific zones were considered, the bottom-bark location appeared to possess significantly lower modulus than the rest of the locations and the middle-intermediate zone did not possess dissimilarly higher modulus (Table 3.19). Like Douglas-fir, little variation occurred when rupture stress was considered (Table 3.20), with the exception of the top-intermediate zone, which indicated significantly lower strength values. Based on this data, it is again reasonable to assume little variation occurs from zone to zone in western hemlock trees.

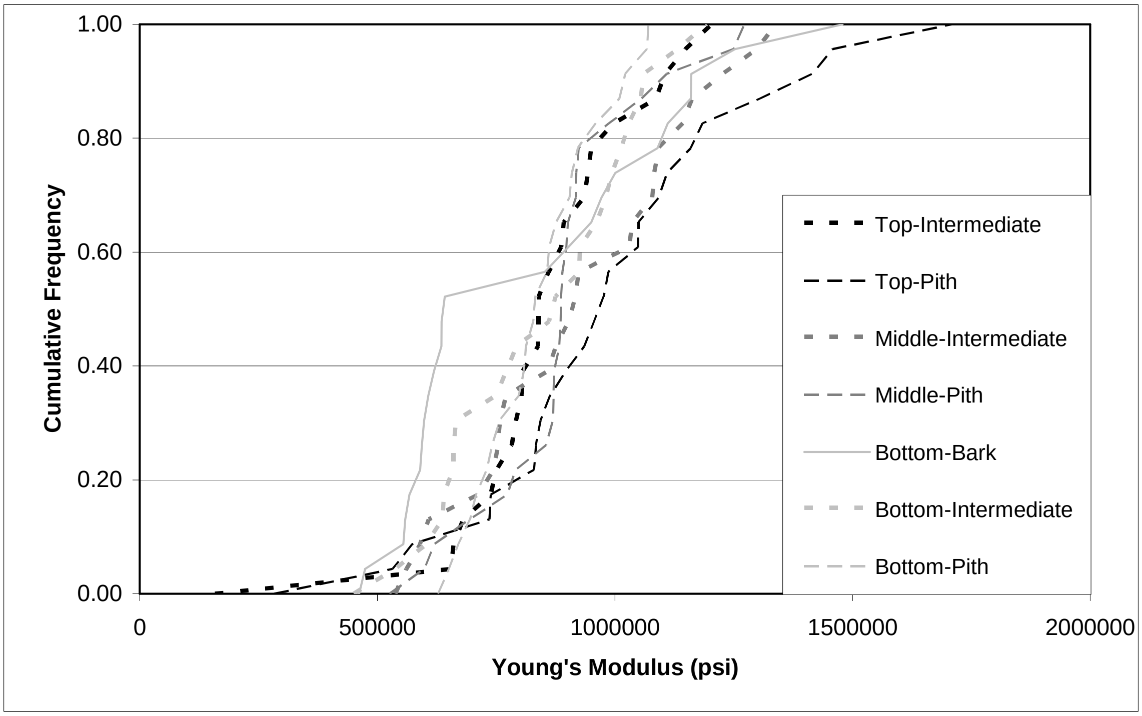

Figure 3.17. Cumulative distributions of western hemlock strand Young's modulus based on location.

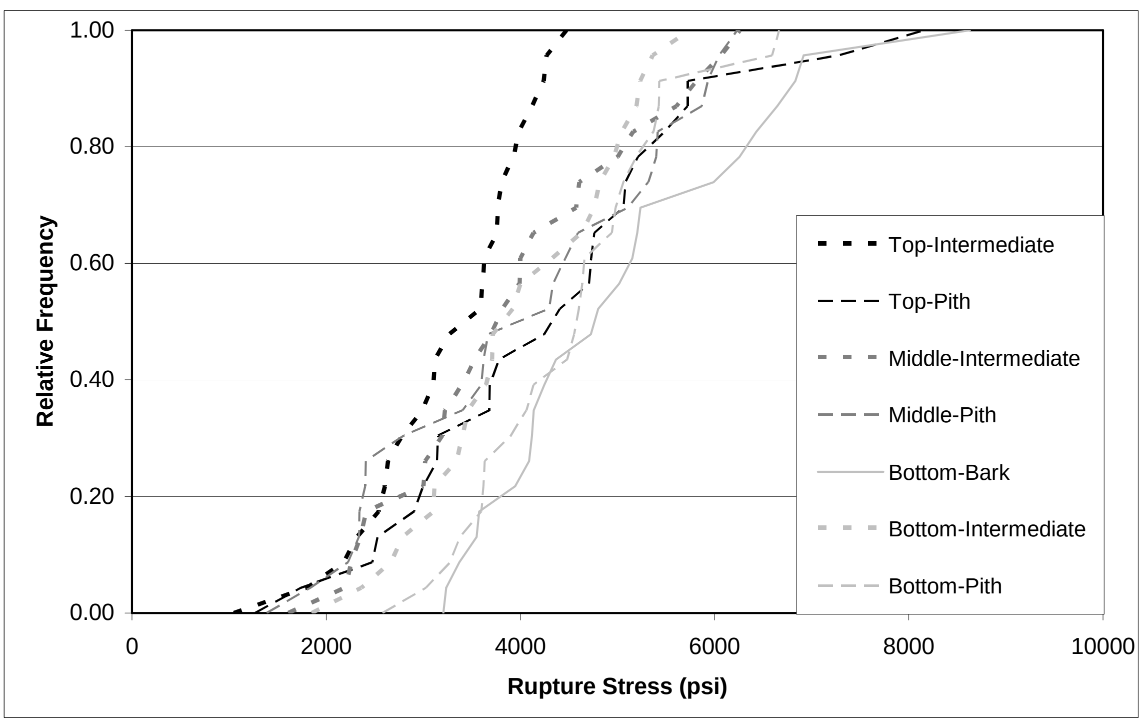

Figure 3.18. Cumulative distributions of western hemlock strand rupture stress based on location.

Table 3.19. K-S p-values for western hemlock strand Young's modulus based on location.

Western Hemlock	Young's Modulus (psi)						
	T-I	T-P	M-I	M-P	B-B	B-I	B-P
Top-Intermediate	1.000	-	-	-	-	-	-
Top-Pith	**0.109**	1.000	-	-	-	-	-
Middle-Intermediate	**0.378**	**0.840**	1.000	-	-	-	-
Middle-Pith	**0.213**	**0.050**	**0.378**	1.000	-	-	-
Bottom-Bark	0.003	0.021	**0.050**	0.021	1.000	-	-
Bottom-Intermediate	**0.604**	**0.378**	**0.378**	**0.378**	**0.050**	1.000	-
Bottom-Pith	**0.840**	**0.050**	**0.109**	**0.109**	0.003	**0.378**	1.000

Table 3.20. K-S p-values for western hemlock strand rupture stress based on location.

Western Hemlock	Rupture Stress (psi)						
	T-I	T-P	M-I	M-P	B-B	B-I	B-P
Top-Intermediate	1.000	-	-	-	-	-	-
Top-Pith	0.008	1.000	-	-	-	-	-
Middle-Intermediate	**0.109**	**0.604**	1.000	-	-	-	-
Middle-Pith	0.008	**0.604**	**0.840**	1.000	-	-	-
Bottom-Bark	0.000	**0.109**	**0.050**	**0.109**	1.000	-	-
Bottom-Intermediate	**0.050**	**0.840**	**0.980**	**0.604**	**0.109**	1.000	-
Bottom-Pith	0.000	**0.378**	**0.213**	**0.213**	**0.604**	**0.378**	1.000

Comparison of Results

Probability density functions were fit to the strand data to describe the property distributions. Chi-squared goodness of fit tests were used to determine how well the normal probability density function described the experimental distribution, while the Kolmogorov-Smirnov goodness of fit test was used for the Weibull probability density function (Table 3.21). Good fit values ($p > 0.05$) are indicated in bold. In two cases, the normal distribution did not fit its respective data well, while the Weibull distribution only failed to accurately represent the Douglas-fir tensile Young's modulus once; however, visual inspection indicated the Weibull distribution was still a better fit.

Table 3.21. Probability density function parameters and p-values of strand specimen properties.

Probability Density Function / Physical Property	Normal			Weibull		
	μ	σ	Chi-Squared p-value	α	β	Kolmogorov-Smirnov p-value
Dougals-Fir						
Tension						
Young's Modulus (psi)	934,410	392,077	0.000	2.461	1,053,743	0.001
Rupture Stress (psi)	4,403	1,555	0.010	2.840	4,920	**0.084**
Poisson's Ratio	1	0	**0.107**	3.284	1	**0.381**
Western Hemlock						
Tension						
Young's Modulus (psi)	874,332	229,936	**0.367**	4.028	960,747	**0.465**
Rupture Stress (psi)	4,108	1,352	**0.863**	3.265	4,579	**0.939**
Poisson's Ratio	0	0	**0.195**	2.626	1	**0.844**

Finally, the strand data was compared with the previously discussed clear specimen properties to establish reduction factors for strand properties with respect to small clear specimen properties. The distributions, shown in Figures 3.19-3.22 represent cumulative distributions of each clear specimen test and the strand tests. Tables 3.22-3.26 contain mean values of strength and modulus and a reduction factor, or ratio of strand values to clear specimen values (reduction factors, shown as S/F, S/T, and S/C represent respective "Strand" modulus or strength value divided by "Flexural", "Tensile", or "Compressive" modulus or strength). The respective tables and figures can be used in combination to estimate how well one property will compare to another and indicate where it is not appropriate use a mean value and reduction factor to calculate a strand property. Table 3.22 contains the mean modulus values and reduction factors for the Douglas-fir clear specimen and strand combinations. While Table 3.22 contains strand reduction factors for flexure, tension, and compression, it is important to consider Figure 3.19 to determine if these reductions are appropriate. Based on Figure 3.19, it is reasonable to assume strand tensile Young's modulus could be approximated using bending modulus of elasticity values with the reduction factor of 0.70, or depending on location of interest, a slightly higher or lower value. Compression values may also be used for strand modulus evaluation; however, the tension cumulative distribution has a significantly lower slope.

Table 3.22. Mean modulus values and associated reduction factors for Douglas-fir strand modulus.

Douglas-Fir	Strand Young's Modulus (psi)	Flexural Modulus of Elasticity (psi)	Tensile Young's Modulus (psi)	Compressive Young's Modulus (psi)	Ratio of S/F	S/T	S/C
Species Average	934,410	1,330,000	1,510,000	1,420,000	0.70	0.62	0.66
By Elevation							
Top	939,977	1,219,800	1,402,100	1,445,600	0.77	0.67	0.65
Middle	1,030,423	1,368,500	1,530,700	1,502,200	0.75	0.67	0.69
Bottom	834,685	1,334,900	1,490,700	1,358,500	0.63	0.56	0.61
By Radial Location							
Pith	863,691	1,188,300	1,345,200	1,262,900	0.73	0.64	0.68
Intermediate	1,066,608	1,413,800	1,569,200	1,578,800	0.75	0.68	0.68
Bark	842,190	1,441,800	1,759,400	1,500,300	0.58	0.48	0.56

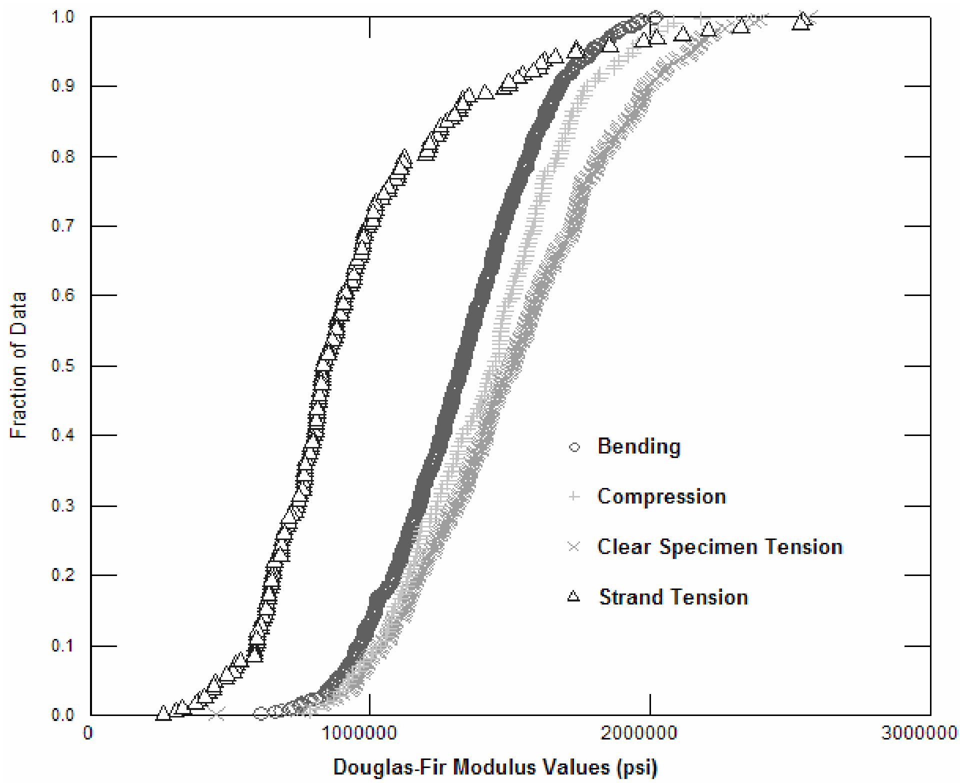

Figure 3.19. Experimental cumulative distributions of Douglas-fir modulus properties.

Figure 3.20 presents experimental cumulative distributions of strength data from small clear specimen and strand testing. In this figure, distribution curves cross each other, creating a condition where use of a reduction factor could drastically over or underestimate properties based on the magnitude of deviation from the mean expected strength; however, ultimate strength in tension and compression may not truly reflect clear specimen strength as many specimens failed at the grips and therefore, outside the gage length. In this case, it is advisable to use bending modulus of rupture reduction factors to estimate strand rupture stress (Table 3.23).

Table 3.23. Mean strength values and associated reduction factors for Douglas-fir strand strength.

Douglas-Fir	Strand Rupture Stress (psi)	Flexural Modulus of Rupture (psi)	Tensile Rupture Stress (psi)	Compressive Rupture Stress (psi)	Ratio of		
					S/F	S/T	S/C
Species Average	4,403	9,570	9,890	4,840	0.46	0.45	0.91
By Elevation							
Top	4,065	8,780	8,700	4,730	0.46	0.47	0.86
Middle	4,240	9,480	9,180	4,966	0.45	0.46	0.85
Bottom	4,790	10,080	10,710	4,940	0.48	0.45	0.97
By Radial Location							
Pith	4,392	9,270	9,160	4,790	0.47	0.48	0.92
Intermediate	4,767	9,630	9,820	5,000	0.50	0.49	0.95
Bark	3,871	9,880	10,530	4,810	0.39	0.37	0.80

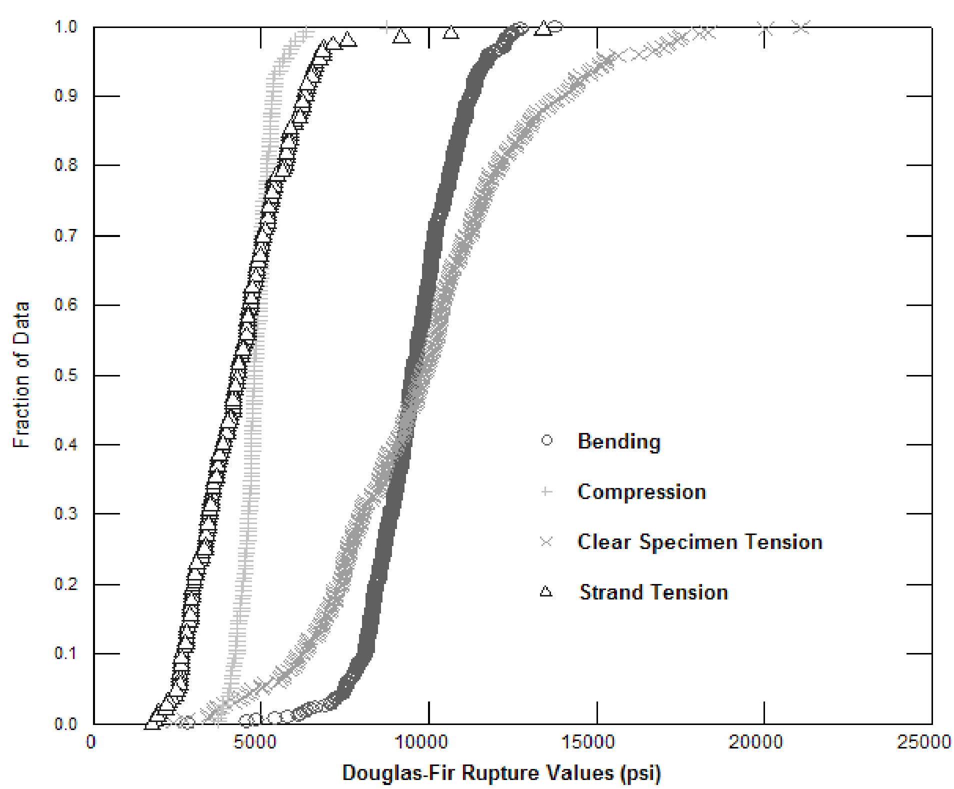

Figure 3.20. Experimental cumulative distributions of Douglas-fir strength properties.

Western hemlock modulus cumulative density distributions did not vary much other than differences in means (Figure 3.21). Therefore, one could reasonably assume any of the reduction factors presented in Table 3.24 can accurately estimate strand modulus.

Table 3.24. Mean modulus values and associated reduction factors for western hemlock strand modulus.

Western Hemlock	Strand Young's Modulus (psi)	Flexural Modulus of Elasticity (psi)	Tensile Young's Modulus (psi)	Compressive Young's Modulus (psi)	Ratio of		
					S/F	S/T	S/C
Species Average	874,332	1,060,000	1,110,000	1,040,000	0.82	0.79	0.84
By Elevation							
Top	913,942	999,600	1,103,700	1,026,200	0.91	0.83	0.89
Middle	901,154	1,085,000	1,136,000	1,099,800	0.83	0.79	0.82
Bottom	830,045	1,084,000	1,060,000	1,043,700	0.77	0.78	0.80
By Radial Location							
Pith	901,220	982,000	1,025,100	977,700	0.92	0.88	0.92
Intermediate	868,522	1,120,400	1,202,300	1,138,800	0.78	0.72	0.76
Bark	811,101	1,234,700	1,007,100	1,163,300	0.66	0.81	0.70

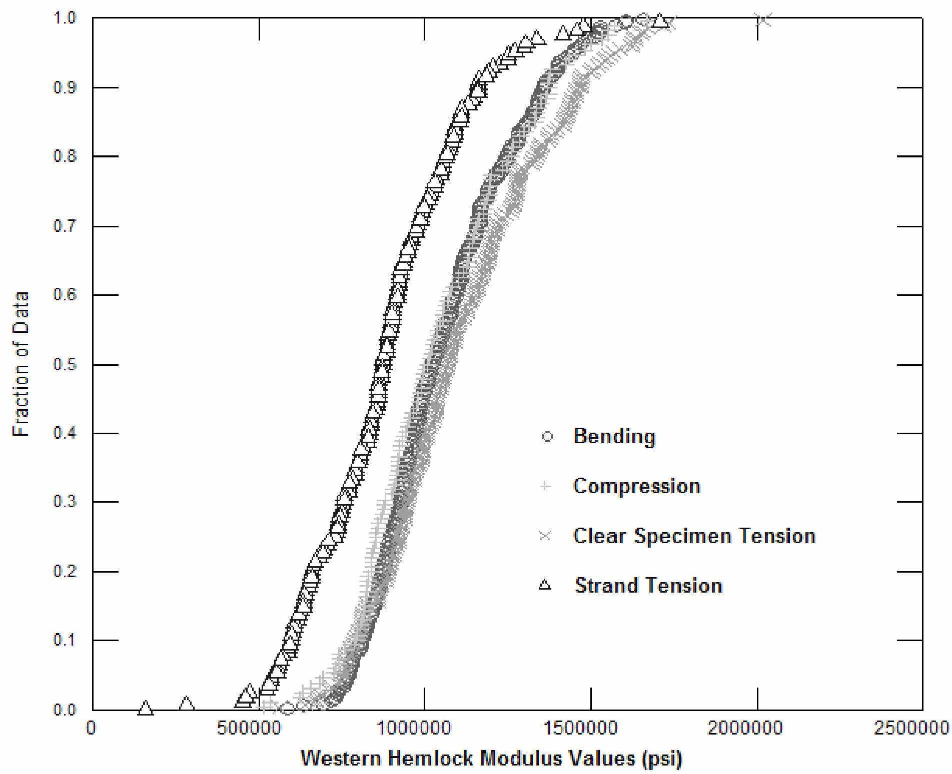

Figure 3.21. Experimental cumulative distributions of western hemlock modulus properties.

Western hemlock cumulative strength curve slopes varied drastically, similar to those of Douglas-fir, most likely because failures were initiated at the grips or outside the gage length. Based on Figure 3.22, it is again advisable only to use bending modulus of rupture reduction factor for estimation of strand strength.

Table 3.25. Mean strength values and associated reduction factors for western hemlock strand strength.

Western Hemlock	Strand Rupture Stress (psi)	Flexural Modulus of Rupture (psi)	Tensile Rupture Stress (psi)	Compressive Rupture Stress (psi)	Ratio of S/F	S/T	S/C
Species Average	4,108	8,500	9,380	4,010	0.48	0.44	1.02
By Elevation							
Top	3,739	7,950	8,600	3,880	0.47	0.43	0.96
Middle	3,916	8,400	9,340	4,020	0.47	0.42	0.97
Bottom	4,481	9,080	9,800	4,210	0.49	0.46	1.06
By Radial Location							
Pith	4,233	8,570	9,430	4,100	0.49	0.45	1.03
Intermediate	3,690	8,420	9,460	4,060	0.44	0.39	0.91
Bark	4,987	9,120	7,780	4,080	0.55	0.64	1.22

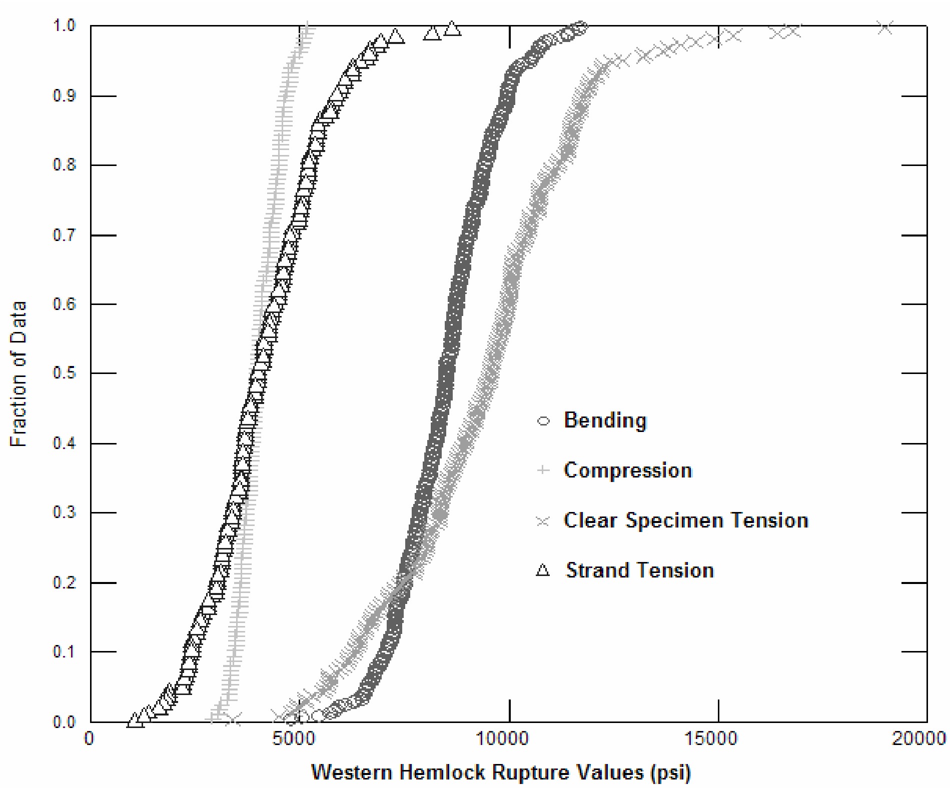

Figure 3.22. Experimental cumulative distributions of western hemlock strength properties.

Conclusions

The main objective of the second portion of this study was to characterize the furnish properties of small diameter, fast grown Douglas-fir and western hemlock critical to the production of engineered wood composites. Ultimately, a better understanding of these properties will lead to a more effective and efficient manufacturing process of strand and particle products. This understanding will lead to new ways in which existing small diameter, stands can be better utilized.

Particle Size Analysis

Sieve analysis of the wood flour created from Douglas-fir did not vary beyond 5% with respect to location or grouping in most cases, with the greatest variation taking place within the percent passing the #20 and #40 size pans. Regardless of grouping by location, the largest overall percentage of material was always retained by the #60 mesh.

Western hemlock also showed little variation with respect to location; however, unlike Douglas-fir, a much larger overall percent of the material was retained by #40 mesh. Also, unlike Douglas-fir which showed an increasing percent retained trend up to the #60 screen, the percent retained of western hemlock material was equivalent in the #40 and #60 screens with significantly lower amounts of material being retained in the remaining screens, including the pan.

pH and Buffering Capacity

Analysis of pH and buffering capacity did not show significant variation with respect to location within the tree when Douglas-fir was considered, with the exception of the innermost lower location. This bottom-pith location was significantly more acidic and required additional base buffer when titrated to a pH of 7.0. When western hemlock was considered, the bottom-pith location again was the most acidic location; however, the magnitude of the difference was much less severe.

Tensile Properties of Strands

As with clear specimen counterparts, the highest strength and modulus values were often located at the mid-height and intermediate diameter. When strength and modulus distributions were evaluated with a two sample Kolmogorov-Smirnov goodness of fit test, little variation occurred with respect to modulus or strength in both species. Although not significant by K-S p-values, modulus actually increased with height in both species (Douglas-fir increased 23%, western hemlock increased 10%).

Reduction factors for strand properties based on small clear specimen properties were estimated. As for modulus, the reduction factors ranged between 0.62-0.70 for Douglas-fir and 0.79-0.84 for western hemlock. When considering reduction in strength, it is recommended to only apply the reduction factor based on bending strength of small clear specimens to obtain strand strength values. These values were 0.46 and 0.48 for Douglas-fir and western hemlock respectively.

Recommendations

Clear trends and little variation with respect to specimen location within the trees were shown when particle size, pH and buffering capacity, and strand strength and modulus were considered. This indicates that while some variation may occur within a tree, outside factors such as location, growing conditions, and processing parameters likely play a much larger role. Due to the small size (diameter and height) of the trees tested in this research, certain constraints existed when preparing test specimens. The variety of tests conducted per location dictated that a larger volume of material was required per location, which limited the number of locations within the trees which could be considered. Ideally, this research will serve as an identifier of properties which require further and more refined research. Test locations which indicated unusual or variable data highlights the need and scope of further, more refined research.

Additionally, vast amounts of past research have shown silvicultural aspects play a vital role in end product quality. Unfortunately, these test results pertain to trees from one location only. To clearly identify species specific properties, further research needs to be conducted in a similar fashion on trees from different locations which are processed in varying manners. Only in this way can species specific trends begin to be noted in a generalized manner.

References

Ahmad, M. 2000. Analysis of calcutta bamboo for structural composites material. Doctoral Dissertation, Virginia Polytechnic Institute and State University. August.

Albert, L., Nemeth, Z.I., Halasz, G., Koloszar, J., Varga, S., and Takacs, L. Radial variation of pH and buffer capacity in the red-heartwooded beech (Fagus silvatica L.) wood. Holz als Roh- und Werkstoff 57.1 (1999):75-76.

ASTM E-11 (2004), "Standard specification for wire cloth and sieves for testing purposes." ASTM International

Beall, F.C. and Eickner, H.W. 1970. Thermal degradation of wood components: A review of the literature. U.S.D.A. Forest Products Laboratory. Research Paper 130. Madison, Wisconsin.

Bodig, J. 1962. Wettability related to gluabilities of five Philippine mahoganies. Forest Products Journal. 12(6):265-270

Bodig, J. and B. A. Jayne. 1982. Mechanics of wood and wood composites. Van Nostrand Reinhold Company, New York, NY

Chow, S.Z. and Pickles, K.J. 1971. Thermal softening and degradation of wood and bark. Wood and Fiber Science: 3(3):166–178

Freeman, H.G. 1959. Relation between physical and chemical properties of wood and adhesion. Forest Products Journal. 9(12):451-458

Freeman, H.G. and Wangaard, F.F. 1960. The effect of the wettability of wood on the Glue-line behavior of two urea resins. Forest Products Journal. 10(6):311-315

Geimer, R.L., Mahoney, R.J., Loehnertz, P.J., and Meyer, R.W. 1985. Influence of processing-induced damage on strength of flakes and flakeboards. USDA Forest Service Research Paper. FPL 463. 15 pp.

Hse, C.Y. 1972. Wettability of souther pine veneer by phenol-formaldehyde wood adhesives. Forest Products Journal. 22(1):51-56

Jahan-Latibari, A. 1982. The response of aspen flakes and flakeboard to flake surface modifications. Ph.D. Dissertation. Washington State University. 135 pp.

Johns, W.E. and Niazi, K.A. 1980. Effect of pH and buffering capacity of wood on the gelation time of urea-formaldehyde resin. Wood and Fiber Science. 12(4):255-263

Jones, R.M. 1999. Mechanics of composite materials. 2nd Edition. Taylor & Francis, Philadelphia, PA.

Kelly, M.W. 1977. Critical literature review of relationships between processing parameters and physical properties of particleboard. USDA Forest Service Research Paper. FPL 10. 65 pp.

Koehler, A. 1955. Guide to determining slope of grain in lumber and veneer. Forest Products Laboratory Report 1585, Madison, WI.

Langum, C.E. 2007. Characterization of Pacific Northwest Softwoods for Wood Composites Production. Masters Thesis. Washington State University.

Mahoney, R.J. 1980. Physical changes in wood particles induced by the particleboard hot-pressing operation. M.S. Thesis. Washington State University. 35pp.

Maloney, T. 1993. Modern particleboard & dry-process fiberboard manufacturing. Second Edition, Miller Freeman, Inc.

Maloney, T. 1970. Resin distribution in layered particleboard. Forest Products Journal. 20(1):45-52

Marra, A.A. 1992. Technology of wood bonding. Van Nostrand Reinhold, New York, NY.

Olson, B.D. 1996. Developing wood composites using small diameter timber resources from dense, stagnant stands. Masters Thesis. Washington State University.

Price, E.W. 1976. Determining tensile properties of sweetgum veneer flakes. Forest Products Journal. 26(10):50-53

Shi, S.Q. and Gardner, D.J. 2001. Dynamic adhesive wettability of wood. Wood and Fiber Science. 33(1):58-68

Stark, N.M. and Berger, M.J. 1997. Effect of particle size on properties of wood-flour reinforced polypropylene composites. The fourth international conference on woodfiber-plastic composites. USDA Forest Products Society.

Wellons, J.D. 1980. Wettability and gluability of Douglas-fir veneer. Forest Products Journal. 30(7):53-55

Wu, Q., Cai, Z., and Lee, J.N. 2005. Tensile and dimensional properties of wood strands made from plantation southern pine lumber. Forest Products Journal. 55(2):87-92

Xing, C., Zhang, S.Y., and Deng, J. 2004. Effect of wood acidity and catalyst on UF resin gel time. Holzforschung. (58)4:408-412

Yadama, V. 2002. Characterization and modeling of oriented strand composites. Ph.D. Dissertation. Washington State University. 193 pp.

Yadama, V. and Wolcott, M.P. 2006. Elastic properties of hot-pressed aspen strands. Wood and Fiber Science. 38(4):742-750

Chapter 4: Conclusions

The goal of this research was to characterize wood from small diameter trees to effectively utilize them in engineered wood composites. This research focused on examining the variation in physical and mechanical properties of small-diameter Douglas-fir and western hemlock from the Olympic Peninsula of Washington State relevant to the production of wood-based composites. Project goals consisted of analyzing density profiles and conducting flexure, tension, and compression tests on clear specimens to determine respective modulus and rupture stress values. Following the analysis of clear specimen properties, wood furnish properties important to modern engineered wood composites were investigated. This furnish was evaluated to identify differences based on location; properties evaluated were wood flour particle size distribution, pH and buffering capacity, and tensile Young's modulus and rupture stress of typical OSB strands.

Results from the density profiles indicated both species consisted of a large overall percentage of juvenile timber. These profiles were utilized to determine zones of possible changes in mechanical properties to which the clear specimens were then tested accordingly. Mechanical testing of clear specimens indicated the highest values of strength and modulus in tension, compression, and flexure could be expected from the bottom or mid-height regions. Although some variation was encountered between species, the general trends remained the same. Statistical analysis indicated most properties decreased with increasing height and proximity to the pith; however, some properties were unaffected by location. These properties include: compressive modulus in western hemlock was found to be unaffected by height within the tree, compressive strength was unaffected by radial location in both species, and tensile Young's modulus was unaffected by height in both species. Additionally, Weibull and normal probability density functions were fit to all distributions for future property estimation.

Particle size distributions of the wood furnish by location indicated very little variation with respect to location in both species; however, western hemlock did produce a greater overall percent of larger particles based on one particular processing technique. Similarly to the particle size distribution, analysis of pH and buffering capacity showed very little variation with respect to location in both species. Douglas-fir however, was considerably more acidic.

Strand testing indicated density and grain angle of the specimen played a much larger role in the quality of the strand than location. Unlike clear specimen tensile properties, when height was considered, little variation with respect to strength or stiffness was encountered. As previous reports have noted, average strength and modulus reductions of up to 50% can be expected when comparing strand properties to clear specimen properties due to processing induced damage.

Through tensile testing of strands and comparison to clear specimen properties, equations and parameters for future strand property modeling were developed. Transformation equations which relate strand modulus to grain angle were estimated for both species. Additionally, Weibull and normal probability density function parameters were determined for strength and modulus properties. Finally, reduction factors for estimation of strand properties with clear specimen properties were calculated.