Mesostructure Elastic Properties in Loblolly Pine[1]

Cramer, S[1], Kretschmann, D[2], Lakes, R[3], Schmidt, T[1]

[1]Dept. of Civil and Environmental Engineering, University of Wisconsin-Madison, Madison, WI 53706
[2]USDA FS Forest Products Laboratory, 1 Gifford Pinchot Drive, Madison, WI 53705
[3]Dept. of Engineering Physics, University of Wisconsin-Madison, Madison, WI 53706

Correspondence to: cramer@engr.wisc.edu

Extended Abstract

An obvious visual feature of wood structure in many coniferous species, and especially pines, is the presence of annual growth rings. The growth rings are not completely uniform in width and often provide a record of weather and climate-based events that had an impact on growth. These events have impacts on the formation of the tapered cylindrical layer of earlywood in the early part of the growing season followed by the formation of the layer of latewood in the latter part of the growing season (Larson 1969). Cell diameter and secondary wall thickness are the main characteristics distinguishing earlywood from latewood. However these two characteristics can be altered independently by different factors. Although there is a general understanding of the difference between earlywood and latewood, there is not a definition of latewood tracheids that satisfies all conditions. Silvaculture practices impact the growth process including the formation of earlywood and latewood. The move to managed tree plantations has generally resulted in wider rings with greater proportions of earlywood, expected outcomes from strategies that include thinning, pruning and fertilization. The earlywood and latewood bands represent the mesostructure of wood. The microstructure is made up of individual cells and the typical macrostructure assumptions ignore the growth rings where wood is assumed to be a homogeneous, orthotropic continuum.

While some consideration of latewood proportion is considered in the grading of wood products, the macrostructure assumption of material homogeneity has been accepted practice in the structural design of wood products for at least 75 years. Common sense and scientific evidence suggest that the mechanical properties of earlywood are significantly different than those of latewood. These mechanical properties have not been extensively studied, the variations in properties have not been determined and the resulting impacts on product performance have not been defined. By measuring these properties and developing a means to predict their values an understanding can be developed on the role they play in wood product quality and performance. The immediate objective of this study was to measure the individual elastic properties of matched earlywood and latewood specimens with the longer range objective to develop a foundation for property predictions and mechanical modeling. Specifically we present new data defining modulus of elasticity values, shear modulus values, related properties and their variations for loblolly pine (Pinus taeda L.) from a tree plantation in Arkansas.

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Several investigators have examined the properties of lobllolly pine earlywood versus those of latewood including MacMillan (1968) examined difference in cell wall sizes. Megraw (1985) established that the specific gravity of loblolly pine latewood to be three times that of earlywood of a given ring and similar findings have been reported by others (Paul (1958) Goggans (1964), Hodge and Purnell (1993)). Biblis (1969) studied the variations in the specific gravity and the modulus of elasticity within the earlywood and latewood zones and found differences in earlywood and latewood moduli as high as a factor of 7. Groom, Shaler and Mott (2002a, 2002b, 2002c) measured the specific gravity and modulus of elasticity of individual earlywood and latewood fibers. Specimens were obtained by macerating samples from a 48-year-old loblolly pine tree harvested from a plantation in Arkansas. They found latewood modulus of elasticity to be approximately 30% higher than that of earlywood.

This study involved sampling loblolly pine (Pinus taeda L.) trees from approximately 80 acres of commercial plantation in Arkansas. The fertilization and pruning history of the plantation were recorded as well as the location and directional orientation of each stem. Two 1.5 m bolts were collected from each stem – one at breast height and the other beginning at approximately 5 m and shipped to the USDA Forest Service Forest Products Laboratory (FPL) in Madison, WI. Specimens were manufactured from the individual earlywood and latewood bands of rings 3, 6, 12 and where possible ring 18. Four specimens were removed from each band corresponding to the north, south, east and west directions of the bolt. These specimens were subject to measurements of longitudinal modulus of elasticity (E_L), shear modulus in the longitudinal-transverse plane ($G_{L\perp}$), specific gravity based on green volume and microfibril angle. Modulus of elasticity and shear modulus were measured three times as part of a comprehensive process to minimize test induced variability. The relative humidity and temperature were monitored and controlled during testing within plus or minus 10% of 50% relative humidity and plus or minus 3 degrees. Because of the influence of height, the data analysis presented was separated by height. Two general height categories were studied. The first was near the base at a height of approximately 0.6 m and will be referred to as lower bolts. The upper bolts had an approximate height of 6 m from the base with one intermediate height of 3.3 m.

Once at FPL, the bolts were cut following a detailed process resulting in small earlywood or latewood specimens (1mm by 1mm by 30mm subsequently stored under controlled environmental conditions. Dimensions of the small specimens were established using an optical stereo microscope at a magnification of 64X. Microfibril angles were measured using x-ray diffraction using methods developed by Kretschmann et al. (1998) and Verrill et al. (2001). A broadband viscoelastic spectroscopy (BVS) instrument, previously developed to study viscoelastic materials, was used to determine the moduli of the specimens (Brodt et al. 1995, Chen and Lakes 1989). This instrument was chosen due to the small dimensions of the specimens and its capability of measuring very small strains, in the range of 10^{-5} to 10^{-7}. In essence, the procedure involved securing the small specimens as cantilevers and inducing deflections.

In the extreme, conifers with a pronounced annual ring mesostructure can be considered to consist of rigid latewood cylinders spaced apart by low density, low stiffness earlywood foam. Mechanically such a structure would resist loads much differently than the assumed homogeneous material. Our test results confirmed the elastic properties of earlywood and latewood to be significantly different. The ratio of latewood E_L to earlywood E_L considering all specimens ranged from approximately 0.8 to 6.5 with an average of 2.3. Because of the biological activities in the tree, wood located at higher portions of the stem had different properties than wood located near the base (lower bolts). In the upper bolts, the ratio of latewood E_L to earlywood E_L was greater (2.7) compared to that in the lower bolts (2.1).

This ratio also increased from an average value of 1.6 in ring 3 to a value of 2.7 in ring 18. Latewood represented 27% of the cross sectional area for rings 3, 6, 12 and 18.

The average earlywood E_L for all specimens was 4.34 GPa. The average E_L for the upper bolts was 5.07 GPa while lower bolts had an average E_L of 3.54 GPa. The average earlywood $G_{L\perp}$ for all specimens was 0.772 GPa with the average for the upper bolts of 0.669 GPa and the average for the lower bolts of 0.862 GPa – opposite the height trend shown for E_L. Relationships between these properties and specific gravity and microfibtril angle were explored.

The average latewood E_L for all specimens was 9.88 GPa. The variability in elastic properties was considerably greater than that for earlywood and additional tests of latewood were conducted to further substantiate trends. The average E_L for the upper bolts was 13.0 GPa while lower bolts had an average E_L of 8.11 GPa. The average latewood $G_{L\perp}$ for all specimens was 1.59 GPa with an average value for the upper bolts of 1.58 GPa and an average $G_{L\perp}$ of 1.67 GPa for the lower bolts.

The data revealed little commonality between earlywood and latewood mechanical properties, even when the specimens were essentially adjacent to each other in the same ring and the same tree. In addition to obviously having different values of elastic mechanical properties, earlywood and latewood properties do not follow similar trends and they do not show relationships with the same parameters. The relationships that do exist in most cases are weak and significant variability persists especially from tree to tree. Moving from macrostructure-scale measurements to mesostructure-scale measurements does not reduce material variability but accentuates it. The variability was not explained by other mechanical factors such as specific gravity although microfibril angle sometimes provided a useful correlation. It is not just low properties that lead to low wood product quality but the inconsistency of properties within a line of wood products or within an individual wood product unit that significantly contributes to low quality and downgrade. Thus anticipating, tracking and controlling property variability is fundamental to producing the highest quality wood products.

Earlywood property variability tended to be low but the material follows few of the anticipated rules in the interrelationship between properties (E vs SG, etc.). Latewood property variability tended to be high and the relationships between other properties were stronger yet the relationships were not sufficiently strong to fully account for the variations. It is proposed the variability in elastic properties is tied to the biological growth process along the line of research presented by Larson (1969). By closely examining biological activity such as branch and crown development, perhaps a linkage to resulting mechanical properties can be established. Such ideas beg further study.

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