New Insights into the Elastic Properties of Wood

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Wood has been used for centuries to make various structures. However, its properties are typically considered on a large scale and assumed to be consistent. This oversimplification can lead to unexpected variations in product performance and less than optimal utilisation of the timber resource. Examination of the intricate structure of pine trees' growth rings formed during the annual growing season provides a chance to determine if wood's properties are as consistent as commonly assumed and, if not, why not. Professor Emeritus Steven Cramer of the University of Wisconsin-Madison has investigated the differences in properties between wood types that comprise the growth rings of loblolly pine trees.

There's More to Growth Rings than Meets the Eye

Humans have long used wood for construction, from support beams in houses and mines to larger structures such as bridges. Unlike modern, human-made materials, which are designed at the smallest of scales (millionths to billionths of a metre) to improve performance and reliability, wood is shaped by natural, biological processes, also at such small scales, but for the purpose of it being and surviving as a tree.

When it comes to the design phase in construction, wood properties are viewed for simplicity on a large scale, with wood being considered homogenous (i.e., the same throughout) and uniform material. This basic assumption does not consider the finer-scale variability of wood properties. As a result, converting a material that has been produced by nature into wooden boards can result in unexpected and undesirable differences in overall board properties such as strength, stiffness and shrinkage. This means it is vital to understand the variability of these finer-scale properties so we can make the most of our wood resources.

A substructure in wood that can be readily observed by the eye without needing specialist equipment is that of growth rings. Growth rings are common structures in coniferous species, notably pines, and represent a tree's annual growth. These rings comprise bands of earlywood and latewood, with earlywood forming during the initial stages of the growing season and being lighter in colour, and latewood forming later in the growing season and producing a darker colour. The width and formation of these bands are directly affected by the growing conditions experienced by a tree, with climate and varying soil conditions resulting in rings that are not uniform and can differ from tree to tree and from year to year in the same tree.

As the demand for sustainable construction products grows in a period of climate change, 'farming' of wood in commercial plantations or forests is set up for quick tree growth and shorter harvest cycles. This fast growth means that growth rings are more widely spaced and have a larger proportion of less dense earlywood than would occur in a slower-growth environment. The resulting wider spacing of growth rings is pushing to the extreme the assumption that wood is a homogenous material on the large scale because the density and mechanical properties of earlywood are significantly different to those of latewood. For example, as fast-grown wood boards shrink nonuniformly along their length more than boards from slow-grown wood, this can have detrimental effects on straightness. Therefore, the performance of wood products can vary in unpredictable ways, negatively affecting the wood product market.

The difference in the properties of earlywood and latewood has not been well investigated. Consequently, the impact these differences have on the behaviour and performance of wood products is not well established. Professor Emeritus Steven Cramer of the University of Wisconsin-Madison, along with his colleagues and students, have conducted a novel investigation into the properties of adjacent earlywood and latewood specimens from loblolly pine trees (Latin: Pinus taeda L.) grown in a commercial plantation in Arkansas, USA. They aimed to create a database of elastic properties of adjacent earlywood and latewood specimens for the loblolly pine as reference values. Additionally, they set out to demonstrate the variability in wood's properties on a fine scale, which has implications for the behaviour of wood products and construction.

Bending and Twisting Wood Specimens

Professor Cramer's research team prepared 338 samples from six loblolly pine trees located across an area of 0.3 km2 in a commercial plantation in Arkansas. Long (1.5 m) rod-like sections were cut from the stems of the loblolly pine trees at heights of approximately 1.2 and 6 m before small blocks comprising both the earlywood and latewood portion of a growth ring were extracted. Blocks were extracted from different growth rings across the width of the tree stem, from near the pith (centre) and towards the outer edge. Once extracted, the blocks were split into earlywood and latewood specimens, which were subsequently sanded down to specimens with dimensions 1 mm x 1 mm x 30 mm – the size of a toothpick.

A micromechanical testing device (broadband viscoelastic spectroscopy device) was then used to determine the elastic properties of the loblolly pine specimens by subjecting the extracted specimens to bending and twisting forces. These bending and twisting forces were created using a magnetic field. The degree to which the specimens strained in response to these forces was measured using a laser. A laser was required to monitor the degree of strain because it was on the order of 10-5 to 10-7 m (0.0001 to 0.0000001 m – very small!).

Big Differences in Elasticity

Using the micromechanical testing device, Professor Cramer's team determined the earlywood and latewood's modulus of elasticity (MOE). The MOE measures how much a material deforms elastically (that is, in a non-permanent way) when subjected to a known force. The average MOE of the earlywood specimens was 4.2 gigapascals (GPa), whereas, for the latewood, it was more than double, at 9.9 GPa.

The MOE in the earlywood remained nearly consistent across the width of the tree's stem, from the pith to the outer edge (i.e., across different growth rings). When comparing specimens taken from various heights in the trees, only a small difference in MOE was observed: specimens higher up the tree had a slightly higher average MOE of 5.1 GPa compared to specimens lower down (3.5 GPa).

A noticeably different pattern, however, was observed in the latewood specimens. Unlike the consistency observed in the earlywood, the MOE of the latewood increased significantly from the pith to the outer edge. When it came to variability with height, the latewood specimens also showed greater MOE higher up the trees compared to sections taken from lower down, with the average MOE of both the lower (8.1 GPa) and upper (9.9 GPa) sections of the trees being much greater than that of the earlywood.

Stiffness Variation Between Earlywood and Latewood

During specimen testing, Professor Cramer's team could also determine specimens' shear modulus: a measure of a given material's stiffness (or rigidity) when subjected to known shearing or twisting forces. The average shear modulus across all earlywood specimens was 0.8 GPa, half the average recorded across all latewood specimens (1.6 GPa).

As was the case for the MOE, the shear modulus of earlywood remained near constant across the width of the trees' stems. The difference in shear modulus of specimens from different heights in the trees was minimal, with the average for the lower sections being 0.9 GPa compared to 0.7 GPa for the higher sections.

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The shear modulus of latewood was more varied across the width of the stem than observed in earlywood, becoming greater from the pith to the outer edge. The latewood's properties again varied with height in the tree. However, the average shear modulus was greater in the lower sections of the tree (1.7 GPa) compared to the higher sections (1.6 GPa) – this was the opposite trend to that observed in the MOE of the latewood.

Wood is Not a Homogenous Material

By investigating the fine-scale elastic properties of earlywood and latewood from a large suite of specimens taken from loblolly pine trees in Arkansas, Professor Cramer and his colleagues demonstrated previously undocumented variability between the wood types, even between adjacent specimens separated by only a few millimetres. While the properties of earlywood were consistent throughout the tree, those of latewood were observed to be much more sensitive to its location in the tree. Individual growth rings often showed as much variability in their elastic properties as was observed across several growth rings covering the width of the tree stem. Overall, big differences in elasticity patterns were observed between earlywood and latewood, confirming that to enable more sophisticated and efficient uses of wood, it should not be viewed as a homogenous material. It is thought that the tree's biological and mechanical responses to the environment cause such great differences in its substructure.

Improving the Performance of Wood Products

Professor Cramer and his colleagues believe that a more thorough understanding of the variation of elastic and other properties at the earlywood and latewood scale can help inform the process of converting natural wood into wood products. Monitoring the variability in these properties and understanding how the biological growth process determines these properties will lead to higher-quality wood products and improved product performance. In the longer term, they aim to develop a means of predicting wood properties, which will assist the construction sector.

MEET THE RESEARCHER

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Professor Emeritus Steven Cramer obtained his Bachelor of Science in Civil and Environmental Engineering from the University of Wisconsin-Madison before obtaining a Master of Science and PhD in Civil Engineering from Colorado State University. Professor Cramer has had a distinguished academic career, which has seen him receive numerous awards for teaching and research, successfully obtaining over $6 million in grant funding, and having three patents to his name. Between 2006 and 2021, Professor Cramer held senior academic positions at the University of Wisconsin-Madison, including Associate Dean and Vice-Provost posts. Professor Cramer's research focuses on construction materials, such as wood and concrete, and the structures they are used in. Notably, he investigates the link between the properties of microstructures in wood and wood's large-scale performance in construction. He uses laboratory-based techniques to evaluate concrete's performance in applications such as pavements.

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FURTHER READING

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