Durability of wood – integration of experimental and numerical approach

If a building is to have a lifetime of fifty years or more, it is important to be able to predict how the construction materials will fare in that timespan. This is particularly challenging for natural materials like wood due to natural differences in the structure. Serena Gambarelli and Josipa Bošnjak at the University of Stuttgart, Germany, employ a hygro-mechanical model that predicts the long-term performance of wood exposed to various environmental conditions. Using an experimental approach they are validating this numerical model to capture the complex behaviour of wood. Their work has deep-rooted relevance for the design of buildings that are truly future-proofed.

Designing buildings for optimised durability is a complicated task. Not only must all of the properties of the isolated material be tested on the laboratory bench, but researchers must also be able to predict how the material will behave in its structural capacity within a building (eg, beam, column, etc). Among other things, scientists and engineers must consider how environmental conditions (temperature and relative humidity) will affect the mechanical properties of the material and the overall performance of the corresponding structural elements.

Some materials, like wood, show significant swelling during wet and humid conditions. This can lead to substantial deformations and cracking, and may compromise the overall serviceability of the building over time. Another relevant environmental factor is temperature variation. Even the toughest of materials, such as metal and stone, can suffer from weathering effects, where hot to cold weather cycles lead to cracking and erosion. Again, these weathering problems, as well as their mutual interaction, affect the internal structure of a material and can result in deterioration of its mechanical properties, particularly over the timescale of decades.

The overall material properties (called the macro-scale properties) of wood – both physical and mechanical – are influenced by the material's behaviour at small scale. Small defects in the microstructure can cause problems in macro-scale properties. Such microstructural defects are either micro-scale (within the micrometer range) or meso-scale (in the millimeter range). For natural materials like wood, there is a great deal of complexity in the material structure at all length scales. Unlike metallic materials such as steel, which are produced under controlled conditions and characterised by a homogeneous crystalline structure (showing the same behaviour in different directions), wood growth is a natural and less controlled process.

Dr Serena Gambarelli and Dr Josipa Bosnjak at the University of Stuttgart, Germany, are employing experimental and numerical methods to investigate the long-term serviceability of complex natural materials such as wood. This means trying to understand the underlying phenomena that affect the hygro-thermo-mechanical material behaviour with respect to material degradation, cracking, and excessive deformation.

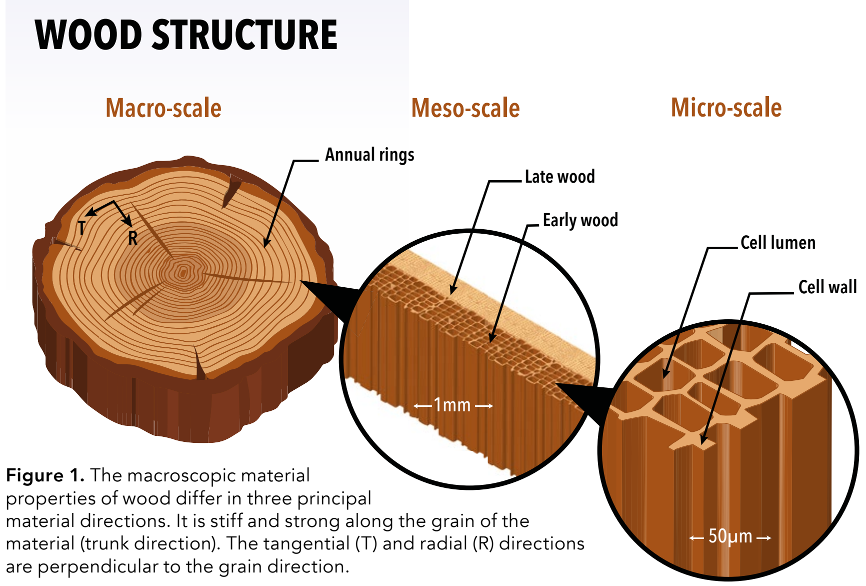

Figure 1. The macroscopic material properties of wood differ in three principal material directions. It is stiff and strong along the grain of the material (trunk direction). The tangential (T) and radial (R) directions are perpendicular to the grain direction.

INTERNAL STRUCTURE OF WOOD

There are countless wood types in the nature. One of the commonly used classifications is that of softwood and hardwood. Hardwood tends to be denser mainly due to its slower growing rate (typically deciduous trees) and exhibits a higher tensile strength than softwood (mostly evergreen). From a sustainability perspective, however, softwood is more attractive. In the framework of the ongoing study, the researchers chose oak and spruce as representatives of these two categories respectively.

The ultimate goal is to provide a basis for the development of durable design methods for timber structures.

Depending on the internal structure of the material, its properties may be constant or vary in different directions. For some materials with crystalline structure, which is symmetrical in all directions, the properties (strength, stiffness) are often independent of the direction of measurement. This is not the case for wood, which is an example of an orthotropic material. For this type of material, macroscopic material properties differ in three principal material directions. Wood tends to be stiff and strong along the grain of the material (trunk direction), which allows the tree to withstand its own weight. The other two relevant directions (tangential and radial) are perpendicular to the grain direction and refer to the orientation of the annual growth rings, namely tangential (T) and radial (R). The annual rings represent the development of the tree trunk over a period of one year and are approximately circular in shape. Macroscopic properties originate from the internal wood structure at meso- and micro-scale. A single year ring is composed of the weaker early wood and stronger late wood (meso-scale). This is due to the different cellular structure at micro-scale. Early wood

Gambarelli and Bošnjak employ a hygro-mechanical model that can predict the long-term performance of wood exposed to various environmental conditions.

consists of wider lumens (transport channels) and thinner cell walls, see figure 1. Hence, its wood is less dense and consequently weaker than the late wood.

It is well-known that wood is strongest in the direction of the grain and most research to date has focused on this aspect because of its relevance for construction: structural elements are always designed to exploit grain direction. On the other hand, the radial and tangential directions have been much less explored. Gambarelli and Bosnjak carefully investigated all three directions of wood, as this is very important for the calibration and validation of the numerical model.

EXPERIMENTAL WORK

The objective of the experiments is to provide a better understanding of the mechanical wood properties as well as the hygro-thermal performance for the two chosen representatives of hardwood (oak) and softwood (spruce). With respect to mechanical behaviour, stiffness, strength, and the full stress–strain response were captured.

The two wood types exhibit a completely different mechanical behaviour under compression, owing to the differences in density and micro-structure. It was further observed that

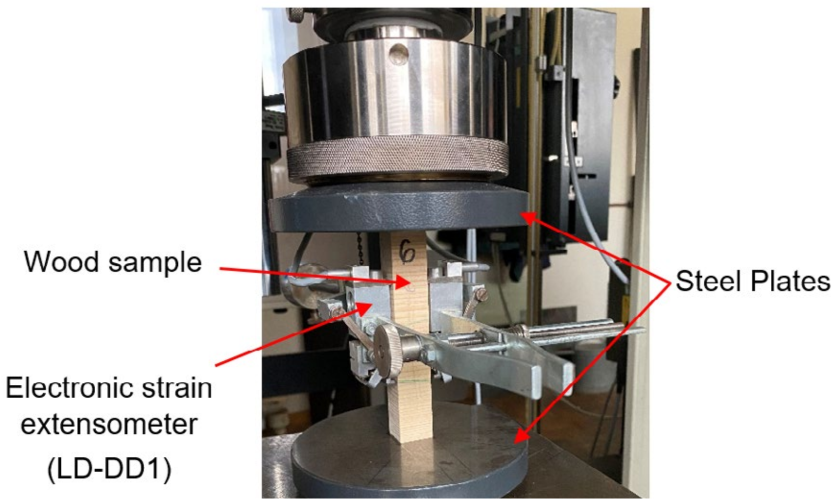

Figure 2. Experimental set-up.

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the two weaker directions (radial and tangential) show a very soft and ductile response as opposed to the quasi-brittle response detected in the grain direction. The researchers are currently investigating the tensile behaviour of the chosen wood types.

One of the most important inputs for the hygro-thermal analysis of wood is the complete sorption curves, which describe the moisture content at different humidity levels. These tests are presently under progress for oak and spruce.

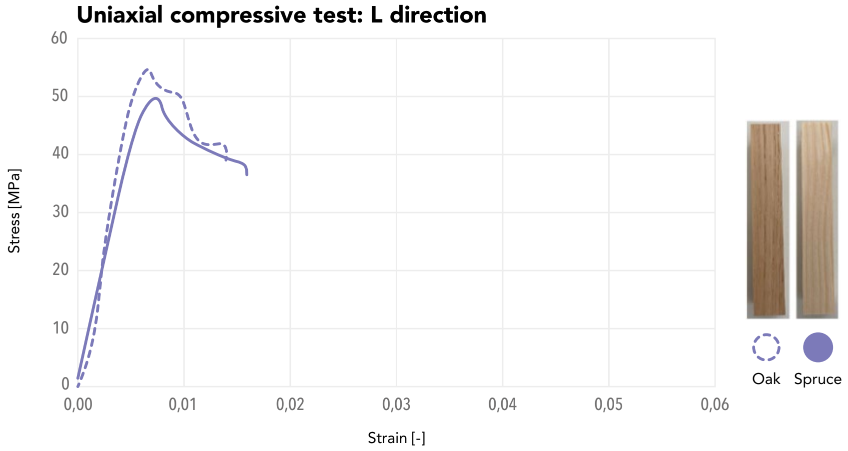
In the next project stage, the obtained data will be input into the numerical model to analyse different hygro-thermal scenarios, also in combination with mechanical load. The most relevant scenarios will also be experimentally simulated, to provide the basis for the validation of the numerical approach. The study will be performed on both natural wood and wooden structural components.

NUMERICAL ANALYSIS

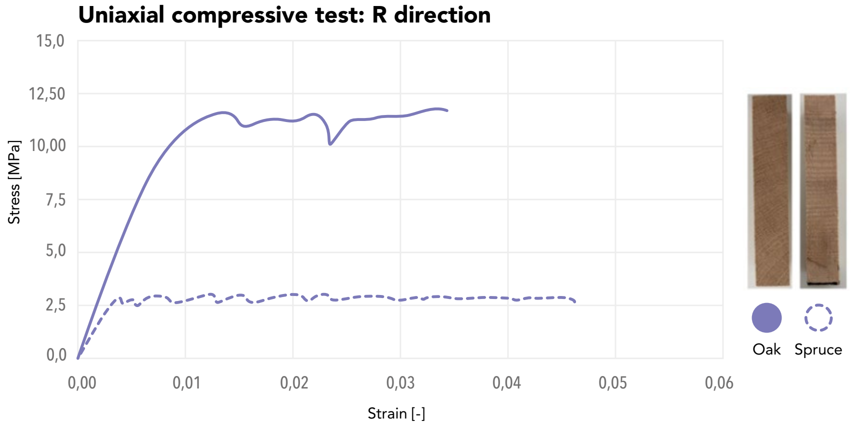
Based on a previous research study, a 3D FE hygro-mechanical model for wood was developed based on the existing hygro- and temperature-dependent microplane model. The numerical framework is integrated into in-house software MASA (MAcroscopic Space Analysis) developed at the University of Stuttgart by Professor Joško Ožbolt's research team.

One of the advantages of the numerical approach is that it is possible to analyse a much greater range of material and load combinations than would be practically feasible in experiments. Having such an advanced and accurate numerical model enables the researchers to predict how wood behaves under coupled mechanical and environmental conditions.

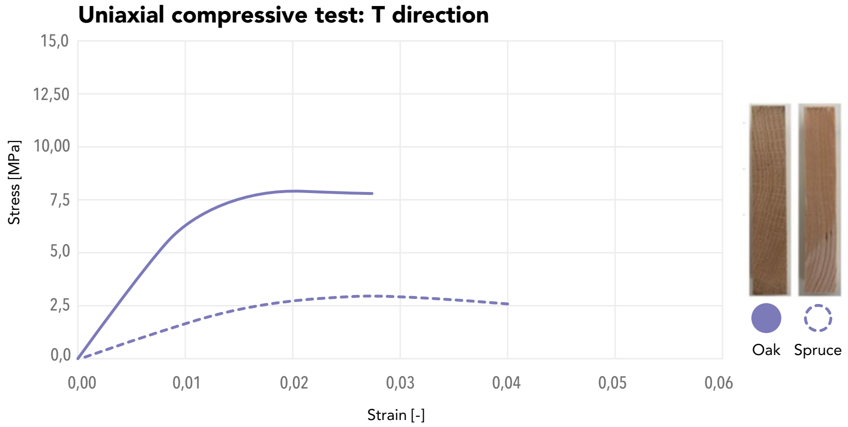
Uniaxial compressive test: L direction



Uniaxial compressive test: R direction



Uniaxial compressive test: T direction

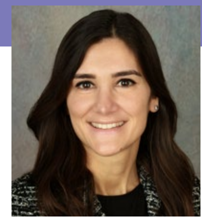


This kind of tool helps to understand the damage processes and can contribute towards the development of better design methods for more durable structures.

The information gathered through Gambarelli and Bosnjak's research is important for future building practices, helping to ensure that buildings can be long-lived without facing failures of the materials involved. Wood represents a challenging engineering material due to its unique and diverse behaviour. Such efforts towards understanding all relevant aspects of material performance may also help us find and exploit other natural materials for their use in construction.

What makes this research challenging is the identification of a reliable link between the material and structural level.

Behind the Research



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Research Objectives

Gambarelli and Bosnjak's research advances our understanding of all relevant aspects of material performance of wood and other important construction materials.

Detail

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Bio

Serena Gambarelli is a senior researcher at the Materials Testing Institute and independent junior research group leader in the Cluster of Excellence IntCDC, University of Stuttgart. She received her PhD from Sapienza, University of Rome. Her research is largely focused on realistic numerical modelling of heterogeneous materials (such as cementitious materials, masonry, wood, etc,) with special focus on micro- and meso-scale analysis of the principal degradation processes induced by different loading types and interactions (corrosion, creep, fire, high temperatures, etc).

Josipa Bošnjak is a senior researcher at the Materials Testing Institute, University of Stuttgart. She earned her PhD from the University of Stuttgart. Her research includes experimental investigation on various building materials (cementitious materials, masonry, etc,) with respect to different degradation processes such as fire, high temperature, corrosion etc.

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References

Gambarelli, S, Ožbolt, J, (2021) 3D hygro-mechanical meso-scale model for wood. *Construction and Building Materials*, 311, 125283. doi.org/10.1016/j.conbuildmat.2021.125283

Personal Response

What further work needs to be carried out for wood to be a long-term sustainable solution in construction?

" It is essential to study new structural solutions with wood composites, which can combine the advantages of hardwood and softwood and minimise their less favourable aspects. Such solutions could, for example, exploit the sustainable nature of softwood and the high performance of hardwood in an optimised manner. A main prerequisite for such developments is a sound understanding of the mechanical, thermal, and hygral performance of wood, with special focus on their mutual interactions. This can be achieved by a combination of experimental and numerical approaches applied to different wood types. "