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Mechanical characterization of wood: An integrative approach ranging from nanoscale to structure

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ABSTRACT

Wood is enjoying increasing popularity in the building sector. In order to fully exploit the potential of this material, particularly in two and three-dimensional structures, improved knowledge of the mechanical behavior of the material and more complex constitutive models are required. We herein present a holistic approach to mechanical material modeling of wood, including a multitude of length scales as well as computational and experimental efforts. This allows to resolve the microstructural origin of the macroscopic material behavior and to finally apply the gained knowledge to structural applications in a timber engineering framework. Focusing on elastoplasticity and viscoelasticity, exemplary results of the performed investigations are presented and their interrelations discussed. Regarding computational approaches, presented developments include multiscale models for prediction of elastic limit states and creep compliances of wood, macroscopic phenomenological models for wood plasticity and the time and moisture-dependent behavior, and their applications to investigations of dowel-joints and glued-laminated timber beams. Accompanying experiments provided additional input data for the computational analyses, therewith completing the set of material properties predicted by the multiscale models. Moreover, they served as the reference basis for model validation at both the material and the structural scale.

1. Introduction

Wood is one of the oldest construction materials known to man. Over thousands of years it has been mainly used in a craft framework, so that current design rules are often based on experience and tradition. In order to exploit the extraordinary ecological potential of this material in terms of making it a mass building material, its structural use also in an industrial framework has to be further enabled and extended. This requires powerful material models. Modern timber constructions are characterized by increasing demand of two and three-dimensional bearing components. Dimensioning and design of such sophisticated structures require powerful material models for numerical simulation tools such as the finite element method. Three-dimensional formulations accounting for the material anisotropy and describing the material beyond linear elasticity are needed, thereby considering for example the possibility of plastic deformations, cracking, and viscoelastic effects.

Moreover, the large variability of the macroscopic material properties has to be understood and suitably described in order to prevent the need for sizable safety factors, resulting in an uneconomic over-dimensioning of timber members in standard applications. Such an understanding and an appropriate resolution of the origin of the macroscopically observed material behavior require consideration of the hierarchical microstructure of the material. The link between microstructural characteristics of individual wood specimens and corresponding macroscopic characteristics can be established by means of homogenization techniques. Multiscale models provide consistent and accurate sets of macroscopic properties of wood in a fully three-dimensional and orthotropic framework. Thus, they are highly valuable for structural simulations, whose predictive and also descriptive capabilities are currently often limited by the lack of suitable input data or the poor accuracy of available data. Also various couplings, e.g. between moisture transport and mechanical behavior, are suitably captured by these models.

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Only a dual approach, combining micromechanical models with powerful numerical algorithms for simulations at structural scale and, thus, spanning all relevant length scales from nanometers to meters, provides the necessary strong basis for modern timber engineering and enables accurate and reliable analysis of wood-based structures and elements. Besides supporting structural analyses and background calculations for standardization, this combination is also expected to contribute to the optimization of production processes such as wood drying. In order to derive a proper understanding of the material behavior, to identify material parameters, and to validate the obtained material models at various length scales, experimental investigations are obligatory and an integral part of each step of the model development.

This paper demonstrates the realization of a holistic approach to material modeling, including a multitude of length scales as well as computational and experimental efforts, taking two characteristic aspects of the mechanical material behavior as examples: elastoplasticity and viscoelasticity, considering also effects upon changing environmental conditions. Table 1 provides an overview of the developments in relation to these two examples and also serves as outline of the paper. Although the presented approaches are applicable to arbitrary wood tissues, the focus is placed on mainly (anatomically simpler) softwood herein for reasons of simplicity and clarity. For elaborate reviews of the state-of-the-art in these fields, we refer to the cited specialized papers by the authors. Particular emphasis is laid on application examples of the developed material models in a timber engineering framework.

First, elastoplasticity will be treated. The material behavior of wood in the small strain regime can be described as being linear-elastic [19]. A high pressure loading will lead to ductile failure [19]. Herein, we briefly discuss microscale processes which might initiate macroscale failure and show the description of an exemplary microscale failure mode in the framework of multiscale models. The resulting estimates of elastic limit states, which are derived from microscale strength properties, serve as the basis for determination of parameters of a macroscopic plasticity model. The formulation of the model and its implementation in a finite element code are sketched next. Finally, its application to the numerical simulation of the mechanical behavior of a steel-to-timber dowel-type connection demonstrates the capability of the simulation tool in a practical engineering context. Experimental validation rests upon a series of tension tests on single dowel connections.

Secondly, the focus is placed on viscoelasticity. As an example of microscale experimental investigations, measurements of the crystal strain in cellulose during creep are presented. A multiscale model is again employed in order to link microscale creep mechanisms to corresponding macroscopic creep compliances. Tests on macroscopic samples provide additional information about influences of changing moisture content on the deformations under continuous mechanical load. The model estimates and test results can be employed for determination of material parameters of a generalized Kelvin-Voigt model, which is well-suited for describing the viscoelastic behavior in the framework of numerical simulations by means of the finite element method. As an example application, the relaxation of production stresses in a glulam beam is examined.

Finally, the paper is summarized and conclusions are drawn. The benefits and advantages of such a comprehensive approach are sketched, but also required improvements in the future are discussed.

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1.1. Hierarchical structure of wood

In order to provide the required basic knowledge for the subsequent (mechanical) explanations, we start with a very brief introduction to wood anatomy (see also Fig. 1 and [16,60]).

Wood is composed of the macromolecules cellulose, hemicellulose, and lignin for the most part. Hemicelluloses and lignin build an amorphous matrix, in which cellulose fibers are embedded. Under wet conditions, also water is incorporated into this polymer network. Cellulose provides stiffness and strength to wood, showing mechanical characteristics closely approaching those of steel. Its fibers show a crystalline core and an amorphous sheeting at dimensions of typically several tens of nanometers in thickness. The resulting fiber-reinforced composite serves as the basic material for building a honeycomb-type cell structure. The cellulose fibers are inclined to the cell axis and wind in the cell wall in a helical fashion. The cells themselves show a hexagonal to rectangular cross-section with typical diameters of 20–80 μm. Different cell dimensions and cell wall thicknesses in different growth regions during a year and, thus, different mass densities, finally result in the growth ring pattern visible to the naked eye.

Altogether, this complex hierarchical structure causes pronounced anisotropy and complexity of the macroscopic material behavior. The mathematical description of the latter as well as further examinations in more detail wherever needed for the mechanical developments are described in the next sections.

2. Modeling elastoplasticity

2.1. Microscale experimental investigations and multiscale modeling

The complex microstructure, where different characteristic structural elements are superimposed to each other at consecutive

Table 1
Overview of developments at different length scales and with different approaches.

	Microscale	Macroscale	Structural scale
Elastoplasticity			
Experimental	Identification of microscale failure mechanisms from various test data	Mechanical tests with different biaxial loading states	Tension tests on dowel-type connections loaded parallel to the grain
Computational	Multiscale model for elastic limit states	Multi-surface plasticity model in a finite element environment	Numerical simulations of elastoplastic behavior of dowel-type connections
Viscoelasticity			
Experimental	Determination of nanoscopic crystal strain during creep by X-ray diffraction	Long-term creep and recovery tests with varying loading histories	–
Computational	Multiscale model for viscoelasticity	Generalized Kelvin–Voigt model in a finite element environment	Numerical simulations of relaxation of production stresses in glulam beam