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Combining Homogenization, Indentation and Bayesian Inference in Estimating the Microfibril Angle of Spruce

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Abstract

It has been shown that the microfibril angle may severely reduce the longitudinal elastic stiffness of wood. The present paper addresses this issue by combining experimental measurements on various scales, homogenization and Bayesian statistical method. To that end, the variation of effective stiffness as a function of microfibril angle is first estimated by combining nanoindentation and homogenization. The results from a series of tensile tests carried out on thin samples of wood containing only a few growth rings are expected to give additional source of information. In the present study both types of data, microscopic as well as macroscopic measurements, are exploited in the framework of Bayesian inference to get improved, posterior, knowledge of the microfibril angle distribution. Owing to a computational demand associated with the Markov chain Monte Carlo method, as the engine of the updating process, the homogenization based on classical micromechanics is adopted.

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1. Introduction

The micromechanical modeling of wood has become a common tool in addressing the influence of various micro-structural features of wood on its effective or macroscopic response. Often, the analytical homogenization [1, 2, 3] based on classical micromechanics models such as the Mori-Tanaka or Self-consistent schemes [4, 5] has been combined with either nanoindentation at the level of cell wall [2, 6, 7] or macroscopic indentation [8, 9] to estimate

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the value of microfibril angle (*MFA*) through the application of a certain inverse approach [2, 7, 10]. This quantity plays a crucial role in providing the overall stiffness and bearing capacity of wood as it may severely reduce its longitudinal stiffness and consequently its strength. It is well known that *MFA* depends on many aspects of wood such as the age, location within the trunk, etc. Thus to avoid a detailed and exhausting analysis of this quantity for a particular piece of wood it is better to accept its random nature. Variability of *MFA* may also be linked to the associated, typically indirect, laboratory determination. Both these two types of uncertainties, aleatory (driven by chance) and epistemic (related to intellectual knowledge), can be taken into account in the application of Bayesian statistical methods [11]. With reference to the elastic properties of wood this approach has successfully been adopted, e.g. in [12] when determining the effective elastic response of glued laminated timber structures.

In the present study we proceed in the footsteps of [12] and formulate a hierarchical Bayesian inference based stochastic model to estimate the variability of *MFA* in spruce. To do so, the results from nanoindentation measurements as well as the results of macroscopic tensile tests performed on thin sheets of spruce are utilized. The link between microstructural features and the macroscopic response is provided through the application of analytical homogenization.

The rest of the paper is organized as follows. Following this introductory part we give in Section 2 a brief account of analytical evaluation of the macroscopic longitudinal Young modulus. The adopted laboratory program will be introduced next in Section 3. Both these sections provide a stepping stone for Bayesian updating presented in Section 4. The achieved results are then summarized in Section 5.

2. Homogenization of wood

Spruce belongs to the class of soft wood typically consisting of hollow 10–30μm wide and 3–7mm long tubes (cells) called tracheids, see Fig. 1a. If zooming in on the cell wall we recognize several sequentially deposited layers building up the wall, Fig. 1b.

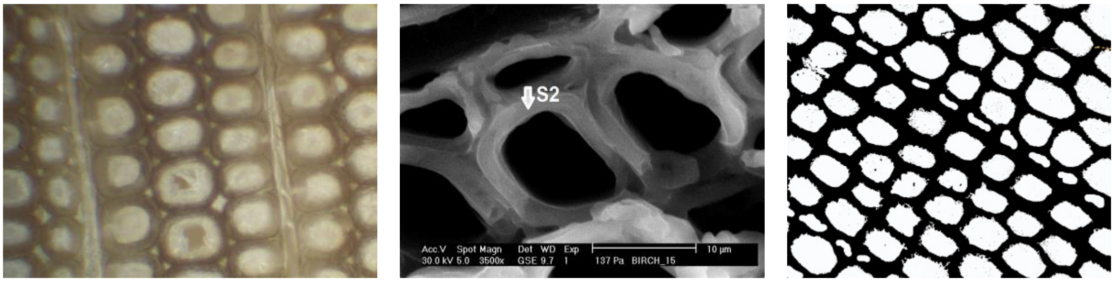

Fig. 1. Microstructure of spruce of: (a) level of tracheids; (b) level of cell wall, (c) binary image.

About 80–90% of the total cell wall thickness is taken by the secondary layer 2 (S2), which is also the major contributor to the mechanical properties of wood. This layer itself is a heterogeneous material composed of amorphous and crystalline cellulose embedded in a matrix of hemicelluloses and lignin. Replacing the heterogeneous S2 layer by an equivalent homogeneous material thus calls for hierarchical homogenization. In the present study this has been achieved with the help of the Mori-Tanaka micromechanical model enhanced by orientation averaging [13] to arrive at the expected transversally isotropic properties of wood at this level of magnification. Here, the resulting longitudinal elastic modulus is already influenced by *MFA*, which represents the inclination of crystalline cellulose from the direction of lumens being the hollow part of tracheids. Due to space limitation, we refer the interested reader to [2, 7, 13] and limit our attention to the distribution of the cell wall longitudinal modulus E_{CW} as a function of *MFA* seen in Fig. 2b.

Since the effective properties of wood also enter the searching process the two additional homogenization steps are needed. The first one involves lumens, the axially aligned cylindrical voids, embedded into transversally isotropic matrix derived from homogenization at the cell wall level. Furthermore, one needs to differentiate between the