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# EFFECTS OF THE CROSS-LINKING OF THE CELLULOSIC FIBRILLAR NETWORK ON THE MACROSCOPIC ELASTIC BEHAVIOUR OF WOOD

Nhat-Tung Phan<sup>1</sup>, François Auslender<sup>1</sup>, Joseph Gril<sup>1,2</sup>, Rostand Moutou Pitti<sup>1,3</sup>

**ABSTRACT:** This study aims at analyzing the influence of the fibrils oscillations and interconnexions on the macroscopic behavior of wood. For that, a multi-scale model of softwood has been developed, with two options for the cell-wall level: a reference with no oscillations (0S) and oscillations and interconnexions in two directions (2S). The cell-wall and tissue steps are made using numerical homogenisation for periodic media, while the succession of earlywood and latewood is dealt with analytically. It is observed that the influence of the fibrils oscillations is significant for some macroscopic moduli such as the effective shear moduli  $\tilde{G}_{LT}$  and  $\tilde{G}_{LR}$  while for other moduli it loses its significance at the macroscopic level, especially for low-density wood. Although the effect of the interconnexions is strong for some components of the elastic behaviour, it loses its significance at the macroscopic level, especially for low-density wood. This can be explained by the interaction of layers from two neighbouring cells that compensate the absence of interaction between fibrils in the 0S model. The effect becomes stronger in the case of a softened matrix.

**KEYWORDS:** macroscopic behaviour, hierarchical models, numerical homogenization, fibrils oscillations.

## 1 INTRODUCTION

Wood is a well-known material in engineering works, from construction material to pulping. The advantages of this material are mainly its availability and its excellent mechanical performance relative to the density, explained by the structural organization of the material [1]. However, the study of wood material has revealed a large variability of mechanical properties and various scales of heterogeneity. Thus, a better understanding of structure-property relationships is required to improve our capacity to design wood-derived products.

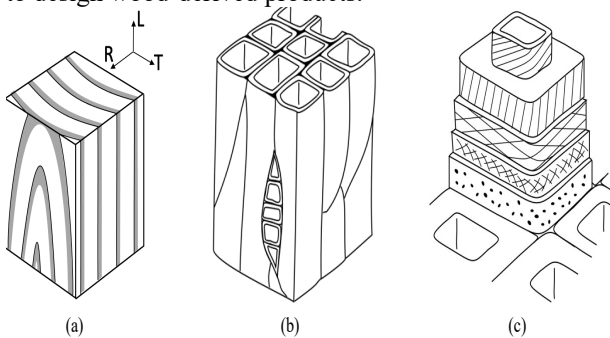


Figure 1: Hierarchical structure and anisotropy of wood

This paper attempts to establish a model (actually a hierarchical set of models) that considers the wood microstructure at three scale levels, from cell walls to annual rings (Figure 1). At each level, different parameters influence the mechanical properties of the next level. The research presented here uses a more realistic description of the wood cell wall at the

microscopic level, which considers that the fibrils are both curved and interconnected instead of the classically straight and parallel fibrils. Hence, we want to analyse the influence of the fibrils oscillations on the effective behaviour at the following levels.

## 2 MULTI-SCALE MODEL

### 2.1 The cell wall level

According to Salmén (2005), the layers of the secondary cell wall can be considered as a reinforced fibre composite where the matrix is a mixture of hemicellulose and lignin, and the fibres correspond to the macrofibrils.

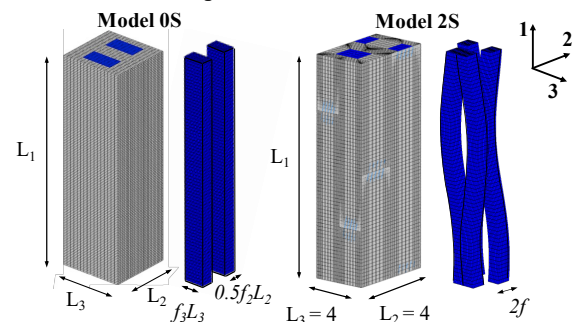


Figure 2: two different morphological models to describe the periodic elementary cell (Cast3M)

Based on experimental observations [3,4], we assume the existence of fibrillar oscillations and interconnections. In the 2S model illustrated in Figure 2, the fibrils can oscillate within both planes (1, 2) and (1, 3). It will be compared to the model 0S with perfectly parallel fibrils.

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The cell-wall material is supposed to be made of the periodic repetition of the elementary unit shown in the figure. Using numerical homogenization techniques with periodic boundary conditions (PBC), we calculate using finite elements (FE) its effective elastic behaviour. The elastic behaviour of the fibrils and the matrix is supposed transversely isotropic and isotropic, respectively, and they are bounded by a perfect interface. Using symmetry arguments related to the geometry of the unit cell and the behavior of the phases, the effective behaviour can be demonstrated to be orthotropic.

## 2.2 Multi-cell tissue level

Earlywood (EW) and latewood (LW) are described as tissues made of periodic arrangement of cells, using typical morphological parameters of softwoods [2] (Figure 3).

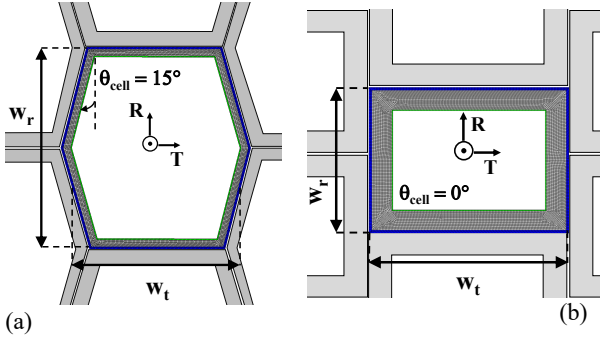


Figure 3: Two microstructures of EW and LW

Each cell wall consists of 3 layers (S1, S2, and S3), incorporating the primary wall and the middle lamella in S1. The effective orthotropic elastic constants of each cell wall, which were differently obtained from the calculations of both models 0S and 2S, are used as input for a FE model at the tissue level.

## 2.3 Wood behaviour

Wood is described as a periodic arrangement of homogeneous EW and LW layers, neglecting ring curvature (Figure. 4). The behaviour in the (L, R, T) directions is calculated using an analytical solution for a plane laminate made of the periodic repetition of two orthotropic elastic layers, whose elastic behaviours are derived by applying both FE homogenization procedures described in Section 2.1 and 2.2

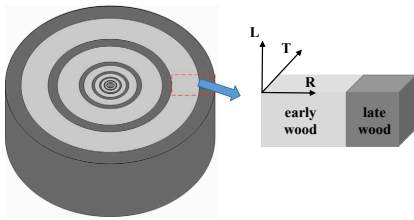


Figure 4: A schematically idealized model for annual-ring

## 3 RESULTS AND DISCUSSION

We reported in Figure 5 the evolution of the coefficient  $\tilde{C}_{66} = \tilde{G}_{12}$  as a function of the fibrils volume fraction. It

can be seen this component is strongly influenced by the effect of fibrils oscillations in the cell wall level in the case of softened matrix.

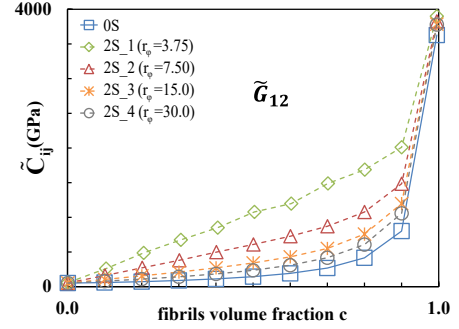


Figure 5: Variations of the effective moduli  $\tilde{C}_{ij}$  as functions of the volume fraction ( $\frac{E_L^F}{E_M} = 1000$ )

Furthermore, for the macroscopic level, Figure 6 shows the macroscopic shear modulus  $\tilde{G}_{LT}$ , which is also influenced by the oscillations and cross-linking of the fibrils as a function of wood density. Experimental data for softwood from [5] are shown for comparison.

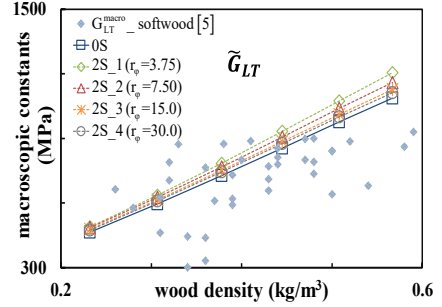


Figure 6: Variations of the effective moduli  $\tilde{G}_{LT}$  as a function of the wood density for different values of the shape ratio  $r_\phi$  (\*)

A similar effect is observed for the component  $\tilde{G}_{13}$  and the shear modulus  $\tilde{G}_{LR}$ , respectively.

(\*) the shape parameter  $r_\phi = L_1/L_2$  5 (Figure 2).

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