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Modelling of the hygroelastic behaviour of normal and compression wood tracheids

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ABSTRACT

Compression wood conifer tracheids show different swelling and stiffness properties than those of usual normal wood, which has a practical function in the living plant: when a conifer shoot is moved from its vertical position, compression wood is formed in the under part of the shoot. The growth rate of the compression wood is faster than in the upper part resulting in a renewed horizontal growth. The actuating and load-carrying function of the compression wood is addressed, on the basis of its special ultrastructure and shape of the tracheids. As a first step, a quantitative model is developed to predict the difference of moisture-induced expansion and axial stiffness between normal wood and compression wood. The model is based on a state space approach using concentric cylinders with anisotropic helical structure for each cell-wall layer, whose hygroelastic properties are in turn determined by a self-consistent concentric cylinder assemblage of the constituent wood polymers. The predicted properties compare well with experimental results found in the literature. Significant differences in both stiffness and hygroexpansion are found for normal and compression wood, primarily due to the large difference in microfibril angle and lignin content. On the basis of these numerical results, some functional arguments for the reason of high microfibril angle, high lignin content and cylindrical structure of compression wood tracheids are supported.

1. Introduction

Plants are able to mechanically actuate their organs by different mechanisms. A striking example is the closure of the Venus flytrap (*Dionaea muscipula*) leaf. When an insect lands into the small trigger hairs, intercellular electrical signals are generated resulting in the trap of the insect in approximately 100 ms (Braam, 2005). Even organs consisting of dead tissues, such as in trees, can be actuated by different mechanism as reviewed by Fratzl et al. (2008). The example of particular interest is here the development of compression wood (CW). When a conifer shoot is moved from its vertical position, CW is formed on the under part of the shoot. The growth rate of the CW is faster than in the upper side resulting in a renewed upward growth (Yamashita et al., 2007). To explain this mechanism, Burgert et al. (2007) have studied the moisture induced deformation of tracheids by use of a saturated sodium iodide solution, which imparts additional swelling of the cell wall beyond the saturation point and observed an opposite deformation upon swelling: normal wood (NW) is shrinking in the longitudinal direction when the moisture content is increasing, whereas CW is elongating. The water influx and efflux in the cell walls was then considered as the driving mechanism for this movement by Fratzl et al. (2008): the water might be used by the tree to correct the growing direction. As a result of these internal stresses, compression wood tracheids are frequently distorted from compression, especially at their tips (Münch, 1940; Wardrop, 1965). The difference in stiffness and moisture-induced swelling for CW and NW is usually regarded as a nuisance when wood is used as an engineering material. Large deformations and stresses leading to fracture can occur in drying of sawn timber where CW is present (Ormarsson et al., 2000). However the difference hygroexpansion has also been used as inspiration for prototypes for moisture-controlled devices when developing biomimetic systems for mechanosensing and actuation (Burgert and Fratzl, 2009; Fratzl and Barth, 2009).

For these reasons it is useful to investigate the relation between cell-wall structure on nanometre and micrometre scale and the tracheid properties to gain increased understanding of the reason of the differences between NW and CW. In this work, an analytical model based on a three-dimensional composite framework is employed to investigate the effect of the difference in composition,

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primary the difference of lignin content, between CW and NW and the effect of the helical structure of wood tracheids, e.g. the microfibril angle (MFA), on hygroelastic properties of the tracheid. The tracheid is regarded as an assembly of coaxial hollow cylinders made of orthotropic material as Neagu and Gamstedt (2007). The hygroelastic response of the assembly due to axisymmetric loading and moisture content changes is obtained by solving the corresponding boundary value problem. This is combined with an analytical ultrastructural homogenisation method (Sutcu, 1992), which is used to determine properties of the cell wall layers from properties of the main wood polymers. The hygroelastic properties of the wood polymers are dependent of the moisture content, which was not the case in previous work (Neagu and Gamstedt, 2007). The difference of chemical composition between NW and CW is taken into account. A review of previous modelling work of ultrastructure–property relationships in wood tracheids has been compiled by Neagu et al. (2006) and Hofstetter and Gamstedt (2009).

The outline of the present paper is as follows. First, a description of the morphology and composition of normal and compression wood tracheids is given. The modelling procedure is then outlined. Finally the results are presented as moisture expansion coefficients under equilibrium conditions and put in relation to experimental findings presented in literature.

2. Morphology of normal and compression wood tracheids

A wood tracheid is generally presented as a hollow layered structure. The different layers illustrated in Fig. 1(b) are designated as (from the outside to the inside of the tracheid): the primary cell wall (P), the outer layer (S1), the middle layer (S2) and the inner layer (S3) of the secondary cell wall. In the wood tissue, the tracheids are surrounded by the middle lamella, which holds the cells together. In the present work, the middle lamella is not considered in the hygroelastic simulations. The adhesive role of the middle lamella is, however, accounted for by constraining rotation, i.e. the no-twist condition. The cylindrical geometry of the tracheids is particularly suitable for severe compression wood (CW) as illustrated in Fig. 2(a) and (b). For normal wood (NW), the outer perimeter of the cross-section of the latewood tracheid is polygonal in the green state, which would induce significant deviations in results from the cylindrical model (Innes, 1995).

The layerwise structure of typical conifer CW and NW is different. CW tracheids have a higher microfibril angle (MFA) in the S2 layer compared with NW (Dinwoodie, 1981). CW contains more lignin and less cellulose in the S2 Layer (Timell, 1986). Wood and Goring (1971) observed that the lignin is more concentrated to the outer portion of the layer S2. A lignin-rich sublayer S2(L) is therefore introduced here. CW lacks an S3 layer (Timell, 1967), and consequently no S3 layer has been accounted in CW model. The influence of the P layer is neglected since it is relatively thin, contains less cellulose and has microfibrils organised in a loose randomly oriented structure in contrast to the well-aligned secondary layer. Furthermore, it is likely that it will be removed during most fibre extraction processes, see e.g. Fernando and Daniel (2004). Table 1 summarizes the composition and morphology of CW and NW tracheids at a moisture content of 12% corresponding to a nominally dry condition for wood. Based on input of the literature, the elastic and hygroexpansion properties of the constrained tracheids (as in the green state in wood) or free individual tracheids was simulated for the coaxial cylindrical geometry as shown in the micrograph in Fig. 2(b) and schematically in Fig. 3.

3. Theory

A wood tracheid is here considered as a long prismatic thick-walled composite tube. The effects due to pits, tapered ends and adjacent ray cells of real tracheids are ignored. Moreover, the MFA is assumed to be constant though the thickness of each layer of the cell wall, i.e. the effects of the transition layers are neglected. Another simplifying assumption is that the moisture content is considered to be independent of residual stresses. It should be noted, however, that for large variations in moisture content, local stresses will develop due to the mismatch in hygroexpansion of the constituents. The corresponding changes in free volume could then affect the local equilibrium moisture content (Neumann and Marom, 1986).

The approach taken here builds on the model of concentric cylinders with helical material axes by Tarn (2002b). Details of the model can be found in Neagu and Gamstedt (2007). The main difference here is that the properties of the wood polymers are considered as a function of the moisture uptake. It should also be underscored the global change of moisture, denoted ΔC in the following, corresponds to the global change of moisture in the whole tracheid, and the hygroexpansion coefficients introduced here are thus expressed as strain in the layer per moisture variation in the cell wall. The local moisture content in each cell-wall layer is experimentally not a tractable parameter since it depends on the local molecular composition, whereas the global moisture content can be directly related to the ambient relative humidity at equilibrium.

3.1. Problem statement

The wood tracheid is modeled as a circular tube composed of n anisotropic layers as shown in Fig. 3. The internal and external radii of the hollow cylinder are noted a and b. The structure is subjected to end loads and surface pressures. Due to symmetry, the

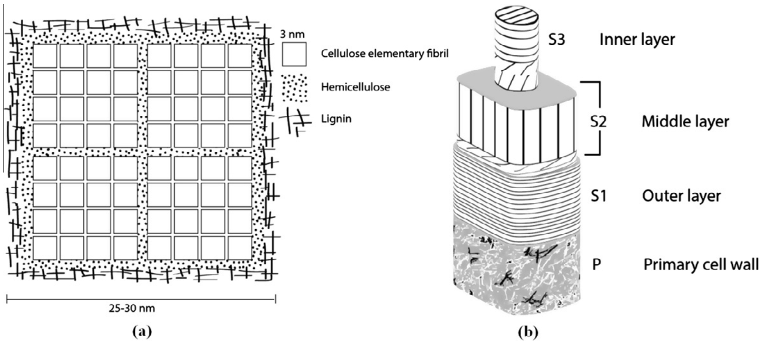

Fig.1. (a) Ultrastructural organisation of cellulose microfibrils, hemicellulose and lignin within the wood cell wall (Fengel, 1969) and (b) schematic illustration of the cell wall of a softwood tracheid with different orientation of cellulose microfibrils in the layers.