An inverse method using X-ray microtomography images and FEM for the identification of the hygroelastic properties of wood fibre wall

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Aims
Wood is an assembly of a variety of more or less slender cells that are generally referred to as wood fibres. The wood fibre wall consists of an assembly of several layers that show differences in their microstructure and chemical composition. The middle layer of the secondary fibre wall (S2 layer) forms the main part of the cell wall and thus controls its mechanical and physical properties. The S2 layer exhibits a complex helical structure containing cellulose microfibrils surrounded by a matrix of lignin or hemicelluloses. Wood fibres constitute the structural element of several engineered materials such as paper, board, and currently developed biocomposites. The use of wood fibres in structural composite materials is nonetheless challenging because of their natural hygroexpansive properties induced by moisture uptake. Micromechanical modelling approaches (e.g. [1]) that aim at describing the fibre hygroexpansive properties and in turn the properties of engineering materials suffer from a lack of accurate experimental data to validate their prediction. By using an inverse method based on the use of X-ray synchrotron microtomography imaging and Finite Element Method analysis, this work thus aims at identifying some of the hygroelastic properties of the complex cellulose-based material forming the S2 cell wall.

Method
The method first relies on the use of X-ray microtomography 3D images of a single wood fibre of Norway spruce taken with an in situ control of the air relative humidity (see Fig. 1). The images were obtained by taking 1500 radiographs (acquisition time of 0.2 s for each) over 180 degrees of the single fibre at each relative humidity step on the beamline ID19 of the ESRF (Grenoble, France). For that the fibre was irradiated by an X-ray monochromatic beam light (energy $E = 17.6$ keV ; $\Delta E/E = 2 \times 10^{-5}$). The transmitted light was converted into visible light using a GGC 6 µm scintillator and recorded using a Frelon Camera (ESRF). The combination of the used optics and of the camera detector size gave a pixel size of 0.35 µm. The 3D images were reconstructed using a filter-back projection algorithm. Such imaging technique was previously proved to be successful to study the hygroscopic behaviour of ligno-cellulosic materials in Viguié et al. [1]. The image obtained in the reference configuration (47%HR) was then used as a support for building a mesh with regular hexahedral finite elements. The meshing technique was adapted to slender hollow tubes such as wood fibres. The core of the method consisted of (i) determining the cross section of the slender object and (ii) detecting the curves that form their inner and outer boundaries (Fig. 2(A)). These operations were followed by constructing layers of nodes from the inner
and outer curves (Fig. 2(B)). The layers of nodes were then connected to form the full mesh that is eventually smoothed (Fig. 2(C)).

**Results**
The as-built mesh was then used for performing FEM calculations accounting for a non-linear anisotropic hygroelastic model of the cell wall (considered here as only composed of the S2 layer). As inputs for the direct FE calculations, microstructure properties such as the main anisotropy direction related to the microfibril angle were supported by measurements in polarized microscopy equipment [3], whereas other mechanical properties were obtained from the literature [1,4]. Therewith, the results of the direct FE simulations of the fibre hygroexpansion were iteratively compared with the 3D microtomography image obtained in the final configuration (80%HR) until the simulated deformed fibre best fitted it: this allowed the hygroexpansion coefficients of the S2 cell-wall layer to be estimated.

![Figure 1](image1.png)
Figure 1: Wood fibre of Norway spruce (HR = 47%). (A) Cross section (B) 3D micrograph. Part length about 280 µm.

![Figure 2](image2.png)
Figure 2: Illustration of the meshing process of a 3D image of wood fibre obtained using X-ray microtomography images as shown in Fig.1. (A) Detection of the inner (in blue) and outer (in green) contours of the fibre cross sections. B) Repartition of the FEM mesh nodes in a fibre cross section. C) Illustration of the complete FEM mesh built from the X-ray image before (left) and after (right) smoothing operation.

**References:**


Table 1: Proportion of root canal volume (coronal, apical and total) occupied by total filling, filling materials and voids after treatment with three different obturation techniques.

<table>
<thead>
<tr>
<th>Percentage (Mean±SD) of the volumes occupied by:</th>
<th>Total filling</th>
<th>Gutta-percha</th>
<th>Sealer</th>
<th>Voids</th>
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<tr>
<td><strong>Coronal part</strong></td>
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<td></td>
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<td>Vertical condensation</td>
<td>96.66±8.48</td>
<td>80.45±10.97</td>
<td>16.21±8.72</td>
<td>3.35±8.48</td>
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<td>Cold lateral condensation</td>
<td>57.83±16.21</td>
<td>33.71±8.72</td>
<td>24.11±10.88</td>
<td>42.17±16.21</td>
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<td>Thermafil</td>
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<td>29.90±18.26</td>
<td>7.92±7.23</td>
<td>62.17±24.31</td>
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<tr>
<td><strong>Apical part</strong></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Vertical condensation</td>
<td>95.92±8.74</td>
<td>78.86±18.46</td>
<td>17.06±12.65</td>
<td>4.08±8.74</td>
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<td>39.09±14.23</td>
<td>29.77±10.40</td>
<td>31.73±19.75</td>
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<td>56.68±16.76</td>
<td>23.31±11.64</td>
<td>20.02±17.12</td>
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<td><strong>Total</strong></td>
<td>96.25±8.31</td>
<td>79.51±12.31</td>
<td>16.73±7.74</td>
<td>3.75±8.31</td>
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<td>41.06±18.60</td>
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*Means with different superscript symbols indicate significant differences (p< 0.05)

References: