3D Experimental Investigation of the Hygro-mechanical Behaviour of Wood at Cellular and Sub-cellular Scale: Detection of Local Deformations

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ABSTRACT

The swelling/shrinkage of spruce wood samples (*Picea Abies*) is documented with high resolution X-Ray Tomography and advanced image analysis tools. We report the reversible moisture-induced global and local deformations at the cellular and sub-cellular scales. In particular, we present sophisticated methods for detecting local deformations in the cell wall. Insight is given on the hygro-mechanical behaviour of wood cell material and on the role of ultra-cellular components in wood, such as bordered pits and rays.

1. INTRODUCTION

Wood is a natural material that grows in wet state but needs to be dried to low moisture content in order to be used as building material. It is well-known that wood when exposed to variations in relative humidity (RH) tends to swell and shrink upon moisture content changes. The hygro-mechanical behaviour at macro-scale is mostly influenced by the global and local deformations occurring at the cellular scale. This work aims to describe experimentally the swelling/shrinkage of spruce wood samples at cellular and sub-cellular scales and to introduce new tools for image analysis.

Experiments at the TOMCAT beamline of the Swiss Light Source, PSI Villigen, and at the Center for X-Ray Tomography of the Ghent University (UGCT), in Belgium, document the three-dimensional, cellular changes of wood samples exposed to a hygroscopic loading. The measurements are complemented with a dynamic vapour sorption analysis on cross-sectional micrometer sized wood samples to provide the sorption curves (moisture content (MC) versus relative humidity (RH)). An affine registration model describes the global swelling/shrinkage behavior of the cellular wood structure, but fails to detect local cellular deformations (Derome et al. 2011). These local deformations are suspected to occur in wood given the presence of singularities, such as the latewood/earlywood interface, rays/tracheid cross-fields and bordered pits, which are the wall cavities linking wood cells to allow water transport. For this reason, we introduce a method to detect and quantify local deformations using a non-affine registration model.

Firstly, we describe the experimental procedure for sample preparation and image acquisition. Then, we introduce an imaging tool for detecting the local deformations in biological materials, and finally, some applications on wood are shown.

2. EXPERIMENTAL PROCEDURE

A brief description of the experimental setup and sample preparation is presented here, more details can be found in Derome et al. (2011) and in Dhondt et al. (2010). The measurements were performed with two different experimental setups: the high-resolution synchrotron radiation phase contrast X-ray

Tomographic Microscope of the TOMCAT beamline at the Swiss Light Source (SLS), PSI, in Switzerland and the X-ray Tomography scanner at the Ghent University at UGCT, in Belgium. In both cases, the wood samples were housed in an environmental chamber located between the X-ray source and the detector, see (Figure 1a). The environmental chamber is in aluminium with two polyimide windows transparent to X-rays. Air flows through inlet and outlet tubes connected to two holes in the chamber side walls, allowing a laminar air flow in the chamber with a speed less than 0.5 cm/s. The conditions of the air are monitored by RH/temperature sensors.
The wood samples were exposed at different RH steps in adsorption and desorption. A typical hygroscopic loading protocol consists of four RH steps in adsorption and desorption, in (Figure 1b). The RH conditions at each step are maintained long enough to ensure moisture equilibrium in the sample, i.e. one hour, as verified by the dynamic vapour sorption (DVS) tests.
The wood specimens were cut with a razor blade to produce thin cross-sectional micrometer-sized wood samples and, then, preconditioned in the DVS machine during two full hygroscopic loops in adsorption and desorption. The samples were fixed vertically to a sample holder using cyanoacrylate glue and then kept in a desiccator in dry or 30%RH conditions until the beginning of the tomographic scan. The resolution achieved with the two experimental setups was: 700 nm for the PSI-setup with 1024x1024x1024 pixels (tangential, radial, longitudinal directions) volumetric datasets acquired in 8 minutes scanning time and 800 nm for the Ghent setup with datasets of 800.8x800.8 μm^2 (tangential and radial, respectively) acquired in 2hr of scanning time. In both cases, the central X-ray photon energy was 20 keV.

(a) (b)

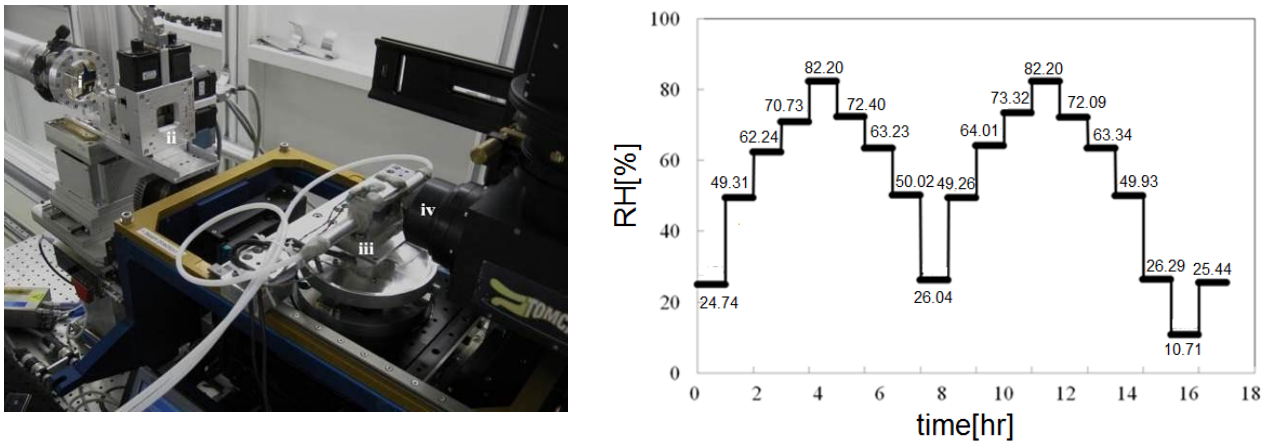

Figure 1: *(a) Photo at Tomcat beamline experimental station, showing (i) end of the X-ray tube (ii) shutter (iii) environmental chamber with the sample inside and the inlet/outlet tubes and (iv) the CCD camera. (b) A typical hygroscopic loading protocol, consisting of two full loops in ad- and desorption: the first one for preconditioning and the second one during the tomographic acquisition.*

3. DATA ANALYSIS: NON-RIGID IMAGE REGISTRATION FOR THE DETECTION OF THE LOCAL DEFORMATIONS IN WOOD

As wood has a low X-ray attenuation coefficient, the tomographic datasets were firstly reconstructed in phase contrast modality (Boone et al., 2009) and then processed with different tools for image analysis. In our previous work, we investigated the affine deformations to quantify the global strains along the three orthotropic directions of wood, i.e. tangential, radial and longitudinal (ε_1, ε_2, ε_3). An affine registration model describes correctly the global swelling/shrinkage behaviour of the wood cell wall but fails to detect the local deformations, see (Figure 2a). For this reason, we propose a method to detect and quantify local deformations in the cell wall using a non-affine registration model. This type of registration employs a Free-Form Deformation (FFD) model based on B-splines (Rueckert et al., 1999). The basic idea of FFD's is to deform an object by manipulating an underlying mesh of control points in order to produce a transformation which allows quantifying the contribution of the local deformations to the global strains. Most of the algorithms presented in literature, such as the one used for this work, are based on the histogram of grey levels. Our idea is to introduce also some morphological operations and use an edge detection procedure (Ding et al., 2000) in the original code, as shown in (Figure 2b), in order to improve the performance of the algorithm in recognizing typical

features in complex biological materials, such as wood.

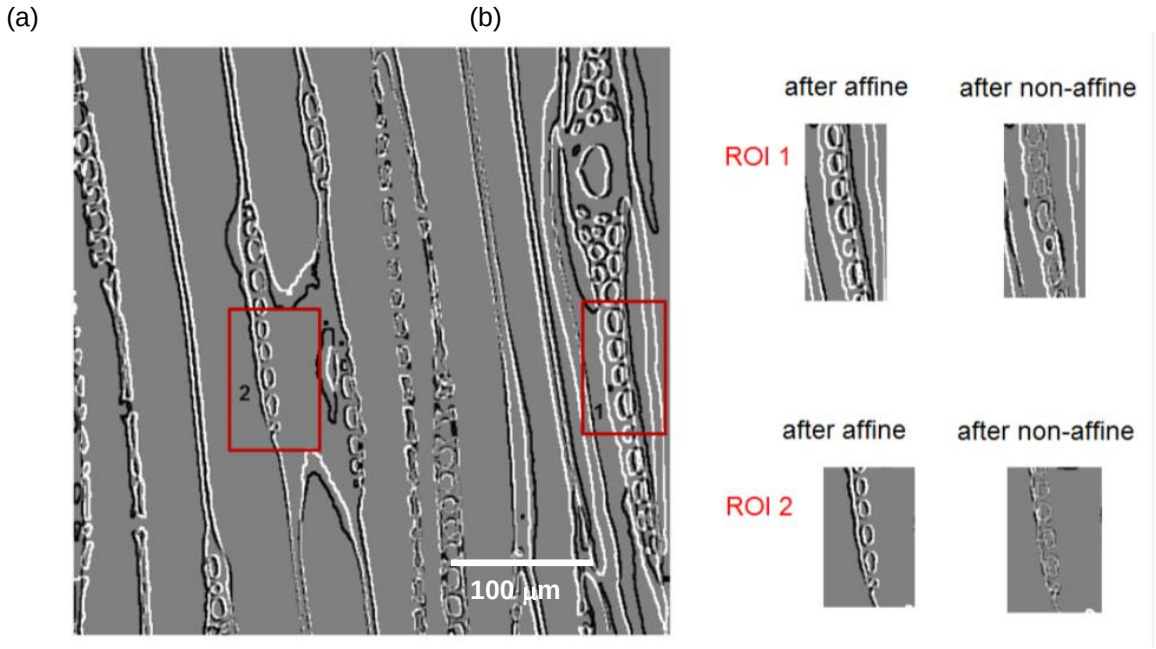

Figure 2: *(a) Difference between reference image (RH=25%, white) and deformed state (RH=85%, black) after affine registration performed on binarized and edged pictures. The local deformation is not captured by affine registration (as shown for two Regions Of Interest), but can be accurately approximated by the non-affine procedure.*

4. RESULTS AND DISCUSSION

The non-affine algorithm allows to calculate the local strains from the gradient of the displacement field, as shown on a sample of combined earlywood and latewood, see (Figure 3). The local strains are considered to significantly contribute to the total deformations of the wood cell wall. In particular, the results suggest that those strains are localized in specific regions, such as close to the rays, at the edges of the thin earlywood cells and at the interface between latewood and earlywood, where latewood seems to control the overall behaviour of a combined sample.

Figure 3: *Comparison between two extremes: quasi-dried state (RH=25%) and wet state (RH=85%), showing: (a) ROI (Region Of Interest) selected for the analysis; (b) the displacement field in a ROI at the boundary between earlywood and latewood and (c) the strain tensors with maximum represented in red colour and minimum in blue, for the same ROI.*

5. CONCLUSION

Analysing the deformations of a complex biological structure, such as wood, by affine and non-affine registration is a powerful tool. We have shown that the hygro-mechanical properties of wood at cellular scale cannot be completely described using global image registration. For this reason, we have introduced a local technique for image registration analysis based on B-splines. The high degree of freedom of the spline functions enables to accurately describe the deformation of complex features on the wood cell wall which strongly contribute to the total behaviour of wood.

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