Hysteretic swelling and shrinkage of latewood and earlywood probed by phase contrast X-ray tomography

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1 Introduction and methodology

Moisture sorption in wood is hysteretic and results in hysteretic swelling and shrinkage. To determine the role of the cellular structure in the volume changes, we investigate the three-dimensional, microscopic, dimensional changes of *Picea abies* (L. Karst) wood samples due to controlled steps of the ambient relative humidity. The study was performed at the wood cellular scale by high resolution synchroton radiation phase-contrast X-ray tomographic microscopy (srPCXTM) at the Tomcat beamline of the Swiss Light Source at Paul Scherrer Institute in Villigen, Switzerland. We study separately latewood and earlywood. The samples are housed in an environmental chamber, as seen in Figure 1a, with controlled air relative humidity. Tomographic images are taken after the samples achieved moisture equilibrium at five adsorption and four desorption steps. More details are found in [1]. Figures b and c illustrate a part of each sample.

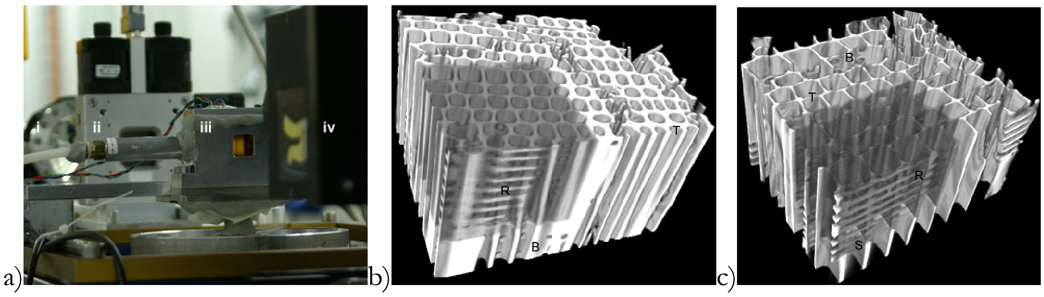

Figure 1 – a) Experimental setup where i-end of evacuated X-ray tube, ii-shutter, iii- sample in environmental chamber with controled the RH, iv-camera; b) 3D rendering of part tomographic data of latewood; c) for earlywood samples.

2 Data analysis

After reconstruction, each tomographic dataset consists of 1024 μCT (microscale computed tomographic) images stacked at one pixel. Each cross-sectional image has 1024 x 1024 pixels. One pixel is 0.7μm. We apply two image analysis methods. Method 1: To determine the swelling/shrinkage strain along the radial, tangential and longitudinal directions between the initial and all the subsequent states, we consider the tomographic images at each pair of states and define the displacement vector field. We assume that the deformation is affine, which is described as the serial combination of a rigid-body (translation plus rotation), shear and scaling deformation. Keeping in mind that, for an affine deformation, the strain tensor components are constant over the domain of interest, after using a minimization procedure, we obtain the principal strains along the tangential, radial and longitudinal directions. Method 2: The cellular morphology of wood may change during swelling/shrinkage. A special case is where the cells shape is invariant, which means the deformed state of the cell structure coincides exactly to its initial state multiplied only by a global scaling factor. This deformation is referred to as homomorphic. Non-homomorphic deformations, which may indicate kinematic incompatibilities in the cellular structure during deformation, are found to play a significant role in the overall mechanical behavior of wood at the mesoscopic and macroscopic scale [2]. To analyze quantitatively to which degree the swelling/shrinkage is homomorphic, a new analysis method consists in performing two registrations: one assuming homomorphic affine deformation and the second assuming full affine deformation. Each image is then segmented and a morphological operator detects the boundaries which are the only pixels retained in the final image. Finally, each registered pair of dataset undergoes a subtraction and differences between the two images are identified in white. The larger the number of white pixels, the worse the performance of the registration processing in aligning the final state image to the initial state one. The number of white pixels thus provides an indirect estimate of the correctness of the initial hypothesis regarding the chosen deformation model, homomorphic or full affine. Figure 2 explains schematically the different steps of the two methods.

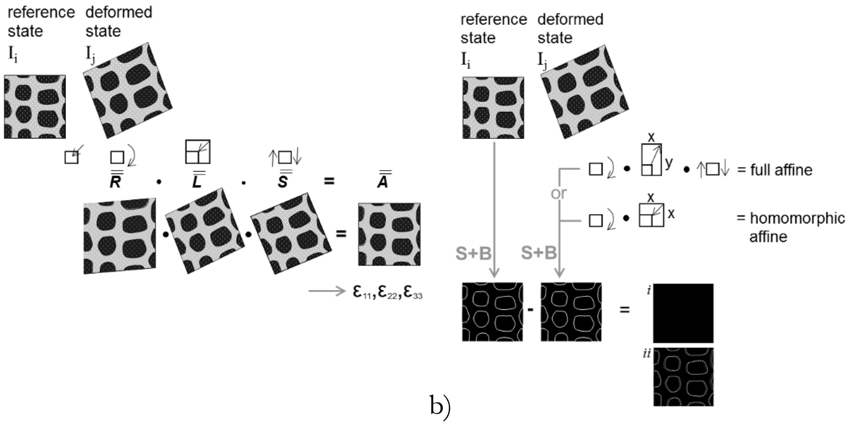

Figure 2 – Schematic representation of the image analysis procedures: a)determination of the principal swelling/shrinkage strains ε_{11}, ε_{22} and ε_{33} by applying affine transformation with the $\overline{\overline{R}}$ (rotation), $\overline{\overline{L}}$ (scaling) and $\overline{\overline{S}}$ (shear) matrices; b) evaluation of degree of homomorphism of the swelling/shrinkage by subtraction of images after full affine transformation (with shear and anisotropic scaling) and homomorphic affine transformation (no shear and isotropic scaling, *i* homomorphic, *ii* non homomorphic cases.

3 Results

Figure 3 shows the strains in tangential and radial directions measured separated on latewood and earlzwood. Figure 4 shows the results where, the total number of white pixels is slightly larger for the homomorphic case than for the full affine case, by a factor of 1.3 for latewood and much larger by a factor of 1.7 for earlywood. For spruce latewood, swelling and shrinkage are found to be larger, more hysteretic and more homomorphic than for earlywood. Furthermore, while latewood undergoes similar strains in the transverse directions, earlywood radial strains are less than a third of the tangential strains. The less homomorphic and smaller swelling/shrinkage of earlywood in radial direction is found to be caused by the presence of rays.

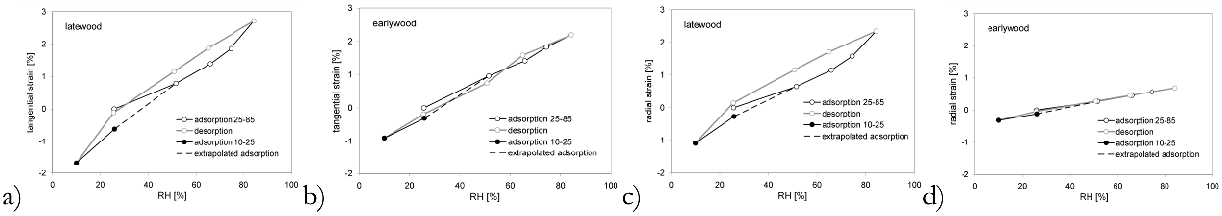

Figure 3 – Strain vs RH for subROI in tangential direction for (a) latewood and (b) earlywood, and in radial direction for (c) latewood and (d) earlywood

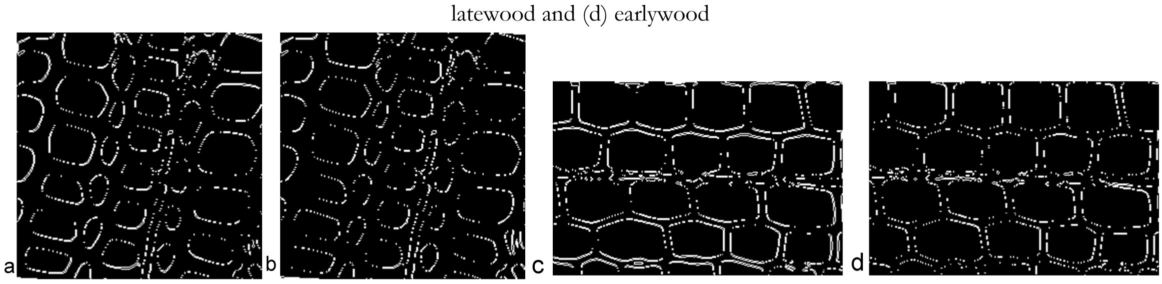

Figure 4 – Results of two different morphological analysis: cases (a) and (c), affine registration with no shear and isotropic scaling (homomorphism); cases (b) and (d), affine registration with shear and anisotropic scaling, not preserving the cellular shape. The white pixels indicate where the affine registration of the final state fails to match the cell boundary location of the initial state.

These observations give strong evidence of an important restraining of free swelling of wood due to the presence of rays in the radial direction. The effect of rays on reducing the radial strain is found to be quite less pronounced in latewood. The reduced effect of rays in latewood may be explained by the higher stiffness of latewood due to its thicker and denser structure. The more pronounced restraining action of rays in earlywood also helps to explain the less homomorphic deformation pattern observed in earlywood.

References

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