A GEOMETRICAL MODEL OF SOFTWOOD ANATOMY FOR FLUID MECHANICS SIMULATIONS.

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SUMMARY

This paper demonstrates a model of softwood geometry that can be used for multiscale modelling of the longitudinal movement of water through spruce wood. Previous results obtained from a high resolution X-ray CT scan and subsequent image analysis of a large number of Norway spruce tracheids were here used to produce a model that can represent the variability in wood anatomy found within a timber joist or log. A demonstration of that model is given.

KEYWORDS: (Wood anatomy, Simulation, Pits, Spruce, Fluid mechanics)

INTRODUCTION

In order to model the longitudinal movement of water through softwood (discussed in an accompanying paper) during the processes of sorption and desorption, a geometrical model of wood microstructure is required. That model should be capable of describing the variability that occurs naturally within wood, rather than an idealised structure, so that realistic behaviour can be expected.

For the purposes of longitudinal movement of water in spruce wood, we consider that only the tracheids are important; this paper is not concerned with other cell types such as radial parenchyma. Tracheids are variable by nature. As is common throughout nature their anatomies are an expression of an interaction between genotype and environment. They are formed by the tree for the dual purposes of water transport and structural support and their size and shape can be traced to the particular requirements of a tree at a particular time during its growth. One of the largest sources of variability in tracheid anatomy in temperate softwood takes place during the growing season (Sirvio & Karenlampi, 2000; Eder *et al.*, 2008; Derome *et al.*, 2012) and is responsible for the growth rings that are visible to the naked eye. In general, earlywood, often called spring wood, is produced during the period where the tree is actively growing above ground and serves the purpose of providing transportation of water from the root to the shoots. Earlywood tracheids are therefore large in diameter and thin walled. During the period of root extension, the tree produces latewood, sometimes called summer wood. The water requirements of the above ground tree have diminished in this part of the growing season, thus latewood is geared more towards providing structural support. Consequentially latewood tracheids are small in diameter and thick walled. While there are other sources of variation in tracheid anatomy, this seasonal variation can be considered as relatively the largest (Sirvio & Karenlampi, 2000) and consequentially the most important source of variation. This is especially true when the aim is to model wood at the macro scale, such as in logs or timber joists for example. Therefore a model of wood geometry should be capable in the first instance of describing the variation within and between earlywood and latewood. Moreover the model should be constructed in such a way that the mean values and / or distributions can be changed to account for variations that could occur due to genetic differences between trees (*e.g.* Hannrup *et al.*, 2004), differences in growing environments and age of the tree amongst others (*e.g.* Park & Spiecker, 2005). Therefore, in order to be extrapolated to wider case studies a model ultimately needs to be capable of accepting parameters that describe distributions around different mean values. Such a model can therefore be considered as statistical.

There are many studies of the variation of the relevant spruce tracheid dimensions, including diameters of bordered pits, present in the literature that has been extensively reviewed by Brändström (Brändström, 2001), although the majority of studies describe the mean rather than the variance. In addition to the parameters relating to component size, we also required information on the location and quantity of bordered pits. Further, we required to consider the longitudinal overlap between tracheids so that our model could realistically describe the amount of water pathways connecting neighbouring tracheids. In this aspect we were unable to find such information in the literature. For all of these reasons we required to make measurements of all of these variables on a large number of tracheids. The only viable way of doing this was high resolution X-ray CT scanning (Van den Bulcke *et al.*, 2009; Dierick *et al.*, 2014) and image analysis. We measured a large number of earlywood and latewood tracheids and produced mathematical functions that describe the variation (Adey-Johnson *et al.* in preparation).

The aim of this paper is to present an example of a statistical model of softwood anatomy that can be used for the purposes of modelling the longitudinal movement of water through wood. This model draws on our experimental work currently being considered for peer reviewed publication and presents a demonstration of our model. The results presented in this written overview are simplified in order that the full version may be reserved for peer reviewed publication.

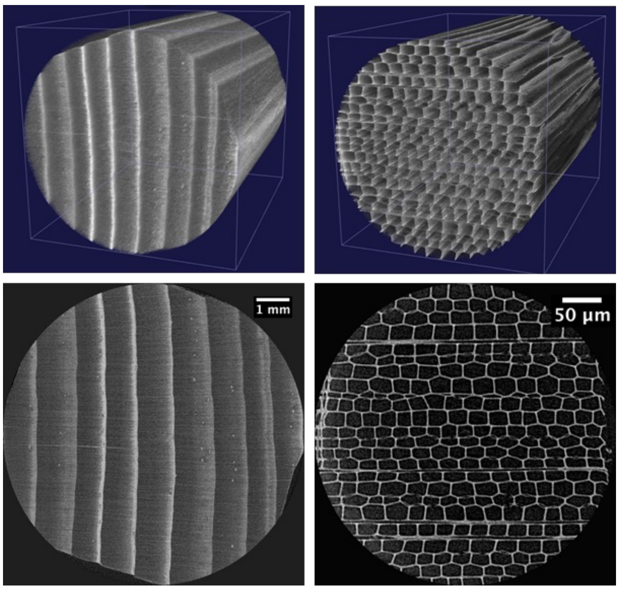

Figure 1. Top: X-ray CT produced 3D volumes of Norway spruce at the macro scale (left hand side) and micro scale (right hand side). The bottom images are slices in which anatomical characteristics can be quantified.

RESULTS

X-ray CT scans of Norway spruce are shown in Fig. 1 at the macro and micro scale. By zooming into these images it is possible to resolve bordered pits as well as all of the necessary anatomical features (Fig. 2).

Distributions of some of the parameters of interest are graphed for a 25 % subset of the measured tracheids (Fig. 3). We have previously used mathematical formulae to model the distribution. During the process of image analysis we also collected {*x,y,z*} coordinates for all of the features of interest to serve as a true to life "control". For reasons relating to our findings, that we will discuss during the presentation, we only required our model to function in two dimensions for our purposes. The statistical information from our earlier study was used to build a (2D) cell microstructural model that replicates the tangential plane of wood. Cells are rendered as irregular hexagons with six straight sides founded on two long parallel sides, which are not necessarily of the same length, and a central top and bottom apex. An example of the graphical model output is shown in Fig. 4 and at a higher magnification in Fig. 5 to demonstrate bordered pits. Essentially a different value is assigned to nodes that represent tracheid walls, bordered pits and tracheid lumina. Empty space outside of the domain is assigned an "outside domain" value. The model uses probabilities based on observations in assigning these values. These probabilities are altered sensibly based on neighbouring nodes. For instance, pits cannot be too close together, lumina cannot be too narrow, tracheids will be within a certain length range *etc*. Consequentially a model representing a variable wood structure, rather than a homogenous idealised structure is produced. Multiple random models were generated and statistically analysed to ensure that they are consistent with each other and with the control.

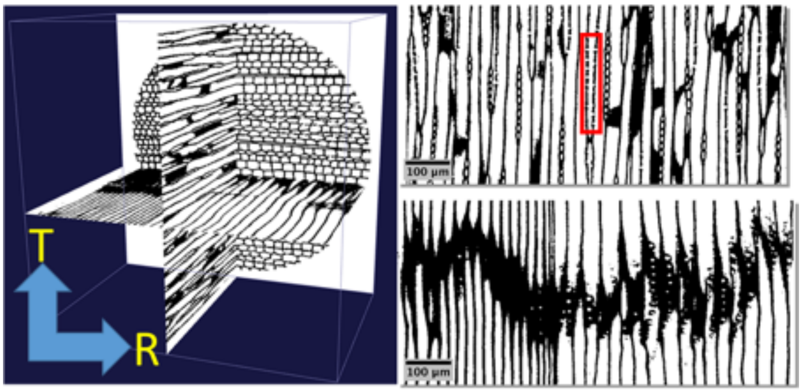

Figure 2. By examining slices from the binarised X-ray CT scans in different wood planes it is possible to observe and measure the fluid pathways. In the tangential or T plane (top right), it is possible to see the bordered pits between neighbouring tracheids. It is also possible to observe and record trends in the start and end points of tracheids in each plane. Our model is based on such measurements.

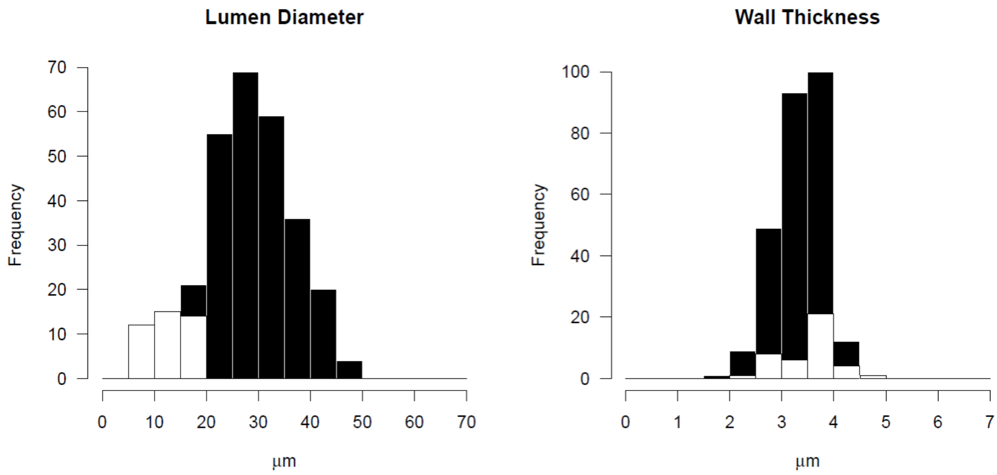

Figure 3. Examples of the distribution of some measurements of anatomical properties we used to model distributions. This is a random sample of ~20% the full data set. Here n = 305, the full data set comprises ~1525 tracheids. Earlywood is shown in black and latewood is white.

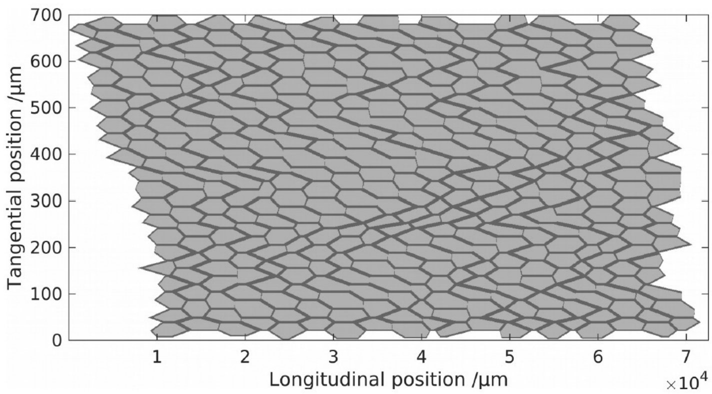

Figure 4. An example of the model output of 400 tracheids. The longitudinal dimension runs from left to right. White is empty space outside of the domain, light grey are tracheid lumina and dark grey are cell walls. Note the axes are not of the same scale, so tracheids appear squashed along their length, and pits are not visible at this scale.

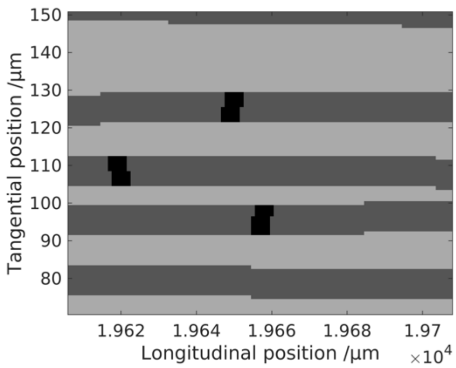

Figure 5. A magnification of a region of Fig. 4 showing bordered pits in black. The axes are now at the same scale.

DISCUSSION

Softwood is a cellular material that serves the dual purposes of providing structural strength and water conduction pathways in trees. As a biological material it has a variable rather than a regular cellular structure. Micromechanical or fluid dynamics models of softwood at the cellular scale need to incorporate this variability in order to perform realistically. With that research purpose in mind, we have created a geometrical model of softwood.

Specifically, we have developed an algorithm to create a non-repeating, two-dimensional, digital mask of spruce at the tracheid scale of any desired dimensions as a matrix material for the testing of micromechanical or fluid dynamics models of wood. We have sought to describe accurately the biological variability by basing the model on statistical properties of a real specimen and to include bordered pits. Further our model allows us to assign an identification and location to each pit within our Cartesian space, this will permit the individual opening and closing of pits should certain criteria (such as pressure) be met within a fluid simulation. In the future we intend to publish the full study and make the model openly available in open source code so that others can insert their own parameters for specific studies. Further work could consider an extension into three dimensions.

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