Modelling the influence of 3D plant fibres morphology on their tensile behaviour

Alessandra Del Masto, Frédérique Trivaudey, Vincent Placet*

Department of Applied Mechanics, FEMTO-ST Institute, UMR CNRS 6174,University of Franche-Comté, F-25000 Besançon, France

* Corresponding author: Email: vincent.placet@univ-fcomte.fr, tel: +33 (0)3 81 66 60 55 - fax: +33 (0)3 81 66 67 00

Natural fibres derived from annual plants are attractive candidates to reinforce organic matrix in high performance composite applications. This use requires an accurate understanding of their mechanical behaviour and the development of efficient models.

Experimental observations clearly showed that most of plant fibres are characterized by an intricate structure, morphology and organisation which make their characterization more complex than for solid circular man-made fibres (*1*). Their geometry depends in particular on their growing, harvesting and processing conditions and might exhibit large dispersions. Researches in our team are mainly focused on hemp, flax and alfa fibres. Such fibres have a typical cell plant structure, with a lumen and a particularly thick wall. They have generally a complex rounded polygonal outer shape which is irregular and non-uniform along length of the fibre and also varies from one fibre to another (*1-4*). The central cavity can be narrow, round or elliptical, with a diameter depending of the plant maturity.
When compared to purely cylindrical geometry, it is possible that such geometrical features could induce effects on the fibre mechanical behaviour including stress concentration, fibre rotation and non-linearity in the tensile response. The randomness in plant fibre shape and associated behaviour can also finally have a significant impact on the mechanical properties and behaviour of their composites, and more exactly on the variability of their mechanical behaviour.

Most of the current mechanical models of plant fibres consider the fibre as a thick-walled cylinder made of an isotropic elastic material (*5-7*). Non circular cross-section (i.e. non-unicity transverse aspect ratios) and the possible variation of the cross-section along the fibre length are generally not addressed in the actual models. So, the aim of this study is to model and investigate the influence of much more complex geometries on the tensile behaviour of plant fibres. The macroscopic 3D model used in this study is based on a previously developed model, described in detail in (*8*, *9*). The fibre wall is considered as an orthotropic material having a helical orientation (corresponding to the cellulose microfibrils) with a viscoelastic constitutive law describing finite transformations through a material rotating frame formulation. The possible variations in cellulose microfibrils orientation along the fibre length (and in particular in dislocation areas) are also taking into account.

In this study, we propose to investigate in particular the influence of the degree of ellipticity of the fibre section and its variation along the fibre length on its tensile behaviour. These fibre geometries does not fit the real ones but are more complex that the classical cylinder which is generally considered. It is a first step before modelling real 3D shapes of fibres. The determination of the 3D shape of the plant fibres still remains a real challenge from an experimental point of view. The difficulty comes from the size and fragility of elementary fibres making preparation and handling challenging. Promising results have been recently obtained in our team on hemp fibres using FIB (Focused Ion Beam) tomography and Optical Coherence Tomography (OCT) (*2*) and also by Joffre (*10*) on wood fibres using X-ray microtomography.

The FE Abaqus® code is used is used to represent the model. Fig. 1 shows several geometries which were modelled in this work. Fig. 2 proposes some numerical results. The stress-strain responses of the fibre when tensile tested are plotted as a function of the ellipticity ratio (for different values comprised between 1 and 0.1). Results clearly show the strong influence of the fibre geometry on its tensile response and particularly in the non-linearity of the response. Geometric issues could explain the different types of tensile behaviour experimentally observed (*11*).

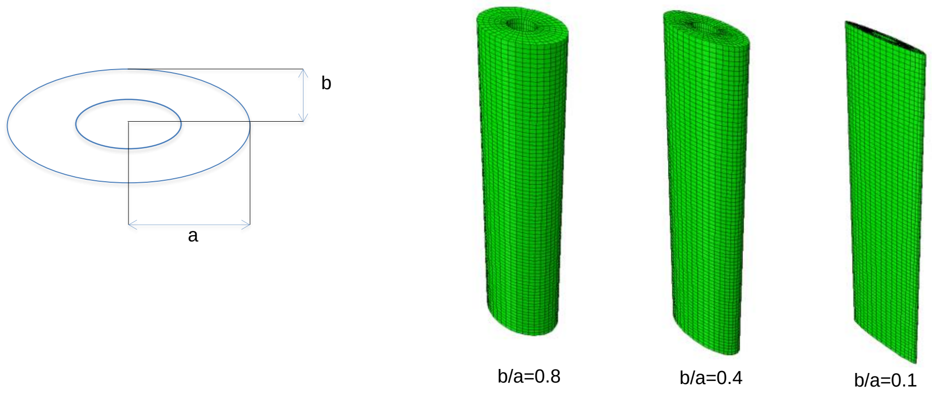

Figure 1: Geometry and mesh of the modelled fibres.

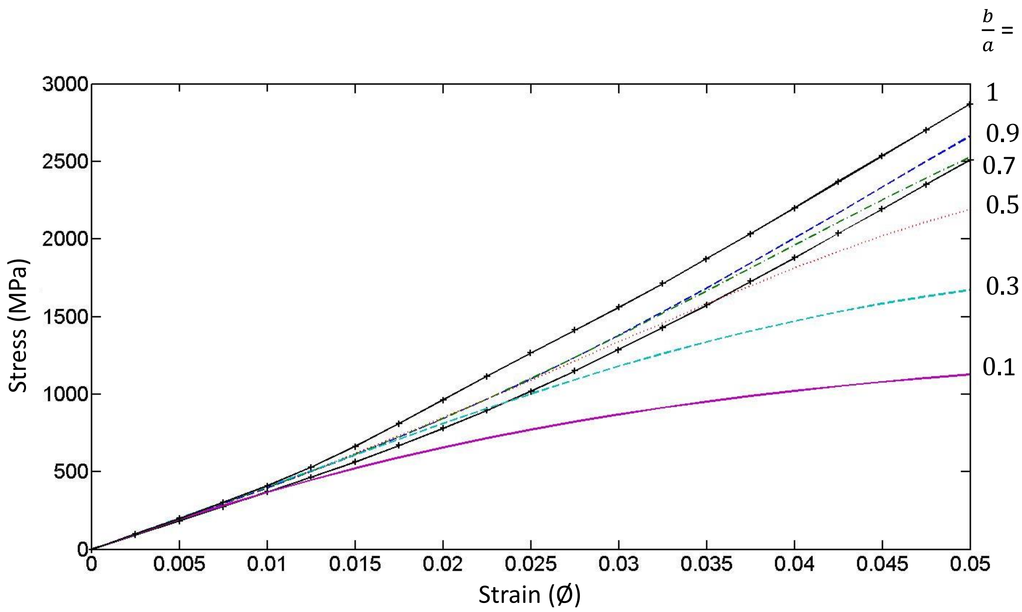

Figure 2: Computed stress-strain curves for different degrees of ellipticity

References:

1. Franck RR. Bast and other plant fibres. Boca Raton, USA, 2005.
2. Placet V, Méteau J, Froehly L, Salut R, Boubakar ML. Investigation of the internal structure of hemp fibres using optical coherence tomography and Focused Ion Beam transverse cutting. Journal of Materials Science 2014; 49 (24): 8317.
3. Mattrand C, Béakou A, Charlet K. Numerical modeling of the flax fiber morphology variability. Composites Part A: Applied Science and Manufacturing 2014; 63 (0): 10.
4. Hanana S, Elloumi A, Placet V, Tounsi H, Belghith H, Bradai C. An efficient enzymatic-based process for the extraction of high-mechanical properties alfa fibres. Industrial Crops and Products 2015; 70 (0): 190.
5. Marklund E, Varna J. Modeling the Effect of Helical Fiber Structure on Wood Fiber Composite Elastic Properties. Applied Composite Materials 2009; 16 (4 DO - 10.1007/s10443-009-9091-9): 245.
6. Neagu RC, Gamstedt EK. Modelling of effects of ultrastructural morphology on the hygroelastic properties of wood fibres. Journal of Materials Science 2007; 42 (24 DO - 10.1007/s10853-006-1199-9): 10254.
7. Nilsson T. Micromechanical modelling of natural fibres for composite materials: Lund, 2006.
8. Trivaudey Fdr, Placet V, Guicheret-Retel V, Boubakar ML. Nonlinear tensile behaviour of elementary hemp fibres. Part II: Modelling using an anisotropic viscoelastic constitutive law in a material rotating frame. Composites Part A: Applied Science and Manufacturing 2015; 68 (0): 346.
9. Placet V, Trivaudey F, Cisse O, Gucheret-Retel V, Boubakar ML. Diameter dependence of the apparent tensile modulus of hemp fibres: A morphological, structural or ultrastructural effect? Composites Part A: Applied Science and Manufacturing 2012; 43 (2): 275.
10. Joffre T. Structure and Mechanical behaviour of Wood-fibre Composites. Uppsala: Uppsala, 2014.
11. Placet V, Cisse O, Boubakar L. Nonlinear tensile behaviour of elementary hemp fibres. Part I: Investigation of the possible origins using repeated progressive loading with in situ microscopic observations. Composites Part A: Applied Science and Manufacturing 2014; 56: 319.