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Tensile deformation of a flax fiber

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Abstract

In this paper we investigate the tensile properties of a natural composite material: the flax fiber. The beginning of the stress-strain curve of a flax fiber upon tensile loading appears markedly non-linear. The hypothesis of a progressive alignment of the cellulose microfibrils with the tensile axis provides a quantitative explanation of this departure from linearity. This hypothesis is confirmed by the similar behavior which characterises hemp and ramie fibers. Besides, it has long been recognized that the natural character of flax fibers induces a large scatter of their mechanical properties. This scatter is shown not to be associated with the pronounced cross-section size variation observed along the fiber profiles. Two fiber size measurement methods are compared in order to check their influence on the property scatter and the decrease of the fiber mechanical properties as a function of the fiber diameter.

Keywords: flax; mechanical properties; morphology; microfibril angle.

I. Introduction

Cellulose-based natural fibres such as flax are promising candidates for reinforcement in polymer matrix composites, as a replacement for the widely used synthetic E-glass fibres. These eco-friendly systems would have wide possible applications, *e.g.* in the automobile industries. The fibres are characterized by the low density (about 1.5g/cm^3), high aspect ratio (700-2000) and good specific properties, with tensile strength and stiffness of flax fibres reported to be as high as 1500 MPa and 90 GPa, respectively [1]. These considerations make them comparable to E-glass fibres (mean tensile strength and stiffness of 2500 MPa and 72 GPa, respectively). However, the natural variability of the structure of these fibres results in the spread of their properties.

The aim of this study is to propose a model of the tensile deformation of an elementary flax fibre. We propose here a new method for the determination of the mechanical properties of a flax fibre, and an interpretation of the deformation behaviour of the fibre based on the description of its tensile curve.

II. The structure of flax fibers

Flax is a 80 cm high plant which possesses strong fibers all along its stem. These fibers can be found at the periphery of a stem cross-section and are gathered in bundles of 10 to 40. Each elementary fiber is itself made of

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concentric cell walls, which differ from each other in terms of thickness and arrangement of their constitutive components. The thickest cell wall (S2) contains numerous cellulosic microfibrils which are oriented at 10° with the fiber axis [2] and are embedded into a pectic and hemicellulosic matrix. These microfibrils represent about 70% [3] of the weight of a flax fiber and are likely to act as the reinforcement material within the fiber. This is schematically depicted in Figure 1.

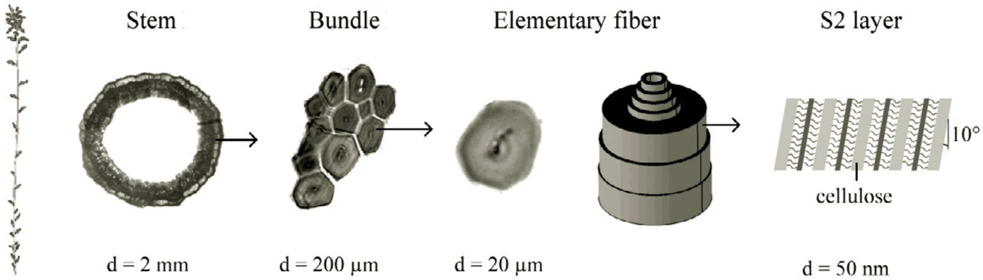


Fig. 1. Flax structure from the stem to the cellulosic fibrils

III. Tensile deformation of flax fibers

Tensile properties and behavior of flax fibers have been determined using a universal MTS-type tensile testing machine equipped with a 2N capacity load cell. The gauge length has been set to 10 mm and the cross-head displacement rate at 1 mm/min. The mean diameter of the sample has been calculated as the average of 5 measurements along the fiber using an optical microscope. A typical stress-strain curve is given in Figure 2.

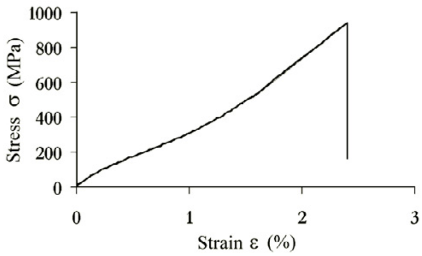


Fig. 2. Example of a stress-strain curve of an elementary flax fiber

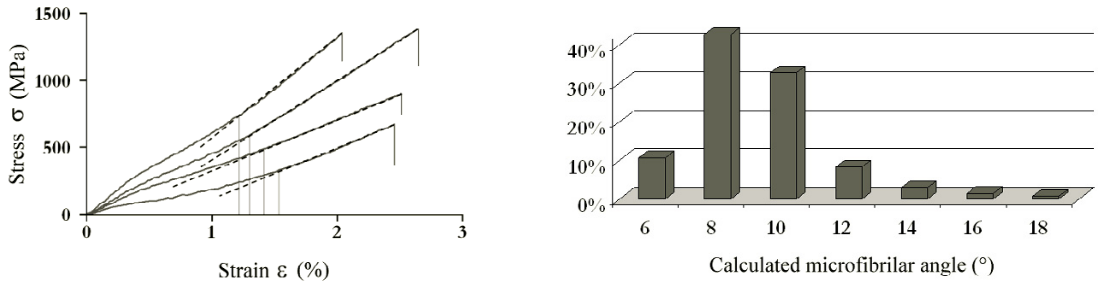
From this curve, three different parts can be distinguished: a first linear part, until about 0.3% of deformation; a second non-linear part, which corresponds to strains from 0.3 to 1.5 %; and the final linear part from the strain of 1.5% and until the final rupture of the fiber. This non-linearity of the tensile behavior of a flax fiber can be interpreted using some structural parameters mentioned above, notably the orientation of the strongest components in the largest cell wall of the fiber. Structural considerations can help in explaining the three different types of behavior observed during a tensile test. The first part could be associated with a global loading of the fiber, through the deformation of each cell wall. Then, the non-linear part could be interpreted as an elasto-visco-plastic deformation of the fiber, especially of the thickest cell wall (S2). This kind of deformation response is likely to be the result of the re-arrangement of the amorphous parts of the wall (mainly made of pectins and hemicelluloses), itself caused by the alignment of the cellulosic microfibrils with the tensile axis. The final linear part is thought to correspond to the elastic response of the aligned microfibrils to the applied tensile strain. Let L_f be the length of a microfibril which initially forms an angle α with the fiber axis. The tension of the fiber brings about a change in the orientation of the microfibrils and a corresponding fiber lengthening ΔL :

$$\Delta L = L_f - L_0 = L_0\left(\frac{1}{\cos\alpha} - 1\right) \quad (1)$$

i.e. a global deformation equal to:

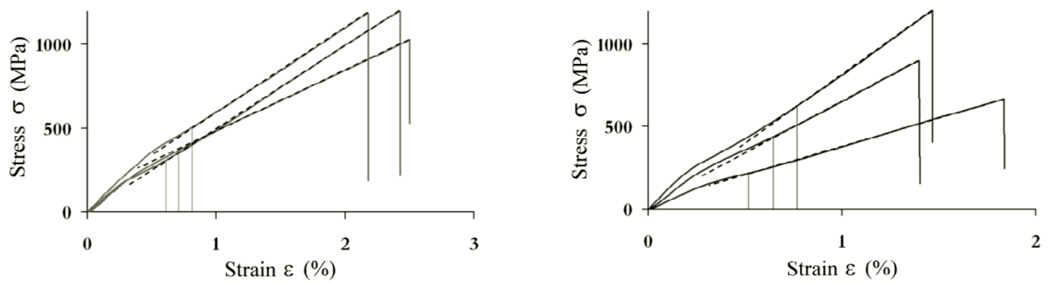
$$\varepsilon = \ln\left(1 + \frac{\Delta L}{L_0}\right) = -\ln(\cos\alpha) \quad (2)$$

Using Eq. 2, the tensile deformation of 1.4% ± 0.7% (see Fig. 3a) corresponds to a twist angle α of 9.6° ± 2.5°. The distribution of the microfibril angles obtained by this calculation is shown in Fig. 3b. These microfibril angles are in the range of those already observed for flax fibers [4-5] mainly by XRD.The same tensile tests as for flax fibers have been carried out on hemp and ramie fibers. Typical stress-strain curves of hemp and ramie fiber are presented in Figures 4a and 4b, respectively. As for the flax fiber, this curve exhibits three different zones. The beginning of the last linear zone corresponds to a mean deformation of 0.73% ± 0.16% and 0.65% ± 0.23%, which gives a microfibril angle of 6.9° ± 0.8° and 6.4° ± 1.2°, for the hemp and ramie fibers, respectively. These values are in good agreement with those reported in literature.



(a) (b)

Fig. 3. (a) Examples of flax fiber tensile curves, showing the strain at which deformation becomes linear again; (b) Distribution of the microfibrilar angle calculated on the basis of the flax fibers tensile curves.



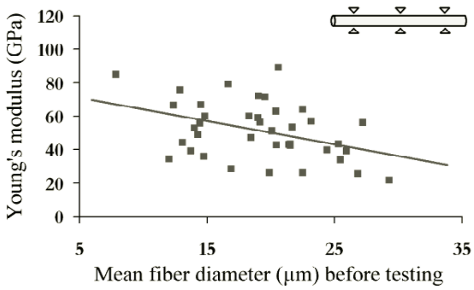
(a) (b)

Fig. 4. Examples of stress-strain curves for (a) hemp fibers and (b) ramie fibers.

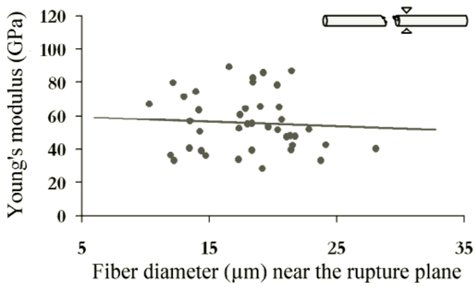
IV. Determination of the mechanical properties

The mechanical properties of elementary flax fibres have been studied by tensile testing. According to several authors [3, 6-10], the mean strength of such fibers is about 1200 MPa, the failure strain is around 2% and the mean Young's modulus reaches 60 GPa. The dependence of the strength with the fibre size has already been addressed in the literature [6, 9, 10] and explained in terms of Weibull's statistics: the larger the fibre is, the higher its probability of containing a defect and thus of failing prematurely, compared to a smaller fibre.

Although Young's modulus presents the same dependence on the fibre size (though generally obscured by a rather large scatter of the values), it has never been clearly justified. Whereas the strength is a function of the sample size, the Young's modulus is defined as an intrinsic parameter that should not vary with the sample dimensions. However, as stated above, the fibre dimension is not easy to define and this causes measurement scatter. An attempt was made to plot the evolution of the Young's modulus as a function of another dimensional parameter, the fibre diameter close to the rupture point. Figure 5 gathers the results obtained for 40 fibres, for which both the mean diameter before the tensile test (average of the measurements made on 5 optical micrographs) and the diameter near the rupture point after the tensile test (measured on a SEM micrograph) have been determined. It can be seen that there is no relationship between the failure point and the mean diameter: the fibre did not fail where its diameter is smallest (weakest point) or largest (i.e. possibly in the presence of a defect), which would have brought about a significant shift towards lower or higher diameter values respectively. The average diameters calculated for these 40 fibres and obtained either by averaging optical micrograph measurements ("mean diameter") or by measuring the fibre dimension near the rupture plane ("failure diameter") are 19 µm ± 5 µm and 18 µm ± 4 µm respectively. It appears that the slope of the Young's modulus-fibre diameter graph, negative when plotted as a function of the mean fibre dimension, is almost horizontal when plotted as a function of the failure diameter. In this case, the modulus reflects correctly the stiffness of the material and can be estimated to be, on average, 56 GPa (rather than 51 GPa obtained with the mean diameter). Nevertheless, whatever the method of calculation used, the scatter of the Young's modulus value remains as high as 17 GPa.



(a)



(b)

Fig. 5. Evolution of the Young's modulus as a function of (a) the mean fibre diameter, (b) the diameter near the fibre failure point

V. Conclusion

Two main characteristics of the flax fiber tensile behavior have been studied by taking into account the specific morphology of these fibers. The non-linearity of the tensile stress-strain curve has been explained by a visco-elasto-plastic deformation of the amorphous polymers within the fiber together with a progressive alignment of its cellulose microfibrils with the tensile axis. The apparent decrease of the Young's modulus as a function of the fiber size almost disappears when the same quantity is plotted against the fiber diameter measured near the rupture. The modeling of the mechanical behavior of the derived composite requires an exact description of the tensile deformation of bundles through probabilistic considerations that take into account the large scattering of the properties and dimensions of flax fibers.

References

[1] Ivens J, Bos HL, Verpoest I. *Proc. Symposium on Renewable Bioproducts* 1997: 58.
[2] Wang HH, Drummond JG, Reath SM, Hunt K, Watson PA. *Wood Science and Technology* 2001; **34**: 493-503.
[3] Batra SK. In: Lewin M, PearceEM, Editors. *Handbook of fiber Chemistry*; 1998: 505-575.
[4] Mukherjee PS, Satyanarayana KG. *Journal of Materials Science* 1996; **21**: 4162.
[5] Bos HL, Donald AM. *Journal of Materials Science* 1999; **34**: 3029-3034.
[6] Baley C. *Composites Part A* 2002; **33**: 939-948.
[7] Davies GC, Bruce DM. *Textile Res. J.* 1998; **68**: 623-629.
[8] Ganster J, Fink HP. In: Brandrup J, Immergut EH, Grulke EA, Wiley EA, Editors. *Polymer handbook* 1999.
[9] Troger F, Wegener G, Seemann C. *Ind Crops Prod* 1998; **8**: 113-121.
[10] Van den Oever MJA, Bos HL, Van Kemenade MJJM. *Appl Compos Mater* 2000; **7**: 387-402.