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Variability of the mechanical properties among flax fiber bundles and strands

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Abstract

This work analyzes the variability of the mechanical properties of flax fiber bundles and strands (a strand is the set of the bundles issuing from the same stem). A first remarkable result is that to obtain average values with good precisions about twenty randomly selected strands are sufficient. Moreover a comparative study of the fracture properties of bundles issued from different strands leads to the assumption that each stem is particular with special properties. A more detailed study shows that correlations exist between the sections of the strands and their mechanical properties. These trends are similar to those reported for unit fibers.

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Keywords: Flax fiber; Mechanical properties; Variability; Bundle; Strand

1. Introduction

One of the aspects that threaten the effective use of plant fibers in the field of structural composites is the great dispersion of their mechanical properties. Indeed, the dispersions observed on the unit fibers are very high compared to those of synthetic fibers [1,2] .The origins of this great variability are numerous, including: differentiated thickening of the walls of the fiber between the bottom and top of the stem [3], growth conditions [4,5], fiber extraction methods (6), volume of material tested [7,8,9] and the likely inadequacy of current methods for the mechanical characterization of plant fibers with particular morphology [10].

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Thus, it would be illusory to seek to manufacture mechanically reliable structural materials from these fibers. However, it should be noted that the basic reinforcement element in structural composites is not the unit fiber but the roving, i.e. a controlled assembly of unit fibers. Therefore, the entities whose properties dispersion is to be checked are fiber bundles or groups of bundles (the strands).

The issue of the variability of the mechanical properties of flax fibers is approached in this work from different points of view. First, we study the possibility of experimentally accessing with good accuracy to reliable average values of the mechanical properties of plant fiber bundles. We then show that the dispersion between stems originating from the same culture is much smaller than those reported for unit fibers. The volume effect of the test specimen on the mechanical properties is discussed in terms of the cross section area and the length of the strands.

2. Materials and methods

2.1. Materials

The study focused on the Arétha variety of flax grown north of Caen in 2012 (altitude 73.47 m), on thick silty soil (3 m). Between sowing and grubbing the precipitation rate and temperatures were favorable for flax growing. However, due to climatic disturbances later, harvesting was delayed (only 75% of the plots were harvested, in October instead of September as usually). All strands were taken from the middle zone of the plant in order to eliminate the additional variability related to the sampling zone [11,1,12].

2.2. Methods

A specific methodology was developed in the laboratory for uniaxial tensile testing bundles or strands of plant fibers [13]. This precaution is explained by the particular morphology of the bundles composed of unit fibers having an average length of 3 to 4 cm held between them by pectin bonds. The methodology included: parallelization of the bundles, their retention by averages of metallic shells and the use of a device which allows uniform clamping in the jaws.

The tests were carried out using Instron 5800R machine equipped with a load cell of capacity 2 kN at a deformation rate of 1% min^{-1}. The cross-section area of the strand was measured after mechanical testing by averages of image analysis software, transversely to the loading axis. It corresponds to the total area of the fibers in the clamping zone in the jaws.

3. Results and discussion

3.1. Representativeness of the average value of a mechanical property

The aim is to evaluate the number of strands to be tested in order to obtain an average of a mechanical parameter (ultimate deformation or strength) which converges sufficiently. The rupture of a strand occurs by the sequential ruin of the bundles that compose it (about 30). Taking the strands in their order of test, average of the considered mechanical property is calculated for the first i broken bundles. The number of bundles tested is sufficiently large when the addition of a new bundle no longer has an effect on the average, i.e. when the average over the first i bundles converges sufficiently towards the “real average” of the set.

In order to estimate the number of strands to be tested for evaluating the average ultimate deformation of a set of strands with a given precision, the convergence of the average deformation of the first i bundles is analyzed in Fig. 1. Knowing that each bundle contains about 30 unit fibers, by testing 10 strands 300 bundles (i.e. 9,000 unit fibers) are loaded in tension: this large number of bundles makes it possible to estimate the average ultimate deformation of a set with accuracy better than 2%. Precision is about 1% when testing 15 strands (see Fig. 1).

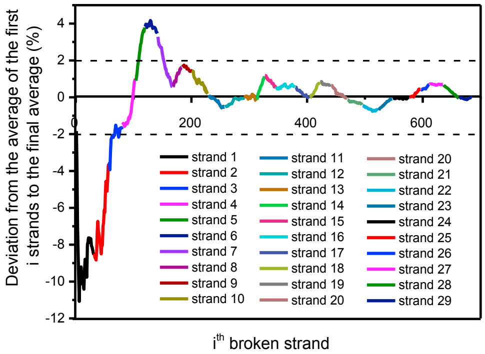


Fig. 1: difference between the averages of the first i strands and the set of strands.

3.2. Particularity of each strand

The issue is to know whether the genotypes as well as the conditions of growth and transformation of a stem give it specific mechanical properties different from those of another stem. Indeed, if the mechanical properties of the bundles are statistically different from one stem to the other, it will be necessary to defibrate the flax sufficiently to be able to disperse the bundles with the weakest properties and thus avoid being confined in an area from which rupture would initiate prematurely.

To this end, a normality test was implemented to assess the likelihood that the ultimate deformations of all the bundles issued from a set of 30 strands come from a normal distribution. The experimental data are well fitted by a normal distribution with values μ=(0.16 ±0.028)%; i.e. about 95% of deformation values lie within two standard deviations (2σ) from the average, μ. If the average of the ultimate deformations of the bundles of a given stem is not within this range, then the properties of these bundles are specific to the stem. In Figure 2, it will be noticed that more than 50% of the strands have ultimate deformations outside the [μ-2σ; μ+2σ] range. So, stems of the same variety of flax grown the same year on the same plot may have different histories that give them specific mechanical properties. Moreover, the ultimate deformations of the bundles in some strands are less dispersed than the others. For example, strand 10 shows an average ultimate deformation greater than our criterion (above μ+2σ) while the average ultimate deformation of strand 15 is smaller than our criterion (below (μ-2σ). Thus the ultimate deformation of a strand is not dictated by the dispersion of the ultimate deformations of the bundles of which it is made.

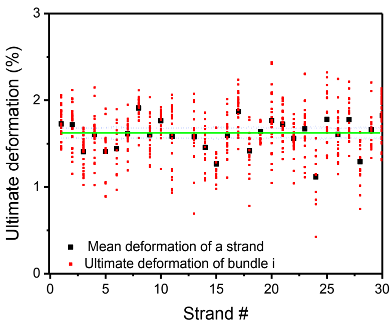


Fig. 2: ultimate deformations of the bundles (red) constituting the strands and average values associated with the strands (black). The green horizontal line represents the average deformation μ of all the bundles and the blue lines the levels (μ-2σ) and (μ+2σ).

The moduli and the strengths of the 30 strands are shown in Figs. 3a and 3b respectively. The red line represents the average value, μ, and the two blue lines are for the values μ-σ and μ+σ. The experimental values are 43.2 ±4.8 GPa for the Young's modulus and 695 ±120 MPa for the strength.

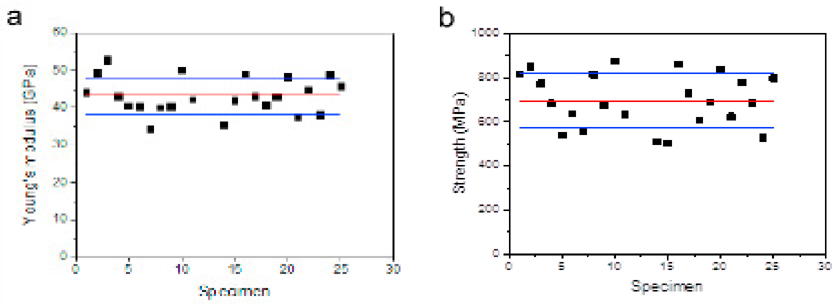


Fig. 3: (a) distribution of the Young's modulus; (b) distribution of the strength.

3.3. Correlation among the mechanical properties of the stems

In Fig. 4a a linear relationship is noticed between the strength and the Young's modulus of the strands. This result is similar to the one reported for hemp fibers [14]. It should be noted that the observed trend is independent of the method used for the estimation of the cross-section areas of the strands because they take part similarly in the evaluations of the two parameters. Fig. 4b shows the strength of the strands vs. the ultimate deformation. The line of regression plotted in this figure fits the actual data with a Young's modulus of 42.9 GPa, which is very close to the average modulus in Fig.3a. The ultimate deformation of the strands exhibits a great dispersion (Fig. 4c) but it does not correlate to the Young's modulus. This means that the fracture is rather governed by the toughness.

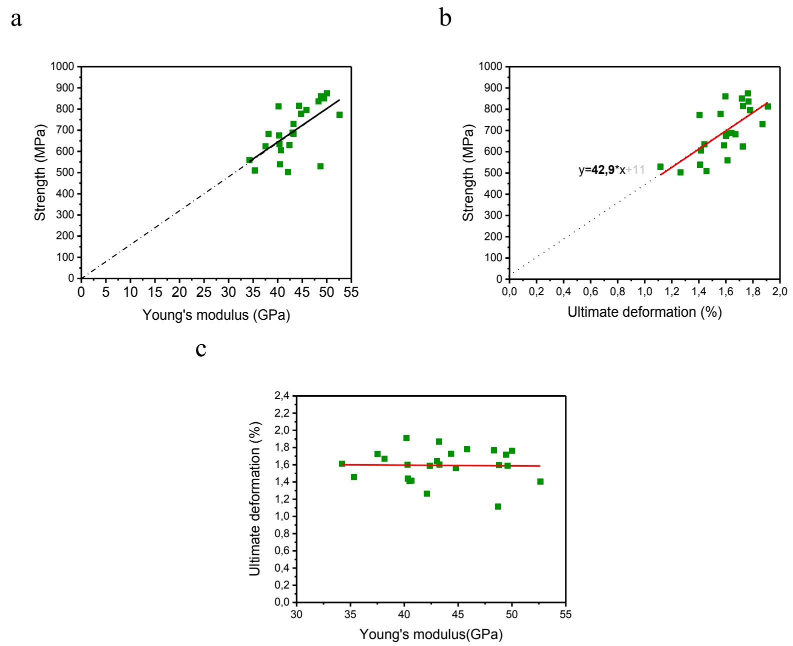
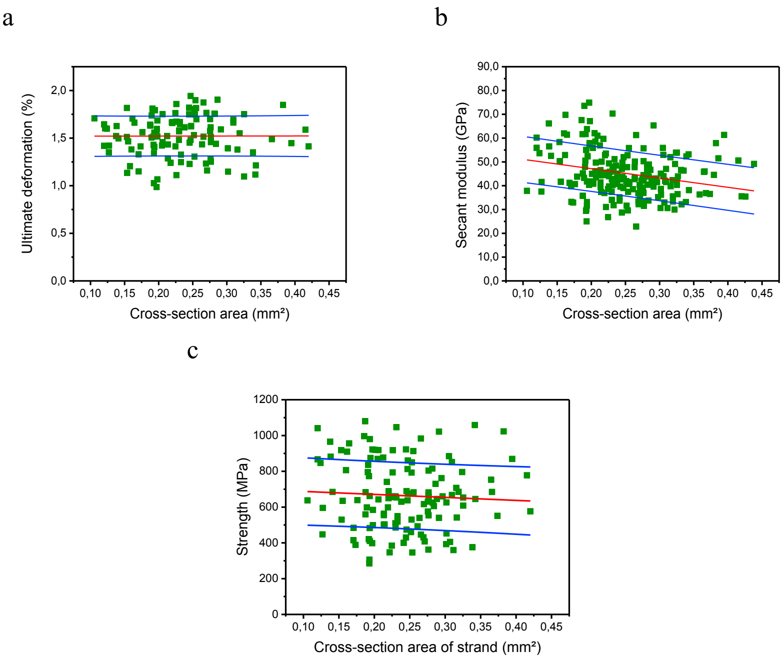


Fig. 4: (a) strength vs. their modulus; (b) strength vs. ultimate deformation; (c) ultimate deformation vs. modulus.

3.4 Size effect of the strand

3.4.1. Cross-section area

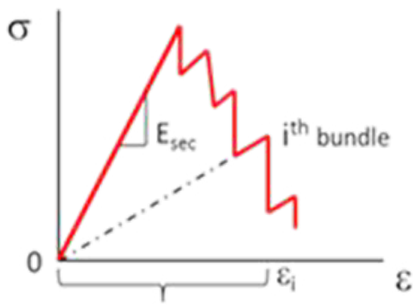
In Figures 5a, 5b and 5c are depicted the ultimate deformation, secant modulus and strength of the strands vs. the cross-section area. The reported secant moduli were corrected by taking into account the compliance of the test set up. Although the experimental measurements are very distributed, it will be noticed that the ultimate deformation of the strand (average of the deformations of the constitutive bundles) is not dependent on its cross-section area. This feature had been reported by different authors in the case of single fibers [1,15] but is a first for strands. On the other hand the modulus decreases by about 20% and the strength by 4% when the cross-section area of the strand is quadrupled. Thus the size of the stem has no noticeable influence on the mechanical properties of the bundles.



Figs. 5: (a) dependence of the strength; (b) modulus; (c) ultimate deformation on the strand cross-section area.

3.43.2. Gauge length

In this section are compared the dependencies of the mechanical properties of unit bundles and strands on the gauge length. An example of the loading curve of a strand is shown in Fig. 6. The sawtooth behavior after the maximum load corresponds to the successive breaks in the fiber bundles. We assume the same modulus for each bundle, equal to the secant modulus of the strand. This hypothesis probably contributes to reducing the dispersion of the strength. Then, the strength of the i^{th} bundle is taken equal to the product of the secant modulus of the strand by the ultimate deformation of bundle *i*.



Figs. 6: schematic representation of the tensile stress-strain behavior of a strand

For a gauge length of 20 mm the average strength of the strands is higher than that of the unit bundles and the associated standard deviation is smaller. This result highlights the averaging effect within a strand (Fig. 7a). The difference between the two averages reduces when the gauge length is increased, but the standard deviations remain much greater for the unit bundles.

The modulus of the strand was calculated from the load vs. load-point displacement curve, gauge length (Lg) and total area of fibers in the specimen. In Figure 7b the modulus of the strand decreases slightly when the gauge length is increased (49.8 GPa for L=20mm and 42.5 GPa for L=50mm) while that of the bundle is constant equal to 60 GPa. Really, the average modulus of unit bundles seems constant because we used the same compliance correction as for the strands. The smaller modulus for the strand is explained by its morphology: for a gauge length of 20 mm, all the bundles are not continuous along this length: it is calculated that 7% of the bundles do not support the applied load. This rate is 22% for a gauge length of 50 mm [16].

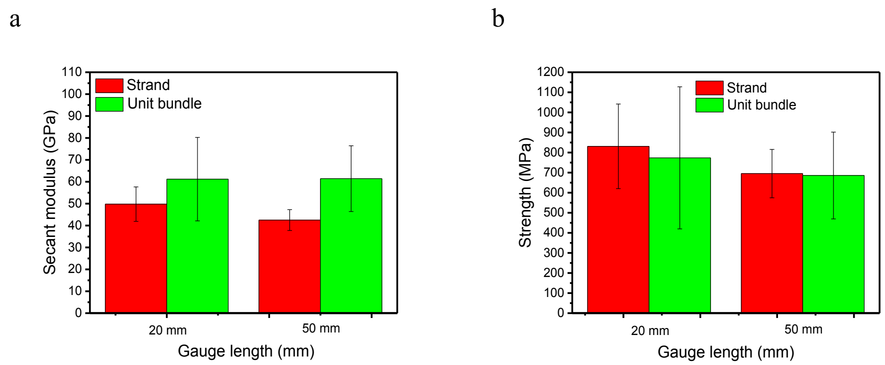


Fig. 7: influence of gauge length on the secant modulus (a) and the strength (b) of the fiber bundles and the strands

Conclusion

These different results indicate that the mechanical properties of flax strands are much less dispersed than those of the unit fibers. Although each stem has particular properties, the representativeness of the average values measured is very good, since the tested population exceeds twenty strands. The volume effect of material tested that had been demonstrated on the unit fibers subsisted on the scale of the strands.

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