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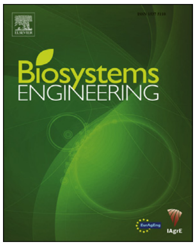

Research Paper

Understanding the lodging stability of green flax stems; The importance of morphology and fibre stiffness

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Flax fibres (*Linum usitatissimum*) with good mechanical properties are required to reinforce polymers. Usually, their characterisation is made on retted and scutched fibres. This work provides a new and original method to both determine the stiffness of green fibres contained inside the plant and to estimate the crop lodging stability.

We studied two recent flax varieties (Eden and Terre de Lin (TDL) 25) with a distinct lodging resistance (respectively high and low). Both varieties, grown under the same conditions, exhibit a similar fibre yield. The analysis conducted is based on the correlation between the bending stiffness of the stems, the distribution of fibres in a cross section and the properties of elementary flax fibres. The results of the mechanical characterisation indicate that the Eden variety has a superiority concerning fibre stiffness (68 GPa versus 55 GPa). The analysis of the bending stiffness of a dried plant at different localisations along the stem and of its fibre distribution in the corresponding cross section allowed us to estimate the fibres average modulus. Results obtained by this method were very close to the tensile tests values. The same procedure was used on green stems to approach the living state of the plant and to determine the Young's modulus of green fibres. The results highlighted a variation of fibre stiffness between the green state and the dried state (around +25%). The results enabled the use of a simplified buckling model, which confirmed the superiority of the Eden variety in lodging resistance. Thus, the analysis of the mechanical properties of flax stems and their structure could be a selection criterion.

1. Introduction

Flax could be considered to be one of the most efficient vegetal reinforcements for composite materials in the replacement of glass fibres for specific applications (Pillin et al., 2011; Rahman Khan et al., 2011; Shinoj, Visvanathan, & Panigrahi, 2010). Indeed, these fibres have good specific mechanical properties (Baley & Bourmaud, 2014), constitute a renewable and biodegradable resource, their life cycle analysis is positive (Le Duigou, Davies, & Baley, 2011) and they are available in Europe.

To make efficient composites, it is necessary to obtain optimal fibre individualisation (Akin, Foulk, Dodd, & McAlister,

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Nomenclature

TDL	Terre de Lin
TGA	Thermo Gravimetric Analysis
EI (Nm^2)	Bending Stiffness
F (N)	Applied Force
L (m)	Length
D (mm)	External diameter
d (mm)	Interior diameter
Pcr (g)	Critical Load
H (m)	Height

2001) and a high quality fibre matrix interface (Le Duigou, Bourmaud, Balnois, Davies, & Baley, 2012) but the initial fibre mechanical properties are also a key point. Indeed, the mechanical properties of the final composites are dependent on the closed reinforcement properties (Peltola, Pääkkönen, Jetsu, & Heinemann, 2014). There is a significant quantity of flax varieties (Bert, 2013) and each one has its typical gene pool, inducing direct consequences on its structure and biochemical composition. This biochemical composition could be linked to the fibres' mechanical properties. Comparative work on the fibre structure of different varieties of flax (Alix, Philippe, Morvan, & Baley, 2008) has shown stiffness differences related to the cellulose content in the cell walls. The varieties with the highest cellulose content were represented with cellulose microfibrils the closest together and a less well-developed matrix between microfibrils. The bridges between glucomanan chains have been proposed as an explanation of the differences of stiffness observed (Alix et al., 2008). The impact of the fibre structure on the mechanical properties was confirmed in recent works by Lefeuvre et al. (Lefeuvre, Bourmaud, Morvan, & Baley, 2014) on other flax varieties.

Thus, the different flax varieties could exhibit distinct structures and, consequently, performances. Otherwise, at the plant scale, the stem microstructure could vary according to the gene pool variety as well as the growing conditions. The fibre growth can be detailed in several successive steps. The first one is the fibre-cell multiplication at the top of the stem (Esau, 1977); the number of fibres in the stem section is dependent on the gene pool variety. Secondly, there is an elongation of each fibre for a period of 3–5 days per fibre (Snegireva et al., 2010) and of around 5–20 mm per day (Ageeva et al., 2005) to reach up to 100 mm (Gorshkova et al., 2003). This elongation is called intrusive growth (due to the penetration of each fibre through the shared lamella between neighbouring cells (Ageeva et al., 2005)), and occurs by diffuse symplastic growth along the entire cell (Ageeva et al., 2005; Snegireva, Ageeva, Vorob'ev, Anisimov, & Gorshkova, 2006; Snegireva et al., 2010). The elongation takes place in the top 30–50 mm of the stem above a particular point, the snap-point, defined by Gorshkova, Chemikosova, Lozovaya, and Carpita (1997). Below this snap-point, the stiffness of the stem increases significantly. The last step of the elaboration of the fibre, which could be assimilated to a nano-structured composite material, is the thickening of the walls which occurs below the snap point. This thickening is produced by the cellulose synthesis of a secondary cell wall, which occurs layer by layer. The formation of microfibrils and their association with the non-cellulosic polymers are complex, resulting in multilayer fibre-reinforced composite-wall structures composed of three main layers S1 (~0.5–2 μm), S2 (~5–10 μm) and S3 (~0.5–1 μm). S2, the main structural layer, carries the majority of the mechanical performance and the physical properties of the fibre. S3 surrounds a cavity known as a lumen, whose volume is inversely proportional to that of the secondary cell walls. Gorshkova et al. (2003) proved that the cell walls of the outer fibres in the bundle thickened first, the thickening of the other cell walls proceeded last, until the maturity of the plant, taking around 2 months. Depending on the outer conditions, the degree of maturity could be different between the outer and inner fibres. In the same way, thickening differences could occur along the stem, due to climate variations between the first and the last thickened fibres. Thus, according to the variety or the growing conditions, the cell wall development could create some plants with various architectures, fibre structures or mechanical fibre properties. Moreover, the thickening of the fibre areas could vary, inducing stems with highly different mechanical performances. Various parameters have an influence on the growing of flax: The number of seeds per square metre, the soil preparation and the choice of the variety (function of the precocity of the area) were controlled, the accumulated temperatures received by the plants (Bert, 2013) was checked before harvesting as well as the germination rate.

In the case of flax, the stiffness of the stem has a direct impact on its lodging resistance which is a primordial parameter of the varietal selection work. Lodging of flax stems is generally noticed after heavy rainfall and strong winds, as well as with high nitrogen amounts in the ground, inducing rapid plant growth. Consequently, the distribution of the water drops on the plant increases its mass and, with windy conditions, the risk of instability becomes even more significant. Sometimes, the flax is able to be raised but if it cannot be, its quality would be poor, especially if the lodging occurs during the growing stage of the plant. The period around flowering is a critical stage for the success of the cultivation. Several parameters influence the plant stiffness: the diameter of the stem, the distribution and percentage of fibres in the section, the number of fibres, the thickening of the secondary cell walls (presence or not of lumen), the stiffness and the diameter of the fibres.

The stability of the plants has been the subject of many research papers. For example, the stability of trees has been studied by various authors (Jaouen, Alméras, Coutand, & Fournier, 2007; McMahon, 1973; Niklas, 1994; Spatz, Köhler, & Speck, 1998). McMahon (1973) studied, for numerous species of trees, the relation between the height and the diameter of the trunk. In a diagram having the height related to the diameter of the trunk he notes that the experimental results remain lower than a theoretical limit of buckling. The risk of buckling was calculated starting from the expressions suggested by Greenhill (1881). The initial model was modified and simplified to compare to vertical beams of a constant diameter, supporting a uniformly distributed loading; Niklas (1993, 1995) widened this approach with various plants, of which one was grass. Jaouen et al. (2007) analyse the origin of the expressions usually used to estimate the risk of buckling.