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Influence of the morphology characters of the stem on the lodging resistance of Marylin flax

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ABSTRACT

Flax fibres are widely used for composites reinforcement. Within the plant, these fibres have a mechanical support role for the stem, participating especially in the resistance against lodging. Flax stems (*Linum usitatissimum*) of the Marylin variety were cultivated in the same geographical zone over 4 successive years. Various parameters influencing the stem stiffness were analysed: the height and the diameter of the stems, their internal organization including the proportion of fibre bundles, the diameter and mechanical properties of elementary fibres. It was shown that the fibre yield and number of fibres increased with the height of the plants, the number of fibres being maximal at medium height. In addition, the fibres' diameter decreases with the height of the stem because of the growth mechanisms. No correlation was found between the fibres' mechanical properties and the height of the plants. Lastly, flexural tests on stems made it possible to correlate their stiffness with the Young modulus of the elementary fibres as well as their internal organization. This result confirmed the crucial role of fibres in the support of the plant and in particular in the lodging behaviour.

1. Introduction

Within an approach of eco-design, flax fibres (*Linum usitatissimum*) can replace glass fibres to reinforce composite materials. Nevertheless, the available data in the literature shows that their properties are usually scattered (Batra, 1998; Charlet et al., 2007, 2009; Davies and Bruce, 1998; Troger et al., 1998) and the industrialists contemplate the difficulties of the yearly reproducibility of the plant fibre performances. However, we showed that some flax samples or varieties present high specific mechanical properties (Baley, 2002) and they allow a reduction of the majority of the environmental impacts (Le Duigou et al., 2010). In addition, a work of synthesis (Baley and Bourmaud, 2014) shows that, by comparing tests carried out under similar conditions, flax fibres exhibit reproducible specific mechanical properties which are close to those of glass fibres, especially for the stiffness.

Flax, cultivated for several millennia, is the object of varietal selection work to increase the production of fibres (one refers to fibre flax) or the production of seeds (one refers to seed flax). The intellectual property, and thus the protection of a new variety is generally ensured for 20 years. Consequently, there are evolutions in the cultivated varieties in the course of time. The selection of plants is not made according to the mechanical properties of fibres; the fibre yield is favoured in order to ensure a sufficient income for the farmers. Thus, today, textiles remains the first outlet and the selection of a new variety of fibre flax is a function of the requests of the farmers, the flax scutchers and the spinners with various criteria. From the point of view of the customers and spinning, it is important to have fibres with a large smoothness, a good regularity and resistance which induce an increased ease of spinning because of the facilitated individualization of fibres. Flax growing is also controlled by economic constraints; the straw production by hectare and the output of all co products of the plant are essential parameters to continue the cultivation of the flax. Flax grows best on soils with high water-holding capacity and good inherent fertility; a light and deep ground will support the development and the rooting of the plant. The cultivation of flax needs a wet environment with a regular alternation of rain and sun. Thus, a period of drought or excess rain would stress seedlings, impact the growth, including the height and diameter of the stem, and affect the fibre formation (Chemikosova et al., 2006; Milthorpe, 1945). As any plant, flax

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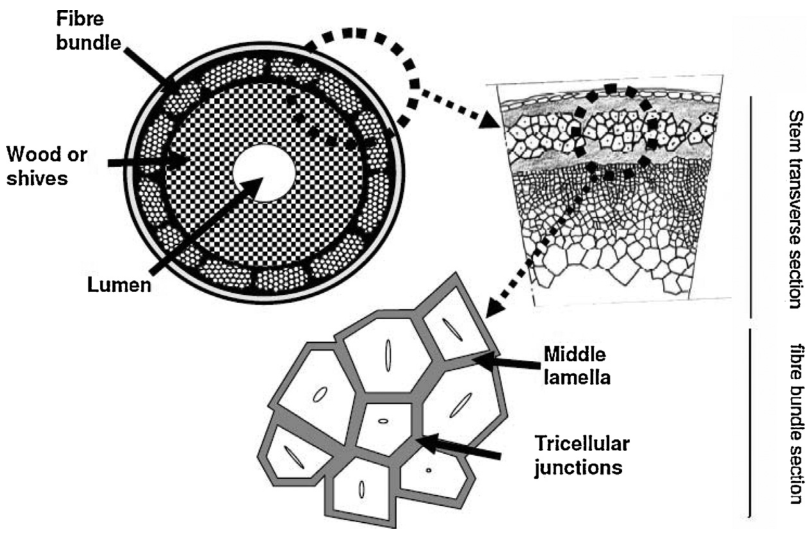

Fig. 1. Multi scale chematical presentation of a flax stem morphology. Adapted from (Esau, 1953).

can undergo attacks from insects and diseases and the cultivators favour resistance to the blight or fusarium as well as a vegetative precocity and lateness. The work of varietal selection also concerns the behaviour of lodging which is a primordial parameter; it can be defined as displacement of plant shoots from their normal vertical position. This instability originates because of buckling of the stems due to abundant rain, strong winds or numerous visiting animals (Menoux et al., 1982). Indeed in case of severe lodging, the plants might be lying down on the ground. Lodging of flax stems is highly influenced by the stem stiffness, the environmental solicitations and especially the additional water weight. Consequently, the distribution of the water drops on the plant increases its mass, and with wind, the risk of instability becomes even more significant. Sometimes, the flax is able to be raised (up to seven times according to the liners) but if it cannot, the quality of fibres and seeds is poor, especially if the lodging occurs during the fast growing stage of the plant. Thus, the period around flowering is a critical stage for the success of the cultivation (Menoux et al., 1982).

The stability of the plants has been the subject of many research papers. For example, the study of the stability of trees was studied by various authors (Jaouen et al., 2007; McMahon, 1973; Niklas, 1994). McMahon (1973) reported for numerous species of trees, a relationship between the height and the diameter of the trunk. The risk of buckling was calculated starting from the expressions suggested by Greenhill (1881). In this model the trees are compared to vertical beams of 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) analysed the origin of the expressions usually used to estimate the risk of buckling. These different works highlight a notion of a critical stability threshold which is generally not raised by trees or plants.

For a simple approach, the critical load of the buckling of a vertical beam of constant section and subjected to its own weight (loading uniformly distributed) was studied by Timoshenko (1940) using the resistance of materials. The critical load P_{cr} is expressed by:

$$P_{cr} = \frac{78.3 \times EI}{H^2} \quad (1)$$

with EI the flexion stiffness of the beam, E the Young modulus, I the quadratic moment of inertia and H the height of the beam. It is noted that the critical load of buckling is directly proportional to the rigidity in the inflection of the beam.

The examination of a cut of a stem of flax shows that the fibres are assembled in bundles and are regularly distributed at the periphery of the stem (Fig. 1) (Esau, 1953). The fibre bundles could be assimilated to support materials by playing a significant role on the mechanical stiffness. The connections between the fibres themselves and between the fibre bundles, and the rest of the plant are ensured by the middle lamellae and tri cellular junctions (Jauneau et al., 1992; Morvan et al., 2003). Within the plant, cohesion between fibres is also important (Morvan et al., 2003). Thus, to extract fibres, dew retting is necessary before mechanical extraction; it partly removes the calcium pectate, responsible for the cohesion between cells and tissues (Akin et al., 2007, 2001; Sharma et al., 1999). Within the stem, the fibres are the elements which contribute most to the flexion stiffness of the flax stem (EI). Thus, to limit the risk of buckling when the height of the stem increases, the flexion stiffness of the stem must increase in the lower part.

Several parameters influence this 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 one lumen), the stiffness and the diameter of the fibres. To explore such effects, two experimental approaches are possible. The first one followed by Milthorpe (1945) was to study the development of fibres at different stages of stem maturity and in relation to the water supply and light intensity. The second, followed in the present paper, was to examine at stem maturity the fibre development and the plant growth of flax cultivated in the same geographical area (Plateau du Neubourg, Normandy, France) over 4 successive years (2009–2012). The climatic conditions were not identical one year on the other, and consequently, the heights of the studied flax stems vary according to the years. Initially, we analysed the fibre yield and the mechanical properties of these fibres according to the height of the stems. Then, on a selected batch, we examined by optical microscopy the variations of the diameters of fibres at three levels of the stem and as a function of the height as well as the diameters of the stem. The structure of the stems was analysed in terms of shape/size and proportion of fibres in the section. These data enabled us to correlate this architecture of the stems with their flexural properties which were then measured.

2. Experimental

2.1. Flax fibres

The plant material consisted of 11 fibre batches of Marylin textile flax grown in 2009–2012 (Table 1). The technical fibres, dew-retted and scutched, were provided by the CTLN Company