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Research Paper

Mechanical properties of maize fibre bundles and their contribution to lodging resistance

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Tensile properties of fibre bundles were estimated according to their location in the stem. The average tensile modulus and tensile strength in the core group of the fibre bundles (4.44 ± 0.28 GPa and 32.35 ± 2.07 MPa, respectively) were significant lower than that in the skin group (10.80 ± 0.62 GPa and 92.65 ± 6.23 MPa, respectively). The large variation of tensile properties can be attributed to the large difference in the ratio of the areas of the vascular bundle sheath and the fibre cell wall thickness. Gradient distribution of bundle stiffness is found along the radial and axial direction of stem. Such gradient distribution increases the stiffness of basal stem; thus it is a key factor of lodging resistance for maize plants.

1. Introduction

Maize is an important crop in China and worldwide. Its yield has increased greatly since 1950s due to improvements in genetics and crop management (Ci et al., 2011). Although the tolerance of stalk lodging has been improved consistently, lodging is still one of the most important factors for the reduction of maize yield. The crop yield reduces about 5%–25% when plant lodging occurs (M. S. Zuber & Kang, 1978). Lodging resistance is correlated to many factors, including the basal stem diameter, the stem strength (U. Zuber et al., 1999), the stem wall thickness (Hall, Sposaro, & Chimenti, 2010), the rind puncture resistance (Kang, Din, Zhang, & Magari, 1999), the height (Navabi, Iqbal, Strenzke, & Spaner, 2006) and the mass of the plant above the ground.

The maize stem can be regarded as a cantilever that is loaded by bending moments that vary during growth. The maximum moment appears at the base of the stem. It is well accepted that all plants should have evolved to have sufficient strength to withstand this load through genetic adaptation to environments. However, on one hand, when plants suffer extreme climatic conditions, the external force increases and plant lodging will occur inevitably. On the other hand, plant

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Nomenclature

Abbreviations

MX	Metaxylem vessel
Ph	Phloem tissue
PX	Protoxylem vessel
Sv	Transverse sectional area occupied by vessels and phloem tissue in fibre bundle
VBS	Vascular bundle sheath

Symbols

d	Diameter, m
E	Elastic modulus, Pa
E_f	Elastic modulus of fibre, Pa
E_l	Elastic modulus of composite in longitudinal direction, Pa
E_m	Elastic modulus of matrix, Pa
g	Gravitational acceleration, m s^{-2}
k	Numerical constant correlated to the shape, 1
l_{cr}	Critical length of plant stem, m
n	Number of fibre bundles in the stem, 1
s_a	Average cross-sectional area of a single fibre bundle, m^2
S_f	Total cross-sectional area of the fibre bundle, m^2
S_s	Total cross-sectional area of the maize stem, m^2
v_f	Volume fraction of fibre, %

Greek symbols

ρ	Mass per unit volume, kg m^{-3}

breeders always seek ways to improve lodging resistance. Fibre bundles are the main load-bearing structure of the stem. Therefore, it is crucial and meaningful to determine the mechanical properties of maize fibre bundles for maize cultivation. Unlike synthetic fibres, which can be made to have uniform properties, natural fibre exhibits large stiffness variations. The main reason for these variations is the variability of gradient structures at different levels, such as the gradient distribution of density in fibre cross section and the various orientations of microfibrils and different thicknesses of each sublayer of cell wall. Fibre bundles are composed of numerous elementary fibre cells, which are divided into several laminate structures (N. Wang, Liu, & Peng, 2013). Adjacent cells are bonded with each other by the middle laminate. In addition, the mechanical properties of the composed laminates are determined by their components, cellulose arrangement (Bergander & Salmén, 2002) and moisture content (Astley, Harrington, & Stol, 1997). Such complex multiscale structure leads to large mechanical variability of fibre bundles. Many researchers have studied the variability of fibre bundles at different levels. Sun, Zhao, Wang, and Ma (2014) calculated the effects of volume fraction of cellulose crystal and the microfibril angle in S2 layer (the middle layer of secondary wall) on the axial Young's modulus of natural fibres through a multiscale model. Zhai, Li, Pan, Sugiyama, and Itoh (2012) found that fibre bundles in different layers presented distinguishable stiffness and anatomy. Liu, Huang, Wang, and Lei (2015) studied the variations of morphology and tensile modulus of palm fibre bundles in leaf sheath at different locations. Charlet et al. (2007) concluded that cellulose content of the flax fibre was highest in the middle zone, thus, leading to the highest tensile modulus at this region. Gradient structures at different levels are thought to be beneficial for avoiding stress concentration under the given conditions (Ruggeberg et al., 2008). It can be inferred that such gradient stiffness and morphology of fibre bundles also affect the stability of maize stem.

So far, many investigations have been reported on the associations between the numbers of large/small vascular bundles and lodging resistance, but few studies are directly focused on the mechanical properties of crops fibre bundles. Khanna (1991) found that lodging resistance increases as the number of vascular bundles increases in wheat. However, other researchers reported that the number of vascular bundles was not significantly related to the lodging resistance in spring wheat (U. Zuber et al., 1999) or barley (Dunn & Briggs, 1989). These conflicting results indicate that the mechanisms of fibre bundles in relation with lodging resistance are still unclear. For a better understanding of the stability of maize plant, the mechanical properties of maize fibre bundles need to be fully studied. However, few publications have reported on the mechanical properties of maize fibre bundles and their contribution to lodging resistance.

The present study therefore focuses on the mechanical properties of maize fibre bundles. The stiffness of bundles at different heights was tested. The ultrastructures of bundles were observed by scanning electron microscope in order to help understand the mechanism of stiffness variations. For a better understanding of the relation between the mechanical properties of fibre bundles and the lodging resistance, the geometric parameters of maize stem and fibre bundles were measured.

2. Materials and methods

2.1. *Samples preparation*

Stems (around 1.8 m long) were collected from mature maize plants. The height and the diameter of the stems were measured by using a measuring tape and a digital calliper, respectively. Firstly, the stems were cut into 6 pieces and numbered sequentially from base to top (Fig. 1). Each piece was around 300 mm and included 2 to 4 internodes. Afterwards, they were retted in a sealed container at room temperature (24–30 °C) for 20 days. After retting, the stems were softer (the gums in the stem completely dissolved in the water) and the fibre bundles were then carefully extracted from the stems by hand using sufficient water. The obtained fibre bundles were then dried in air (Fig. 2), packed in a plastic bag and stored in a refrigerator. In order to retain their integral structures, no further treatment was carried out to the bundles.

2.2. *The influence of retting on the morphology of fibre bundles*

It is hard to measure directly the stiffness of green fibre bundles due to the difficulty in separating bundle and