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Stiffness and toughness gradation of bamboo from a damage tolerance perspective

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ABSTRACT

Typical bamboo plants, in order to gain phototropic advantage over other land plants, are known to achieve heights of up to 20 m. They have also evolved radially graded and have almost transversely isotropic elastic properties (with the longitudinal direction being the axis of isotropy) primarily owing to the areal distribution of fibre bundles. These bundles are densely packed in the outer periphery of the cross section and sparsely in the inner. As shown in a previous work (Mannan et al., 2016), the axial modulus of a bamboo culm can be estimated from a careful measurement of the angle that cellulose microfibrils make with the axis of the fibres and their areal density distribution. In the first part of this paper, using these micromechanical estimates as the starting point and a combination of digital image correlation and Finite Element simulations, more complete information about the overall stiffness of a culm and its variation across the radius is obtained. Further, these stiffness measurements are used to determine crack resistance curves for almost all crack growth and loading direction combinations possible in a radially graded, transversely isotropic material. Finally, these fracture toughness measurements are used to show how the radially graded stiffness and toughness helps bamboo to convert flaws of all orientations into ones that propagate in a splitting mode along the length of the fibres. It is surmised that, under bending loads, the fracture toughnesses in various orientations have evolved in a manner as to trigger easy kinking of all flaws to the longitudinal direction.

1. Introduction

Bamboo is a tall and slender land plant with a hollow, circular and gently tapering stem. Like many other natural materials, bamboo too is a multiscale composite (see, Fig. 1). The basic building block at the lowest length scale is a composite material consisting of very strong and mostly single crystalline cellulose in a hemicellulose-lignin matrix. Using a toolbox consisting of this basic building block, like in many other natural materials (Wegst et al., 2014), a strong and tough structure is synthesised. At the macroscopic level, the major contributors to the stiffness are bundles of fibrils oriented almost parallel to the axial direction. These bundles are close packed groups of circular fibrils, which in turn, are basically dense sclerenchyma cells reinforced by favourably aligned cellulose-hemicellulose-lignin building blocks. These fibre bundles are interspersed in a matrix composed of prismatic, hollow and thin-walled parenchymatous cells. The matrix resembles closed-cell foam. The parenchyma cell walls are also reinforced by the basic building block, albeit oriented less favourably than in the fibrils. Moreover, the fibre bundles are not uniformly dispersed in the matrix but are denser towards the outer periphery. The overall structure allows us to characterise bamboo as a fibre-reinforced, functionally graded, transversely isotropic material (the plane of isotropy being perpendicular to the longitudinal direction) with gradation in properties in the radial direction (see also, Liese, 1998 for a comprehensive discussion of the complete anatomy of a bamboo culm).

In a recent work (Mannan et al., 2016) (see also related works by Tan et al., 2011; Silva et al., 2008), it has been shown that the variation of the graded longitudinal stiffness along the radius closely correlates with the variation in the volume fraction of the fibre bundles. Moreover, the magnitude of the longitudinal stiffness depends on the mean fibril angle (MFA), which is the average orientation of the basic building blocks (i.e. the cellulose-hemicellulose-lignin composite) about the longitudinal axis. In a separate work (Mannan et al., 2017), the MFA at fine resolution over the fibril as well as the parenchyma cell walls has been mapped for a particular species of bamboo. While MFA $\bar{\mu}$ is around 15° (4–29°) in the fibrils, it is much larger (about 35°) in the parenchyma walls. As will be seen later, the average longitudinal stiffness of this species of bamboo turns out to be of the order of

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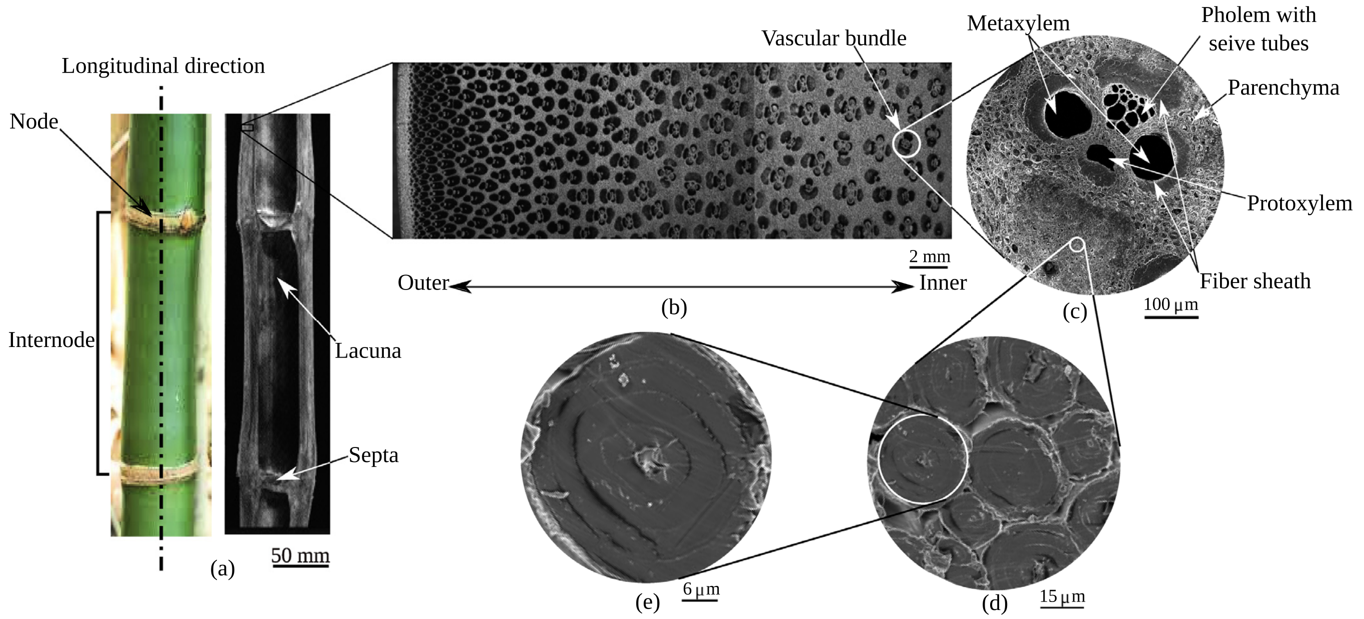

Fig. 1. A longitudinal section bamboo is shown in (a). The cross-section (b) has graded distribution of fibre bundles, denser at the outer radial location. Fibre bundles actually form sheaths around vascular tubes (c). The bundles themselves consist of close packed, almost circular sclerenchyma cells called fibrils (d) which are lamellar structures (e) with different orientations of the basic cellulose-hemicellulose-lignin building blocks in each lamella.

10.9 GPa. This is almost an order of magnitude superior to its averaged transverse stiffness.

The high stiffness of bamboo in the longitudinal direction is, for its survival, an important property. Bamboo can grow as tall as 10–20 m and has to bear its self weight as well as significant bending loads due to external forces due to wind. Maximising its ability to bend while keeping the self weight low seems to be a smart evolutionary strategy that bamboo (and many other plants like palms, see Wegst, 2011) has adopted. It can be shown that (following Wegst, 2011) for the same mass per unit length, bamboo has about 5 times more stiffness in bending compared to a solid circular rod made of the cell wall material. This is mainly because of the fact that much of the matrix in bamboo is made up of cellular parenchyma, which reduces its overall density significantly.

The rationale behind the so-called ‘stellar’ arrangement of the fibre bundles in order to achieve radially graded stiffness is more subtle. Wegst (2011) makes a comparison between the bending stiffness of a beam with graded longitudinal stiffness with one that has homogeneous stiffness (with the value being the average of the graded stiffness) and shows, that for the typical dimensions of the bamboo cross-section, grading may afford a further 30% increase in flexural rigidity. Thus, a stellar arrangement of fibres and a cellular matrix together, adds up to a very significant advantage in terms of flexural rigidity.

As far as its mechanical efficiency as a natural material is concerned, bamboo is superior to most other natural materials in terms of the specific modulus i.e. the ratio of its Young’s modulus and density. This suggests that as a tie in tension, bamboo is very well suited. But, if its efficiency as a beam in flexure is considered, balsa wood, coconut timber and other kinds of timber are superior. In terms of specific strength too (i.e. strength to density ratio), many varieties of silk are superior. However, based on the limited data available on the fracture of natural materials, bamboo turns out to be extremely efficient. Thus, in terms of both load and displacement at failure (Wegst and Ashby, 2004), bamboo ranks above most natural materials including woods, nut shells and cuticle. This observation motivates us to investigate the fracture properties of bamboo further and seek a possible connection between the gradation of properties in the radial direction and fracture.

Cracks in bamboo grow along interfaces between fibre bundles and parenchyma as well as parenchyma and parenchyma. Additionally, the fracture toughness of bamboo also seems to be radially graded. Amada and Untao (2001) have experimentally evaluated fracture toughness K_{Ic} of *Mouso* bamboo (*Phyllostachys edulis* Riv.) and observed that K_{Ic} forms a functionally graded structure. For *Moso* bamboo, both energy release rate (Tan et al., 2011) and crack opening displacement (Zhao et al., 2011) are larger in the low fibre density inner region. Also, the interlaminar fracture toughness in a similar species is known to be rather low in Mode-I (Shao et al., 2009) though under Mode-II the toughness increases significantly. In summary, the splitting modes of failure have lower toughness than the transverse (fibre-cutting modes) modes while all toughness values are graded in the radial direction.

Like in wood (Gibson and Ashby, 1997), several modes of crack propagation can be identified in bamboo. This is shown in Fig. 2. The axis of transverse isotropy is the longitudinal or L direction. The properties are graded in the radial or R direction. Fracture samples can be cut from the culm in the manner shown in the figure. Each sample is denoted by a pair of letters, the first of which is the direction normal to the crack plane and the second gives the direction of crack propagation. The gradation in colour indicates the gradation in fibre density; dark is more dense. In fibre-cutting modes like LR, a + or − sign indicates cases where the crack is on the rarer or denser side, respectively. A complete characterisation will require the determination of toughnesses for all the crack orientations and propagation directions shown. This task in this paper is accomplished for a specific variety of bamboo.

A larger question is how the survival of bamboo is affected by the toughnesses in the various modes and in particular, by the gradation in these properties in the radial direction. Through a combination of simple fracture mechanics based arguments and some Finite Element (FE) simulations, a plausible answer is provided to the question “Why is bamboo functionally graded?”

The paper is organised in the following manner. In a recent work (Mannan et al., 2016), the longitudinal stiffness of bamboo has been characterised, using information about the stiffness of the basic building block (i.e. the cellulose-hemicellulose-lignin complex), the MFA measurements in various cell walls and

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