Effect of Fiber on Tensile Properties of Moso Bamboo

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Bamboo is a natural bio-composite that has outstanding mechanical properties. Fibers are the structural building block of bamboo. Understanding the effect of fiber area on tensile properties of moso bamboo (*Phyllostachys pubescens* Mazei ex. H. Lebaie) will shed light on natural efficient design of bamboo. In this paper, fiber area and tensile properties of bamboo were tested on four bamboo slices, and a relationship found between fiber area and tensile properties. The results indicated that fiber volume increased exponentially in the radial direction from the inside to the outside of the culm wall. Bamboo tensile strength and MOE were linearly proportional to the fiber area. Fiber area also influenced bamboo fracture modes.

Keywords: Fiber area; Fracture modes; Moso bamboo; Radial direction; Tensile properties

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INTRODUCTION

Natural biological materials have a wide range of mechanical properties that are derived from their complex, hierarchical, and adaptable structures (Fratzl and Weinkamer 2007; Dunlop *et al*. 2011; Wegst 2011). Bamboo, as a typical graded fiber-reinforced bio-composite (Ray *et al.* 2005; Wang *et al.* 2012), exhibits remarkable properties and toughness due to its graded and hierarchical structures (Ghavami and Solorzano 1995; Shigeyasu *et al.* 1996; Ghavami *et al.* 2003; Ray *et al*. 2005). Moreover, its structure is graded in both longitudinal and radial directions. In the longitudinal direction, bamboo culm is cylindrical yet hollow and subdivided into several internodes by transverse diaphragms, as shown in Fig. 1(1) (Liese 1985, 1987; Jiang 2002; Wegst 2011). Additionally, the length of the internodes changes gradually from base to top. In the radial direction, the culm is composed of vascular bundles and parenchymal tissues (Liese 1980, 1992, 1998). Moreover, it is noted that vascular bundles are distributed densely in the outer region and sparely in the inner region (Fig. 1(2)) (Parameswaran and Liese 1976; Grosser and Liese 1971); meanwhile, size of the vascular bundles are changing gradually. The bamboo culm can be considered as a composite material, reinforced axially by aligned cellulose fibers embedded in a lignin matrix.

In terms of mechanical properties, bamboo exhibits excellent and directionally graduated mechanical properties due to its gradient and hierarchical structuring. Many papers have indicated that the strength distribution in the culm’s cross-section was proportional to the area of the fiber fraction (Shigeyasu and Untao 2001; Ray *et al.* 2005; Bechtle *et al.* 2010). The tensile strength of bamboo increases from the base to top (Jiang 2002; Wang 2001). Meanwhile in the radial direction, mechanical properties of bamboo increase from the inside to the outside of the culm. Yu *et al.* (2008) reported that the tensile modulus of elasticity of the outer tissue was 3 to 4 times higher than that of the inner. Furthermore, the tensile strength was 2 to 3 times higher as well.

So far, work on the gradient of mechanical properties has focused on bulk mechanical testing and characterizing properties at the macro scale. In addition, reporting on the gradient of bamboo structure and mechanical properties has been done separately. Also, there are limited studies on the quantitative relationship between the area of fiber and the mechanical properties of bamboo.

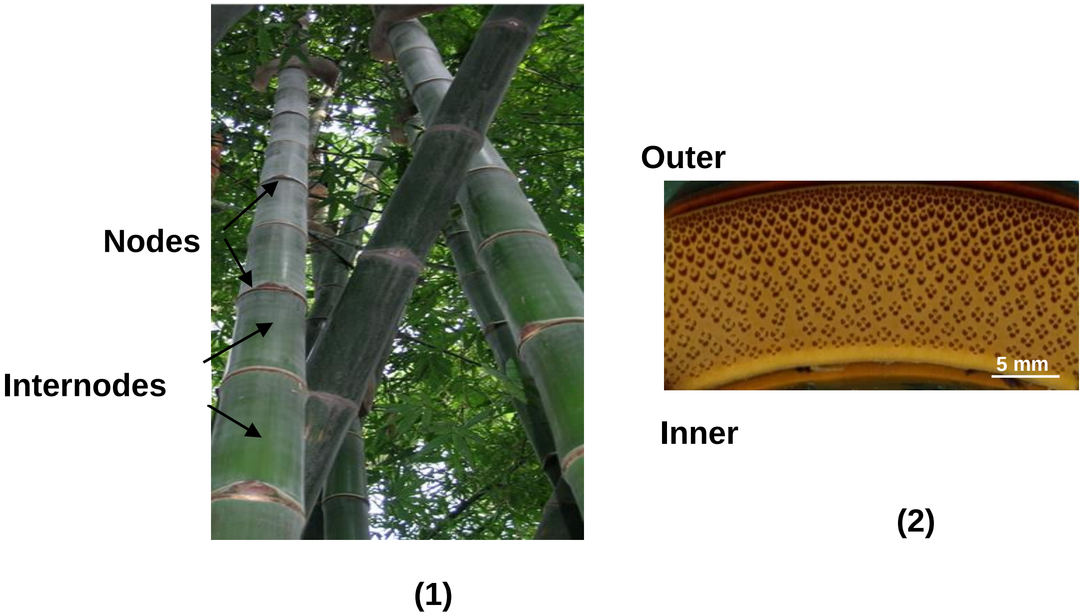


Fig. 1. Hierarchical structures of bamboo: (1) moso bamboo stem, cylinder with nodes and internodes; (2) cross section of culm presenting a typical composite structure of vascular bundles and parenchyma tissues

A systematical investigation of bamboo was therefore studied, focusing on the quantitative relationship between the internal structure of bamboo and the corresponding mechanical properties. This paper quantitatively analyses the effect of fiber area on bamboo tensile properties. Tensile properties were tested on four bamboo slices. Confocal laser scanning microscopy (CLSM) and optical images were used to precisely calculate the fiber area on the corresponding slices of the bamboo. Quantitative relationships among the tensile strength, the modulus of elasticity (MOE), and the fiber area were then established.

EXPERIMENTAL

Materials

Four year-old Moso bamboo culms were obtained from the Fuyang bamboo plantation in Zhejiang province, China. The culm diameter at breast height ranged from 100 to 120 mm, and the average thickness of culm walls was 10 to 12 mm. The culms were air-dried for more than one year before being subjected to mechanical tests. Samples were prepared from internodes between 1.5 and 2.0 m from the base of the bamboo culm.

Methods

Smaller sections with dimensions of 1 (R) × 10 (T) × 120 mm (L) were cut from the middle of the internodes. In order to characterize the fiber distribution and tensile properties gradient across the bamboo culm wall thickness, the sections were split into four slices successively along the radial direction. The slices were numbered 1, 2, 3, and 4, with 1 being on the outer side and 4 bring on the inner side of the culm (Fig. 2). After polishing, the specimens had dimensions of 1 (R) × 10（T) × 120 mm (L) (Fig. 2).

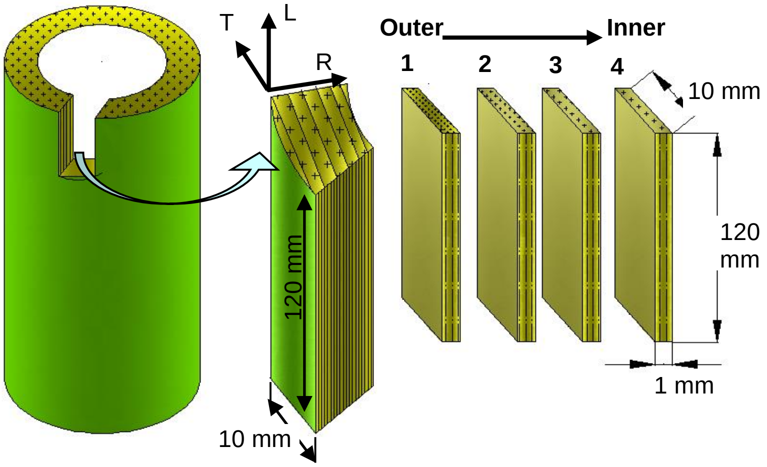


Fig. 2. Schematic of the splitting process and dimensions of bamboo slices along the gradient of fiber bundle density

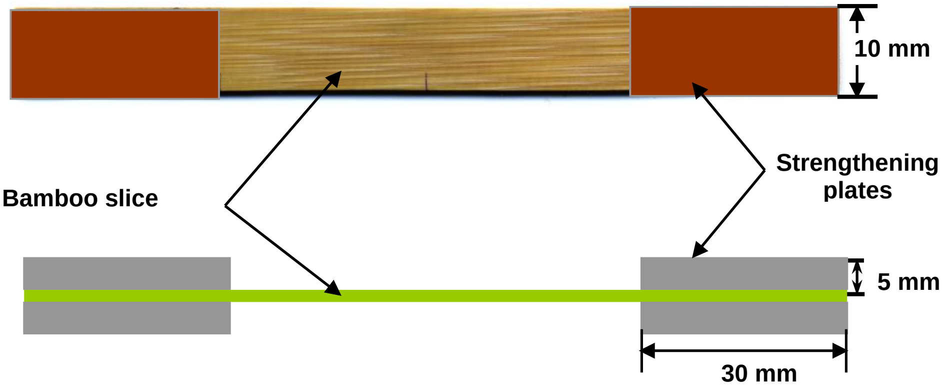
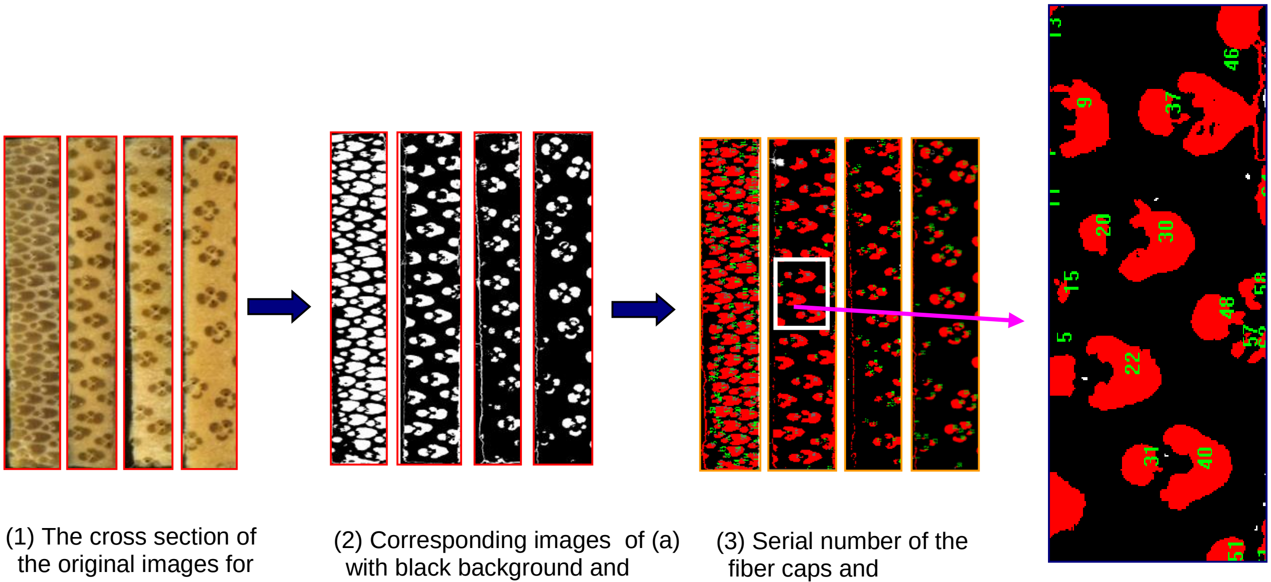


Fig. 3. Schematic of specimens for tensile tests

Before tensile tests, clamping pieces (glass fiber composite sheets) were glued on both ends of the specimens, which assisted in clamping using tensile grips (Fig. 3). Prior to testing, all of the samples were conditioned in a climate-controlled chamber (65% RH and 20 °C) for more than three weeks.

For tensile tests, a tensile tester (Instron, series 5582; Norwood, MA) equipped with a load cell possessing a capacity of 10 kN was applied at displacement rate of 3 mm min^{-1} to fracture. A clamping extension meter, with a 25-mm gauge length, was used to record the strain synchronously. Ten samples were tested for each of specimens 1 through 4 along the radial gradient, and the average calculated.

Fiber area was calculated using digital images and analysis software (Image-Pro Plus). The cross-section close to the fracture were smoothed and polished. The cross-sections were then photographed using a scanner, and images were analyzed by Image-Pro Plus software (Fig. 4).



(1) The cross section of the original images for the four slices

(2) Corresponding images of (a) with black background and white fiber caps

(3) Serial number of the fiber caps and calculations

Fig. 4. Fiber caps area analysis process

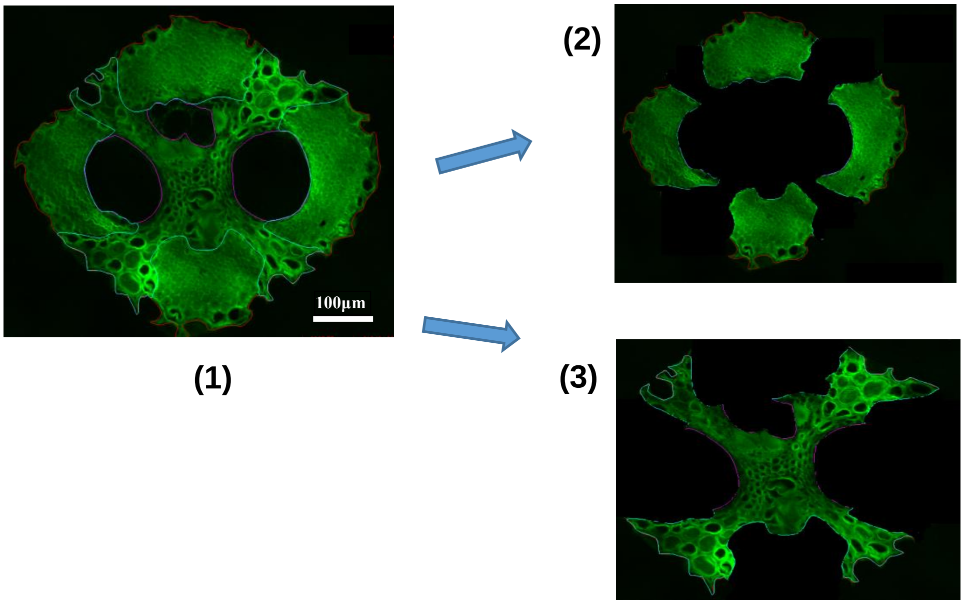


Fig. 5. Structure of a vascular bundle. (1) CLSM images of vascular bundle; (2) Fiber caps of the vascular bundle; (3) Porous phase of vascular bundle

The area of vascular bundles was calculated exactly by confocal laser scanning microscopy (Zeiss LSM 510 Meta; Oberkocken, Germany) (Fig. 5). Vascular bundles were dried and embedded in epoxy droplets. Once polymerized, the embedded bundle were cut into 1.5 μm-thick sections on a microtome and stained in 0.001% (w/v) acridine orange for 4 min. Cross-section of vascular bundle was obtained by CLSM with an excitation wavelength of 514 nm VIS laser module. The outline of fiber caps and porous phase of each vascular bundle was traced. Cross-section areas of fiber cap and parenchyma tissue were measured by Image analysis software (NIH).

RESULTS AND DISCUSSION

The variation of fiber area (computed for each slice) with increase in distance from the inner to the outer side of the bamboo culm is presented in Fig. 6.

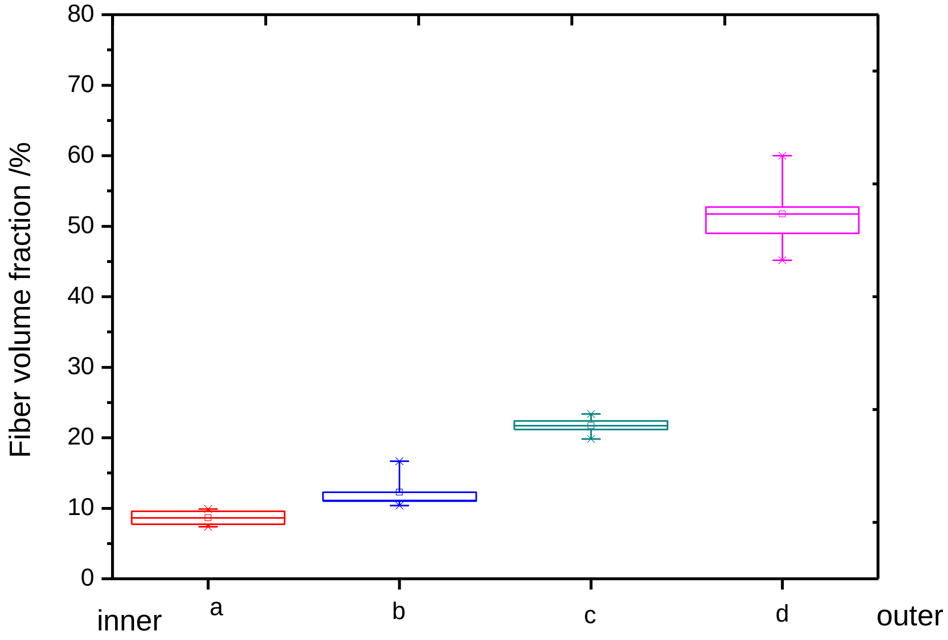


Fig. 6. Variation of fiber area with increase in distance from the inner side of the bamboo culm

The fiber area of four slices was: innermost slice 4: 8.53%, next slice 3: 12.69%, next slice 2: 21.86%, and outermost slice 1: 60%, which increased with progression from the inner side to the outer. Based on the test data, the regression equation of fitted curve was,

$$y = 0.0442e^{0.5676x} \tag{1}$$

where y denotes fiber area, x denotes distance to the inner side, and $R^2 = 0.9787$.

From the CLSM images (Fig. 7(1)), it can be seen that vascular bundles are composed of fiber caps, porous phase, and vessels. On the cross section of bamboo, it was found that the size of vascular bundles decreased towards the inner side of the bamboo, with fiber cap area decreasing, and with the porous phase and vessels size increasing (Fig. 7(2)).

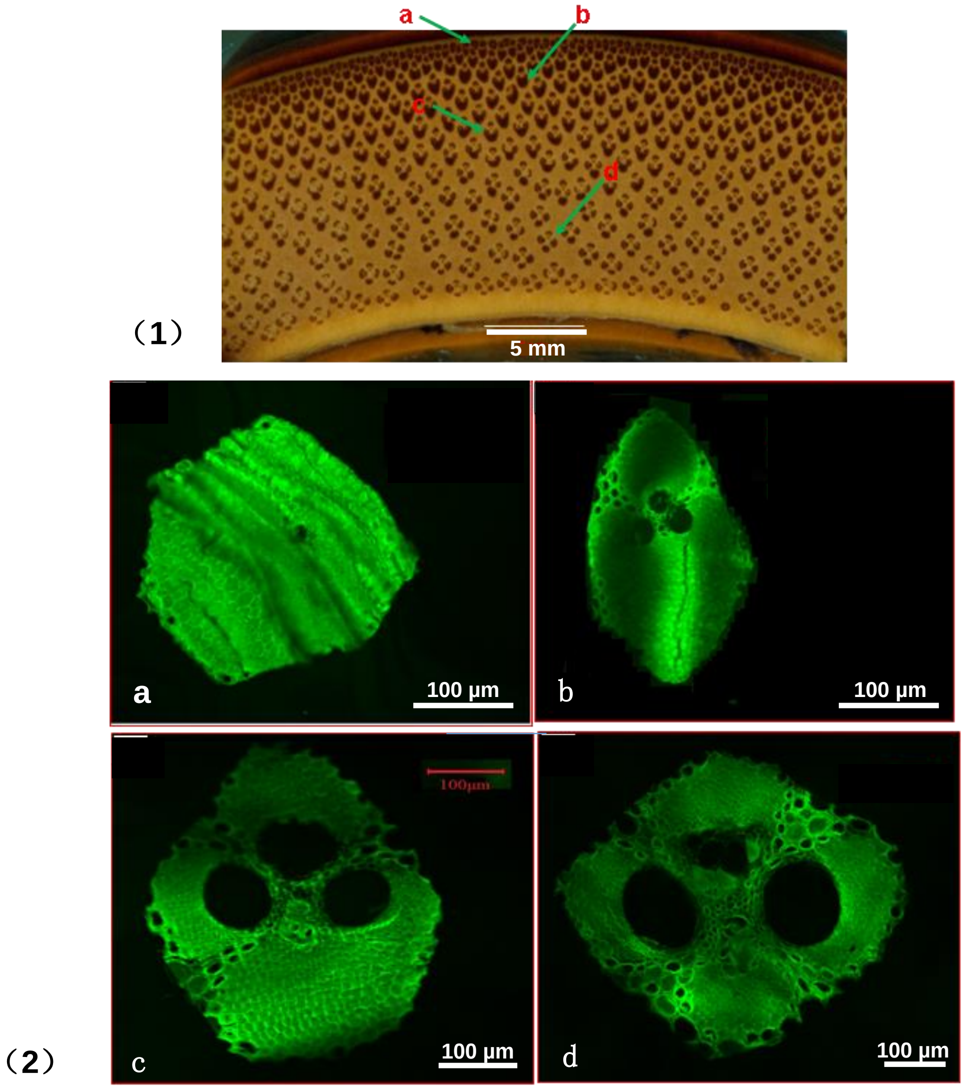


Fig. 7. (1) Graded sizes and shapes of vascular bundles in the radial direction by confocal laser scanning microscopy; (2) position of the four vascular bundles shown in (1) QUOTE y=0.0442 0.5676x

Mechanical properties of composites are mainly decided by the area of fibers. The variation of tensile strength and MOE with increase in distance from the inner side of the bamboo culm in the radial direction is presented in Figs. 8(1) and 8(2). Both of them increased towards the outside. Tensile strength and MOE of the inner slice were 101.85 MPa and 6.65 GPa, respectively, but they increased to 294.26 MPa and 30.3 GPa in the outermost slice, which were 2.89 and 4.56 times of the innermost one.

Moreover, tensile strength and MOE had a high correlation with volume fraction of fibers; variations of both tensile properties with fiber area are presented in Figs 8c and 8d. The tensile strength and MOE also increased as a function of fiber area. Both tensile strength and MOE increased gradually but had a naturally occurring scatter (higher variation) in the samples tested. Figs 8(3) and 8(4) showed that the discrete level of tensile strength and MOE was greater in the outer slices. The statistical equation of tensile strength with fiber area is presented as Eq. 2,

$$y = 428.65x + 32.8\ ,R = 0.9157 \tag{2}$$

where y denotes the tensile strength and x denotes the fiber area.

The linear equation of MOE and fiber density is given as Eq. 3,

$$\mathrm{y = 57.82x + 0.165, R = 0.9525} \tag{3}$$

where y denotes MOE and x denotes fiber area.

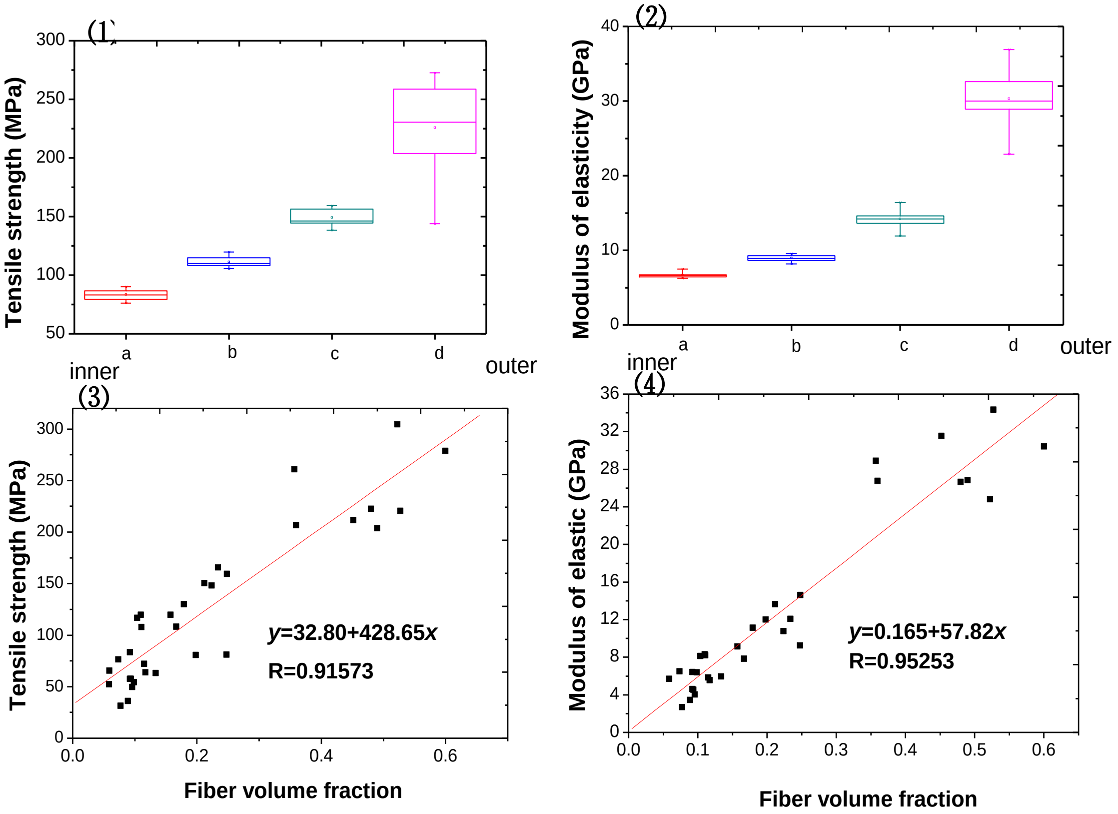


Fig. 8. (1) Gradient of tensile strength in the radial direction; (2) gradient of MOE in the radial direction; (3) relationship between tensile strength and fiber volume; (4) relationship between MOE and fiber volume

Fiber area also defined the fracture modes of bamboo. The fracture modes of four bamboo slices are presented in Fig. 9. It was found that slices with more fibers mainly fractured at the interface of fibers and parenchyma tissue, and that such fracturing involved fibers splitting and breaking (Figs. 9(1) and 9(2)). On the contrary, slices with fewer fibers failed mainly in the parenchyma, and there was a neat pattern of breakage of fiber and tissues (Figs. 9(3) and 9(4)). Tensile properties of the fibers were much higher than those of the parenchyma tissues (Ray *et al.* 2005; Shao *et al*. 2010; Li and Shen 2011; Tan *et al.* 2013). When subjected to tensile loading, bamboo with a high concentration of fibers had splitting and slipping occur before fiber breaking. In addition, the great disparity between the mechanical properties of the fibers and parenchyma tissues also led to interfacial shearing, as depicted in Fig. 9(3).

Fig. 9. Fracture modes of four bamboo slices

CONCLUSIONS

1. The structure and mechanical properties of bamboo were tested accurately by new methods in this paper. Fiber area increased exponentially with increasing distance from the inside of the culm. Tensile properties were in correspondence with the fiber area.
2. Bamboo fibers play a major role in tension. Both tensile strength and MOE of bamboo were in linear relationship with fiber area.
3. Fiber area influenced the fraction modes of bamboo. Interfacial splitting and slipping were the main fracture modes of bamboo with more fibers. However, bamboo with fewer fibers failed with extensive fiber breakage and cracking of parenchyma. Shearing also occurred in the interface of fibers and parenchyma tissues.

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