Variation in Tensile Properties of Single Vascular Bundles in Moso Bamboo

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Abstract

Moso bamboo (*Phyllostachys edulis*), an apt example of an anisotropic, functionally graded composite material, is the most important commercial bamboo species of China. This species has excellent mechanical properties due to its unique vascular bundle structure. This article examines the variation in mechanical properties of single vascular bundles with respect to their location within a bamboo culm. The mechanical exfoliation method was used to prepare the single vascular bundle. This study found that moso bamboo has superior stiffness and strength. Additionally, the variation in properties was large in the radial direction but minimal in longitudinal direction. The large variation in mechanical properties of vascular bundles can be ascribed to the synergistic effect of the fibrous sheath and parenchyma rather than to changes in fibrous sheath properties. This study provides a basis for the structure application for moso bamboo.

Bamboo is an attractive natural material in terms of cost and significant structural and environmental advantages thanks to its abundance, rapid growth, and excellent mechanical properties (Van der Lugt et al. 2006, Li et al. 2020). It has been found in rapidly developing areas of the world where timber resources are often limited (Lou 2010). As renewable resources, bamboo can be used in a wide range of applications, especially moso bamboo (*Phyllostachys edulis*), which is one of the most used species in the world (Deng and Wang 2018). Over the decades, many studies have been conducted on the efficient utilization of bamboo for various products suitable for household, building, decoration, and other fields (Zhou et al. 2019, Balaji et al. 2020,Ye et al. 2020). However, the heterogeneous structure of bamboo culm has hindered its efficient utilization. Bamboo is a typical hierarchical material, and the vascular bundle, which consists of vessels and a large number of fibers surrounded by parenchyma cells, plays a role as the reinforced phase in bamboo composite. They occupy roughly 40 and 50 percent of the entire bamboo stalk, respectively (Chen et al. 2018).

Bamboo does not present secondary growth. Its mechanical strengths are different, depending on the different structural directions (longitudinal, tangential, and radial), making bamboo an orthotropic material too (Ahmad and Kamke 2005). Bamboo's diameter and thickness have a macroscopically graded structure, while the fiber distribution exhibits a microscopically graded architecture (Amada et al. 1997). Many previous studies reported that the vascular bundles varied significantly in size from the exterior to the interior (Li et al. 1960, 1962; Grosser and Liese 1971; Kumar and Dobriyal 1992; Zhou et al. 2012; Santhoshkumar and Bhat 2015).

Furthermore, mechanical properties of fiber bundles of bamboo have been studied previously (Ghavami et al. 2003, Yu et al. 2006b). Amada et al. (1996) found a tensile strength of 0.61 GPa and a tensile modulus of 46 GPa for bamboo fiber bundles, which were calculated indirectly based on the volume ratio of fibers to parenchymal cells and based on the macroscopic tensile modulus and strength of bamboo. Yang and Liu (1996), using the same method, reported a tensile strength and tensile modulus of 547.68 MPa and 27.60 GPa, respectively, for moso bamboo fiber bundles. All these authors reduced the mechanical properties of vascular bundles from the testing results of bamboo thin slices using the rule of mixture.

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Forest Prod. J. 71(3):246–251.
doi:10.13073/FPJ-D-21-00002

However, only a few studies have experimentally analyzed the mechanical properties of bamboo vascular bundles so far. Jiang (2002) reported that the tensile strength of vascular bundles from moso bamboo was 950 MPa while giving no modulus value. Shao et al. (2009) found that the tensile strength and modulus of fiber bundles of moso bamboo were 0.482 and 33.9 GPa, respectively. Previous studies show that there is a linear relationship between the tensile properties of bamboo and volume fractions of vascular bundles. Furthermore, a study by Li and Shen (2011a) shows that it is possible to extract vascular bundles from different height locations of moso bamboo using an alkali treatment method, and they obtained strength values of vascular bundles between 495 and 854 MPa. Wang and Shao (2020) measured the tensile properties of fiber bundles more accurately, and the average tensile strength and tensile elastic modulus were 523.2 MPa and 22.3 GPa, respectively. However, the modulus of elasticity of vascular bundle is calculated by the indirect method, and the quantitative analyses of the variation in longitudinal and radial directions are still absent for the mechanical properties of a single vascular bundle.

In the present work, moso bamboo vascular bundles were picked out using the mechanical stripping method. By means of the tensile test, it aimed to measure the modulus of elasticity more accurately and study the variation law of the tensile properties of single vascular bundles in the longitudinal and radial directions of the bamboo stem.

Material and Methods

Sample preparation

Five four-year-old moso bamboo samples were taken from a plantation located in Huangshan, Anhui Province, China, whose total length and breast diameter ranged from 7.50 to 9.32 m and 9.20 to 10.5 cm. Three straight internodes were cut at heights of 1, 3, and 5 m from the bottom of the bamboo culm and designated as the base, middle, and top sections, respectively. Straight strips with a length of 100 mm and a width of 20 mm were then cut at the thicker end of each culm section from north to south. Each strip was analyzed to determine the mechanical variation of vascular bundles in the radial direction, and from the inside to the outside of the culm, according to the shape and arrangement, the vascular bundles were divided into 14 layers, the first layer near the outer culm wall and the 14th layer near the inner culm wall (Fig. 1). All the strips were subdivided into three slices along the radial direction. Subsequently, the slices were steeped in water for 48 hours. Single vascular bundles were then carefully stripped out from the soft slices under a stereomicroscope. To prevent bending caused by the different shrinkage rates of vascular bundles and surrounding parenchyma in the air, the vascular bundles were kept straight, while the surrounding parenchyma was totally eliminated. Finally, to avoid destruction of tissue during the manual extraction process, the straight vascular bundles were then carefully examined under a microscope. Except for the difficulty of sample preparation in the first and 14th layers, the number of vascular bundle samples in the other layers was 10 to 15.

Tensile test

Once the samples were prepared, a tensile test was carried out using a universal tensile test machine (Instron Micro-

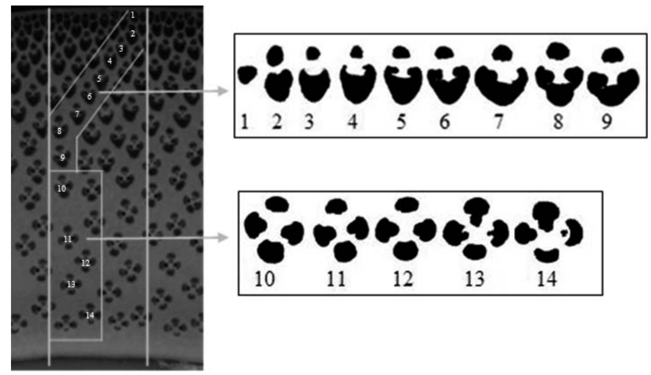

Figure 1.—A single vascular bundle sample stripped from a moso bamboo culm (simplified illustrations of the number of layers represented by a single vascular bundle from the outer to the inner surface of the culm)

tester 5848). The test was conducted with a crosshead speed of 1.5 mm/min and a load cell capacity of 500 N. The strain gauge length of the vascular bundles (about 50 mm) was determined using two black spots on the vascular bundles as well as by indirect detection with a video extensometer from the machine path (Figs. 2a and 2b). As the black spot surrounded the vascular bundle, the video extensometer can capture any slight deformation of the vascular bundle in tension. Four pieces of trapezoidal poplar veneer with 25-mm length and 1-mm thickness were also glued onto the ends of the specimen to avoid any specimen slide from the clamps (Fig. 2c). Tensile testing was carried out under an environment of 20°C at 45 to 50 percent relative humidity.

Area calculations

For the calculations, the areas of every broken vascular bundle were determined with a confocal scanning laser microscope (Meta 510 CSLM; Zeiss). Detailed measurement methods are available in the literature (Shang et al. 2015). The area of vascular bundle was then measured with software provided by the instrument producer (Fig. 2d). The shape of the vascular bundle, including the vessel interiors, parenchyma, fiber, and sieve tubes, was analyzed.

Load-elongation curves generated during the experiment were then converted to stress-strain curves, with the tensile strength and modulus for vascular bundles obtained on the basis of vascular bundle area and the initial span length.

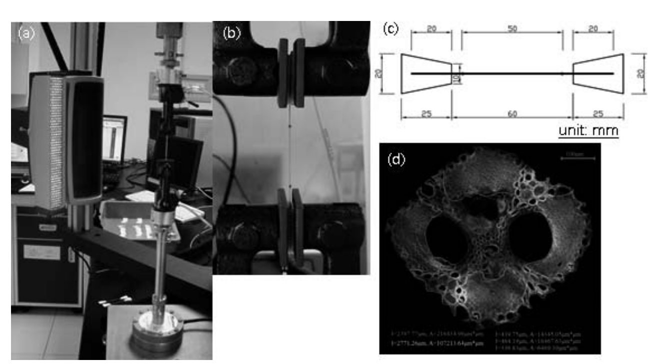

Figure 2.—A single vascular bundle tested in tension (a, b, c) and measured in area (d).

Results and Discussion

Mechanical behavior in tension

All the vascular bundles tested exhibited a linear stress-strain behavior to failure (Fig. 3). This behavior is the same as that found for single bamboo fibers. Yu et al. (2011) proposed that the fibers tested exhibited a quasi-linear stress-strain behavior to failure mode. The vascular bundle is composed mainly of fibers and parenchyma. Tensile strength is proportional to the volume fraction of fibers, and fiber strength is 12 times higher than that of the parenchyma (Lakkad and Patel 1981). The tensile strength and tensile elastic modulus of vascular bundles of 12 layers were obtained as shown in Table 1. The study found that mechanical properties showed an increasing trend along the radial direction from the inside to the outside of the culm, and the stress-strain curve changes dramatically as the volume of vascular bundles increases. It was also found that tensile strength degradation corresponds with fiber density degradation. Hence, the highest strengths correspond to the regions closest to the outer side of the culm with the highest fiber density. Conversely, the lowest strength corresponds to the regions closest to the inner portion of the culm, where fiber density is the lowest.

Radial variation in the mechanical properties

At the macroscopic level, moso bamboo shows large radial variation in the mechanical properties (Zhang et al. 2006). Tensile modulus at locations closer to the outer surface of a culm is more than three to four times larger than comparative value for locations closer to the inner surface. Furthermore, tensile strength closer to the outer surface is more than two to three times larger than values reported for samples taken closer to the inner surface (Yu et al. 2006a). The radial direction in the mechanical properties of bamboo is obviously related to the fiber distribution pattern, which is far denser in the peripheral region of the culm.

Figure 4 shows the radial variation of a single vascular bundle in the mechanical properties. Large variation in the tensile modulus was observed across the second to 13th layer in the samples. The results showed that tensile modulus clearly decreased from the second to the ninth layer, while little change was observed from the 10th to the 13th layer. Tensile strength was also found to be lower in the inner region and increased along the radial direction from the inner to the outer periphery. This distribution pattern is the same as the one found for the axial tensile strength of sliced bamboo specimens (Amada and Untao 2001, Ray et al. 2005, Tan et al. 2011). Therefore, the

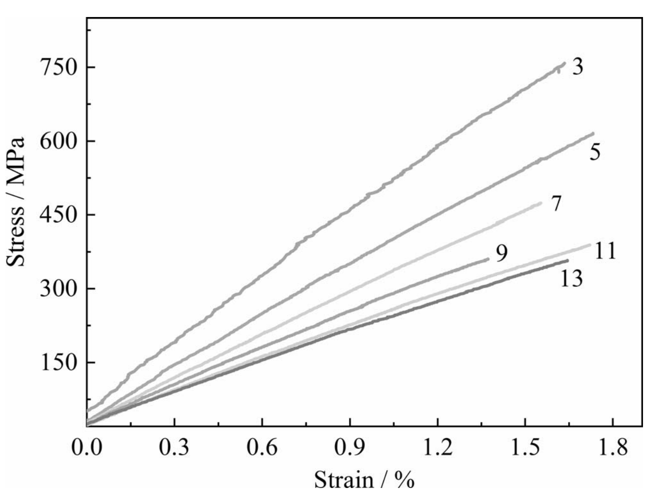

Figure 3.—Stress-strain curves of single moso bamboo vascular bundles in tension (3, 5, 7, 9, 11, and 13 represent numbers of layers)

Table 1.—Descriptive statistics of analysis results of bamboo vascular bundle tensile test.

Layer	Count	Fiber content (%)	Tensile modulus (GPa)	Tensile strength (MPa)
2	12	86.7	44.2	602.7
3	10	81.5	43.9	704.8
4	11	76.2	37.5	596.5
5	10	72.8	36.7	641.0
6	10	69.7	31.7	536.3
7	10	60.4	27.6	484.0
8	10	54.3	26.7	461.8
9	13	53.5	24.8	433.4
10	12	52.0	24.9	428.9
11	10	50.9	22.2	421.3
12	10	49.8	19.4	338.5
13	9	49.1	21.4	364.5

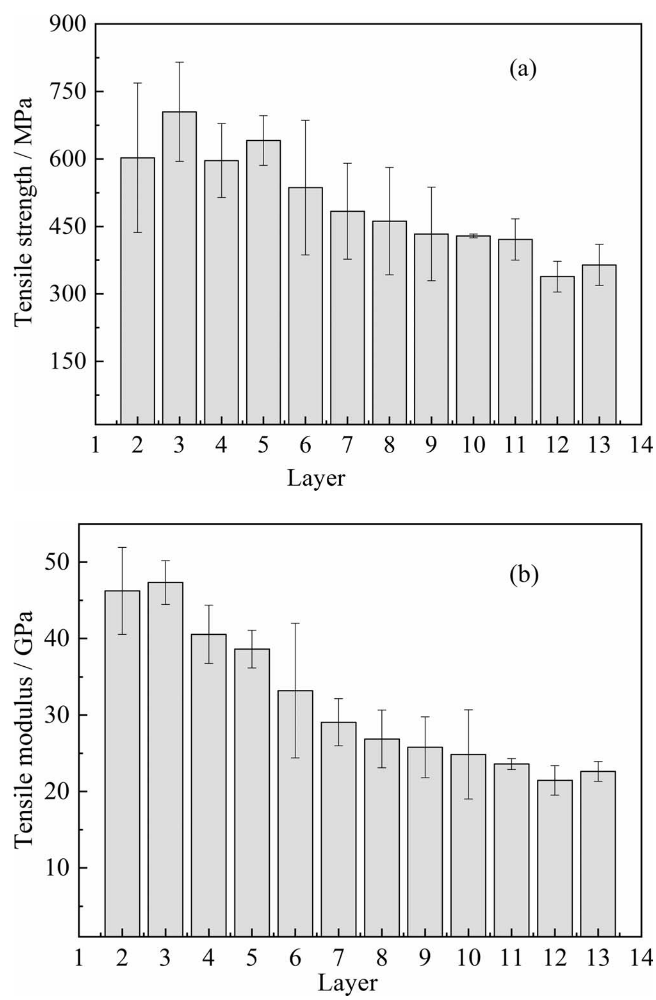

Figure 4.—Radial variations of (a) tensile elastic modulus and (b) tensile strength of moso bamboo vascular bundles.

tensile properties of a single vascular bundle from the outer layer to the inner layer across the cross section of bamboo culm showed a rapid decrease at first, followed by a more moderate decrease.

The mechanical variation in the pattern of a single vascular bundle along the radial direction reported in this article is slightly different from those found in previous studies. Li and Shen (2011b) found a linear increase in bamboo vascular bundle tensile properties along the radial direction from the inner to the outer surface of a culm. However, the vascular bundles in their experiments were extracted from six slices of unequal thickness using an alkali treatment method in which the vascular bundles would be damaged inevitably by chemical reaction. The study of Yang et al. (2017) indicated that alkaline solution could lead to the shrinkage, pits, and microfiber being observed on the bamboo fiber cell wall, where hemicellulose would be degraded seriously when treated with an NaOH solution, leading to the reduction in modulus of elasticity. However, the results are consistent with the observations of Wang and Shao (2020). From the inner to the outer part of the bamboo stem, tensile strength of bamboo fibers tended to increase slightly, and the tensile elastic modulus had obviously increasing tendency. The similarity is that all the specimens we used were peeled by hand after only being soaked in water for several days, and the specimens are connected by an intercellular layer that consisted of pectin and lignin with no change in chemical components.

Longitudinal variation of mechanical properties

Due to an increasing fiber density, the mechanical properties of bamboo also increase along the vertical direction from the bottom to the top of a culm (Li 2004, Correal and Arbeláez 2010). However, this trend is different at the fiber level. Wang et al. (2014) found that the longitudinal variation in tensile properties of bamboo fibers (*Dendrocalamus latiflorus*) was rather small. For the vascular bundles, the trend is also different from those observed at both the macro level and cellular level. The vascular bundles from the 10th to the 14th layers were chosen so that we could study the longitudinal variation, as the difference in area value was small (Shang et al. 2012). As shown in Figure 5, the tensile elastic modulus and the tensile strength decreased from the bottom to the top section, and the tensile elastic modulus varied significantly with height. This result is the opposite of those found in the macroscopic study. These differences may be due to the intervention of parenchymatous ground tissue. This relationship should be investigated in future studies.

The effect of main composite of the vascular bundle

Vascular bundles consist of a fiber sheaths, vessels, sieve tubes, and parenchyma cells around the vessel and sieve tubes. There are two types of morphology for vascular bundles in moso bamboo: semi-open and open (Fig. 1). Vascular bundles from the first to the ninth layer show a semi-open morphology, with vascular bundles arranged in clear regular dimensions with gradually increasing sizes. For the semi-open vascular bundles, in the first layer, the vascular bundle area was found to be smaller than the parenchyma and conducting tissue, and other tissues were absent. Conducting tissue could be seen from the second

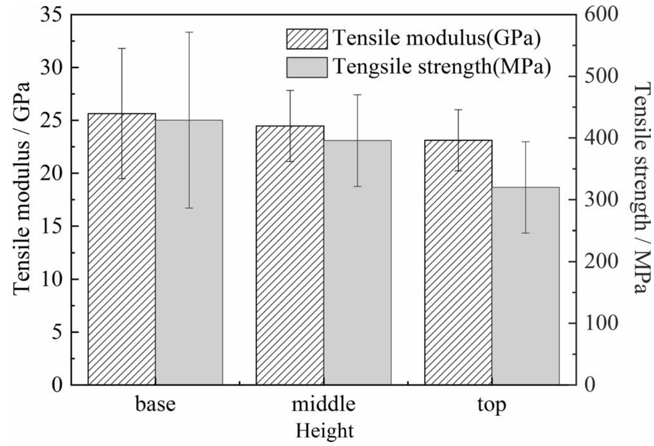

Figure 5.—Height variation in tensile properties in the 10th to 14th layers of moso bamboo vascular bundles.

layer on. In the second layer, both length and the area of the vascular bundle in the radial direction increase within the vascular bundles in the first and second layers, and the area of conducting tissue was usually zero or extremely small, whereas the thick-wall fiber cells were arranged closely to form a tough culm. From the second to the ninth layer, the area of vascular bundle increases from the outer to the inner section. It was observed that the area of fibrous sheath also increased from the outer to the inner section. In addition, fibrous sheath area and radial position (from outer to inner locations) had a significantly positive linear relationship. Conversely, vascular bundles from the 10th to the 14th layer belong to the open morphology type. They were distributed uniformly in the transverse section, while the areas of vascular bundles remain fairly constant. It was found that the relationship between the vessel area and the radial position of the vascular bundle could be represented by a linear equation, but the area of fibrous sheath tended to decline as the radial position increased. Because of this decline, the area of inner vascular bundles remained steady.

Fiber content increased from the 13th to the second layer in the fiber sheath, as shown in Figure 6. From the second to the ninth layer across a bamboo culm, fiber content was found to increase from 54.5 to 86.7 percent, while much smaller variation in fiber content was observed from the 10th to 13th layer, where fiber content decreased from 52 to 49.1 percent. The variation in fiber content was related to morphological variation of the vascular bundle in the radial direction, as shown in Figure 1. It was found that the tensile properties increased from the 13th to the second layer, which was consistent with increasing fiber content in the fiber sheath, as shown in Figure 6.

The remarkable mechanical properties of bamboo are attributed to the closely packed fibers constituting the sheath in the vascular bundles. In order to analyze the effect of main composites, including the fibrous sheath, on the tensile properties of vascular bundles, the tensile properties of the fibrous sheath were calculated, as shown in Figure 7. For the calculation, the authors assumed that the vascular bundle was made only of a porous fibrous sheath that contains vessel cavities, parenchyma, and sieve tubes. The area of fibrous sheath was then substituted for the area of vascular bundles to calculate its tensile modulus and tensile strength. As shown in Figure 7, the radial variation in tensile elastic

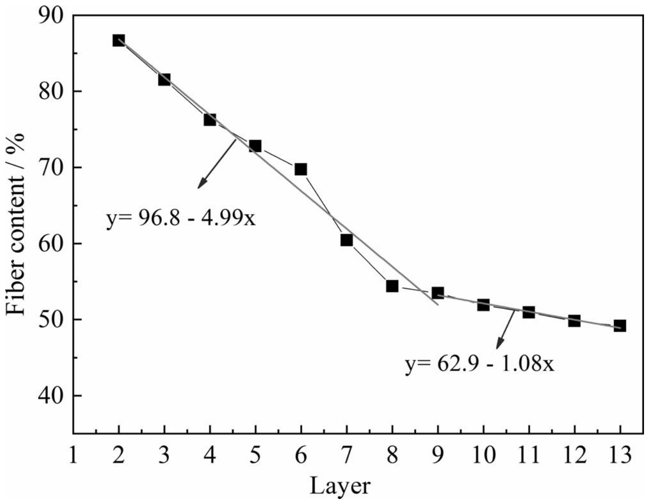

Figure 6.—Relationship between fiber content and radial location of vascular bundles.

modulus and tensile strength at the fibrous sheath level was small. This result seems to agree well with observations for single fibers. Due to their small variation in multifactor authentication, Wang et al. (2014) found that the radial variation of single *D. latiflorus* bamboo fibers in the mechanical properties was small. In comparison, the mechanical properties of vascular bundles in the radial direction decreased from the outer to the inner parts of the culm, while the mechanical properties of the fibrous sheath, which was the main component of the vascular bundles in the radial direction, showed a different pattern of variation. Hence, the mechanical properties of the vascular bundles were related to not only the mechanical properties of fibrous sheath but also the porous properties, which weakens their mechanical properties.

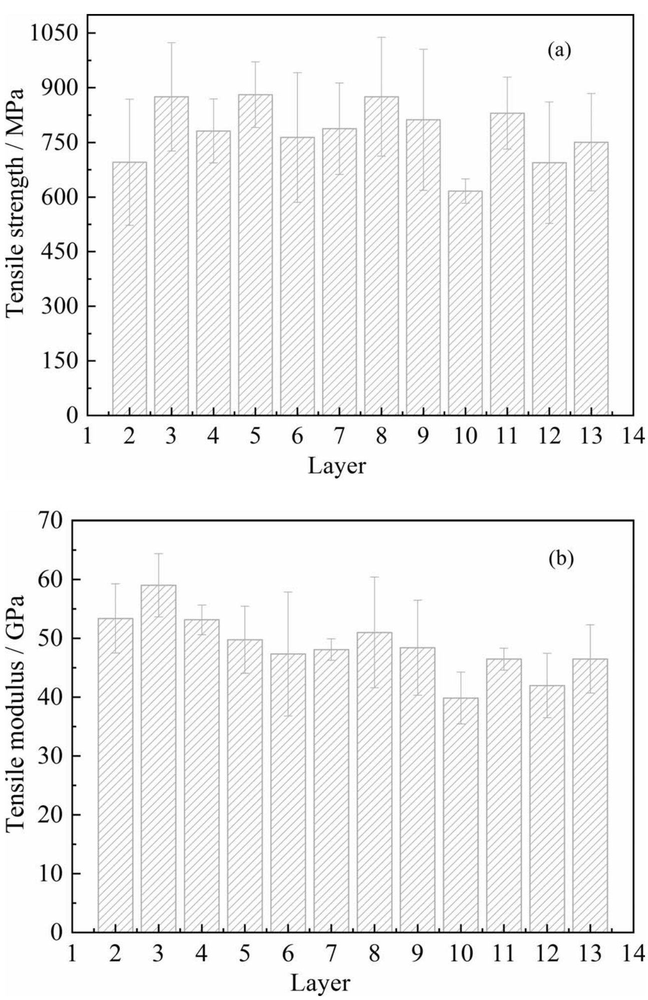

Figure 7.—Radial variations in (a) tensile strength and (b) tensile elastic modulus in moso bamboo fibrous sheath.

Conclusions

Single vascular bundles from moso bamboo show excellent mechanical performance in both stiffness and strength. The mechanical properties in the radial direction decreased sharply at first, followed by a moderate fall from the outer to the inner parts of the culm. This may be due to the fact that the fiber content in the vascular bundles decreases from the outer to the inner parts. The variation in tensile modulus is rather small in the longitudinal direction, while tensile strength actually shows a decreasing trend along the longitudinal direction. Accordingly, the large variation in the mechanical properties of vascular bundles is due to the synergistic effect of the fibrous sheath and parenchyma and not only to changes in fibrous sheath properties. These results can provide support for the application of original bamboo structure.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (grant no. 31670565) and the National Key Research and Development Program of China (grant no. 2016YFD0600904). We would also like to thank Mr. Zhengjun Sun for his guidance on this article as well as the editors and reviewers for their recognition and hard work.

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