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Experimental Investigations on the Mechanical Properties of Bamboo Fiber and Fibril

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Abstract: Bamboo based composite materials are widely used for structural components in building and textile industries. The structural hierarchy across different scales could enhance the strength and toughness of bamboo for load-bearing applications. Firstly, chemical components of bamboo fibril are described, and bamboo fibril specimens are fabricated through chemical solution processing; Secondly, functionally graded mechanical properties of macroscopic bamboo fibers are studied with tensile experiments, and relations between graded mechanical properties and microstructures are explored; Afterwards, hierarchical microstructure characterization of bamboo across different scales are performed using scanning electron microscopy (SEM), and mechanical properties of bamboo fibrils are tested using homemade in-situ micro-tension setup. The results indicate that the elastic modulus, ultimate strain and strength of bamboo fibers are: 5.952 GPa, 0.0136 and 81.13 MPa respectively. The Young's moduli, ultimate strains and fracture strengths of the five fibril samples located in (10.478, 12.285) GPa, (0.0172, 0.0217) and (181.87, 230.50) MPa, respectively. These experimental results suggest that the modulus and ultimate strength of bamboo fibril are higher than that of bamboo fibers which are attributed to several main factors including the ages of the bamboo, bamboo species, multi-lamella structures of the fibrils, geometry differences of fibrils, etc.

Keywords: Bamboo fiber, Fibril, Mechanical properties, Micro-tension

Introduction

Bamboo materials are widely used in musical instruments [1], structural components of buildings [2], and relevant textile industries. Bamboo has developed highly optimized functionally graded hierarchical structures [3] through the evolution process during the past millions of years. The structure of bamboo consists of epidermis, parenchyma cells and vascular bundles, which are surrounded by supporting fibers. From mechanical properties point of view, bamboo can be regarded as a type of fiber reinforced composite. The main functions of bamboo structure are maintaining nutrition transport and providing mechanical strength to withstand external loadings. The optimized composite structure is benefit for withstanding static and dynamic bending loads exerted by the mass of bamboo trunk and wind/storm/snow loading [4]. The gradient bamboo structure and mechanical properties at different hierarchical levels were well optimized along radial direction [5-8]. In the past years, the mechanical properties of bamboo fiber and fibril were studied with different methods. For example, it was reported that the tensile strength and modulus of Japan bamboo fiber are 610 MPa and 46 GPa, respectively [9]. Ray *et al.* [3] reported that the tensile strength of India bamboo composite is ranged between 40 and 170 MPa. Zhou *et al.* [10] reported that the elastic modulus of China bamboo (Phyllostachys edulis (Carr.)) obtained via nano-indentation is 10.4±1.8 GPa.

In this article, relations between mechanical properties and hierarchical structural of bamboo are explored. Firstly, bamboo fiber and fibril specimens are fabricated through mechanical cutting and chemical processing, respectively. Afterwards, the functional graded mechanical properties of bamboo fibers are investigated. Finally, the tensile mechanical properties of micro fibrils are tested with homemade in-situ micro-tension setup.

Experimental

Materials and Chemicals

In this paper, bamboo samples were collected from Taojiang County (the country of bamboo), Hunan Province, China. The particular species are locally known as Nanzhu. The investigated Nanzhu samples (6 years old) are harvested in winter, and dried in the open air for 3 months before the experiments.

Bamboo Fibril Fabrication

The collected bamboo fibers are immersed into mixed alkali solution at 100 ^{o}C for 2 hours. The solution comprised

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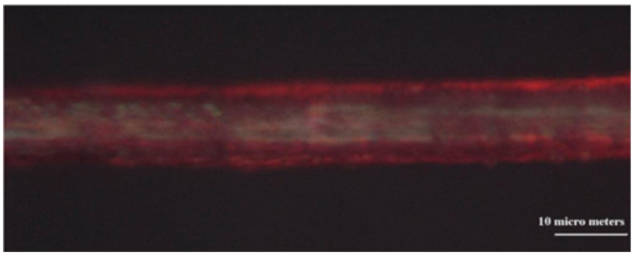

Figure 1. Image of dyed fibrils under optical microscope.

of 10 % NaOH, 2 % sodium pyrophosphate and 3 % additive sodium sulfite solution are manufactured by Sinopharm Chemical Reagent Beijing Co., Ltd., China. Afterwards, the cementing materials in-between neighboring fibrils are removed off, and the fibril are de-bundled. Additive sodium sulfite and sodium pyrophosphate solution is effective for avoiding oxidation of fibrils, and removing cementing materials between fibrils [11-14]. After being decomposed in mixed alkali solution properly, the resultant fibrils are collected and neutralized with acetic acid, then cleaned with de-ionized water adequately. Finally, the harvested bamboo fibrils are dyed red in order to improve the visualization under optical microscope (Figure 1).

Microstructure Characterization of Bamboo with SEM

Bamboo has a higher strength-to-weight ratio than steel and concrete, and is used as renewable and sustainable structural materials for decades. The microstructure characterization of bamboo is investigated using scanning electron microscopy SEM (SS-550, Shimadzu, Japan), as shown in Figure 2 and Figure 3. The shape of vascular bundle at the outer periphery shows elliptical shape, and its long axis is along radial direction. From external to internal region, the shape of vascular bundles changes from elliptical into circular, then elliptical shape again, under which condition the long axis is vertical to the radial direction. The fibers inside the vascular bundle consist of a smaller circular part and a bigger V-type part near the outer region. From the outer to the inner region, the fibers are divided into four neighboring lunar-shape parts gradually. The hollow bamboo fiber and fibril both consist of lamella structures at the macroscopic or microscopic scale. The hierarchical hollow structures of fiber and fibril can enhance the mechanical integrity and toughness of bamboo structures. Thus, bamboo has macroscopic and microscopic optimized structure for bearing multiple environmental loads [11,15].

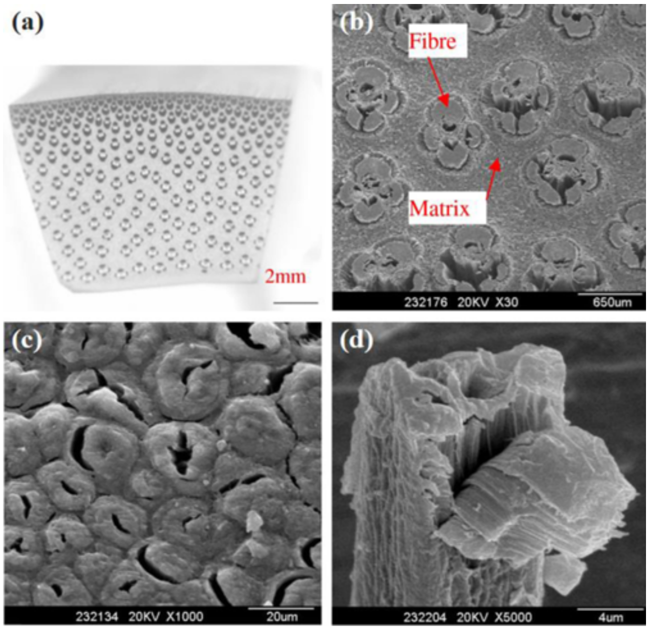

Figure 2. Hierarchical structure of bamboo; (a) bamboo culm, (b) vascular bundles, (c) neighboring fibrils, and (d) single fibril.

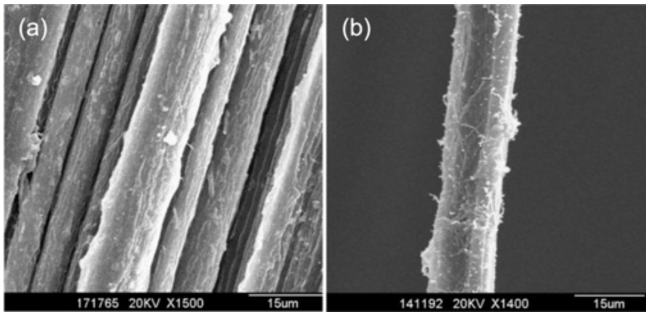

Figure 3. De-bundle process of fibrils; (a) fibril bundles not decomposed fully and (b) fibril decomposed fully.

Results and Discussion

Hierarchical Structure Characterization and Mechanical Testing of Bamboo

The unique robust mechanical properties of bamboo origin from its natural composite structure, including mainly the cellulose microfibrils and lignin-carbohydrate complex matrix. In a bamboo fiber, cellulose microfibrils are surrounded by lignin-carbohydrate complex (LCC) matrices that mainly contain lignin and hemicellulose. Lignin is a natural phenolic macromolecule that mainly exists in the plant secondary cell wall. It is made up of three main phenylpropanoid sub-units, namely p-hydroxyphenyl (H-type), guaiacyl (G-type) and syringyl (S-type) units.

The raw bamboo is cut into 7 equal-thickness slices along radial direction, and 5 elliptical fiber (vascular bundle) specimens are fabricated from each slice for tensile experiments, and the cross-section of the bamboo fibers is treated as elliptical shape. As shown in Figure 4, the tested elastic modulus and ultimate strength show functionally graded properties from the inner to the outer side. The reasons are that the vascular bundles may be viewed as

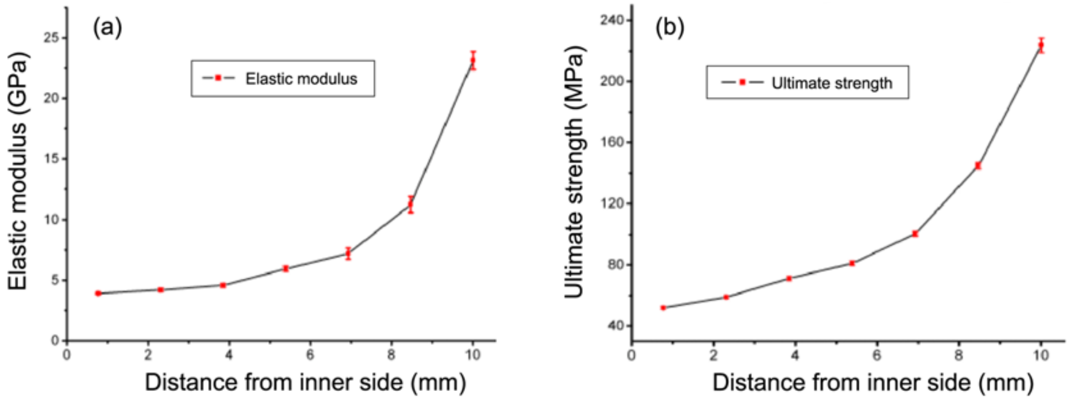

Figure 4. Mechanical properties of vascular bundles; (a) modulus of vascular bundles and (b) ultimate strength of vascular bundles.

composite of fibrils and residual matrix structure (consists of xylem vessels, meta-xylem vessel, and the neighboring thin-wall cells), whose strength is much lower than that of fibrils, and the content proportion of fibrils within the vascular bundles decreases nonlinear from the outer to the inner periphery. In order to understand the mechanical properties of vascular bundles better, the mechanical properties of fibrils should be investigated thoroughly.

In-situ Micro-tension of Fibril

In order to test the mechanical properties of bamboo fibril, a homemade setup was employed to perform in-situ uniaxial micro-tension tests [16]. Figure 5 shows the images of the micro-tension setup and the testing system. The micro-tension setup consists of four main parts: the supporting unit, the PZT actuating unit, the force sensing unit and the specimen loading stage. The supporting unit is a U-type structure made of alumina alloy. The PZT actuating unit consists of four cylinder translation bars, two slides and two PZT actuators. The two slides, with one end connected to the PZT actuator and the other to the supporting spring, are driven by the PZT actuators and can glide symmetrically in the two opposite directions along the cylinder translation bars. The force sensing unit consists of two force sensors, which is made of double-cantilever beams. A programmable control unit is utilized to drive the actuators continually or step by step with DC voltage varying from 0 to 200 V with a resolution of 0.05 V. The PZT actuators may produce displacement range about 100 μm, thus the displacement resolution between two specimen loading stages is 25 nm. As to testing of bamboo fibrils, the double-cantilevered sensors with micro force resolution of 7.8 μN and force range of 0-120 mN is adopted for tensile force measurement.

Before the micro-tension experiments are conducted, the testing system is connected and calibrated carefully. The fibril is fixed on the specimen loading stages, and super glue is used for fixing the fibril on the loading platform. Misalignment of the specimen is adjusted under microscope beforehand, thus the axis direction of bamboo fibril is parallel to the tension axes of the loading platforms. The micro-tensile experiments are conducted under optical microscope (magnification: 1050 X), thus the displacement resolution is 0.18 μm. After fabrication, alignment and fixing steps, the fibril was subjected to uniaxial quasi-static

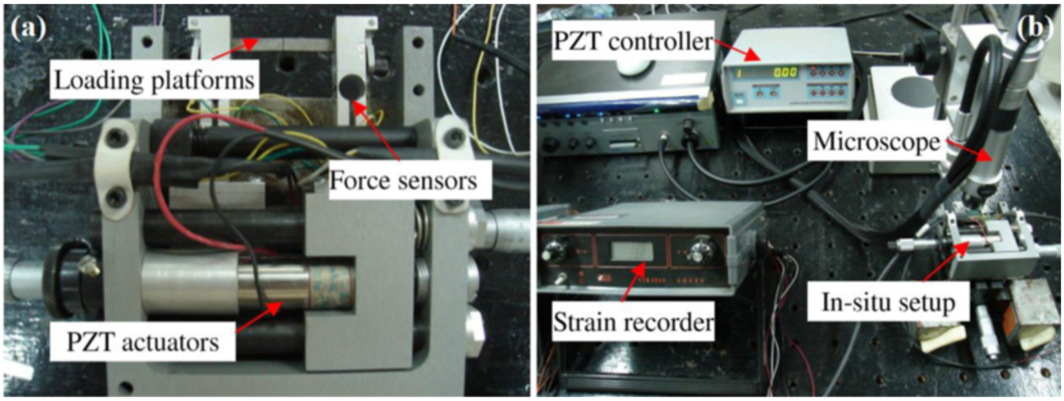

Figure 5. Images of (a) micro-tension setup and (b) testing system.

Table 1. Mechanical properties of the five bamboo fibrils (the diameters and lengths of each bamboo fibril are different)

Samples	Gauge (µm)	Diameter (µm)	Modulus (GPa)	Ultimate strength (MPa)	Ultimate strain (%)
1	173.9	10.8	11.5	200.7	1.84
2	169.4	10.4	12.285	220.5	1.81
3	188.6	17.2	10.487	181.87	1.72
4	206.8	7.44	10.501	222.49	2.088
5	207.5	6.76	10.717	230.5	2.169

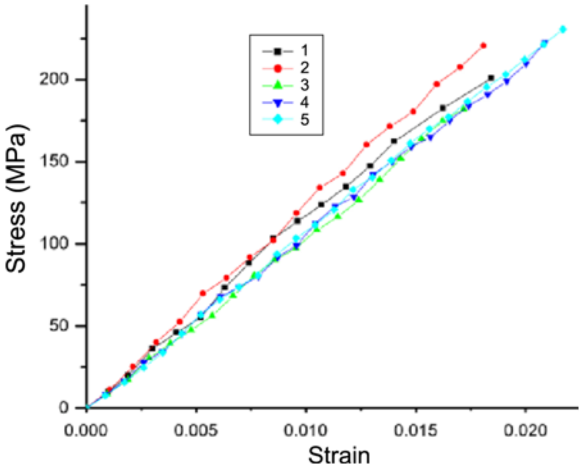

Figure 6. Stress and strain curves of the fibrils.

micro-tension test, and the results are shown in Table 1.

The diameter of the five bamboo fibrils is between 6.7 and 17.2 µm, and the stress-strain curve is given in Figure 6. Due to initial slack behavior of the fibril at the beginning of the micro-tension process, the first two readings are ignored for the calculation of elastic modulus [17]. The elastic modulus, ultimate strain and ultimate strength of the fiber are 5.952 GPa, 0.0136 and 81.13 MPa correspondingly. The Yong's modulus of the five fibril specimens is ranged between 10.478 and 12.285 GPa, and the fracture strength of the fibrils are between 181.87 and 230.50 MPa, the ultimate strain are between 0.0172 and 0.02169. The fibril shows linear mechanical behaviors during the tensile process, and the tensile and fracture images are presented in Figure 7.

In the research, the Young's modulus and the ultimate fracture of fibrils is larger than that of the fibers (vascular bundles). The reasons can be explained as follows: the bamboo fibers consist of fibrils and weak matrix (consists of cementing materials between fibrils, xylem vessels, meta-xylem vessel and neighboring thin-wall cells), and the fiber may be also regarded as fibril-reinforced composite materials, while the bamboo fibril shows highly degree of microstructure-closely related crystalline nature.

Discussion

There are several different reports on the mechanical properties of bamboo fiber and fibrils in literatures. To mention a few, the tensile strength of Japan bamboo fiber is 610 MPa, and the elastic modulus is 46 GPa [9]. The tensile strength of India bamboo composite is between 40 and 170 MPa [3]. The elastic modulus of China bamboo studied via nano-indentation is 10.4±1.8 GPa [10]. These tested results differ from each other, and also differ from our results.

There are several reasons for these differences: (1) the testing methods are differed with each other, and the specimen preparation procedures are also different. (2) The influence of chemical process on the mechanical properties of bamboo fibril that consists of cellulose reinforcement embedded in hemi-cellulose and lignin matrix shows microstructure-closely related crystalline nature, which has very high level of crystalline properties and orientation effect, and 10 % NaOH solution treatment shows little effect on the degree of crystallinity and tensile strength [11-14]. (3) There are Type I and Type II cellulose inside bamboo fibers. The crystalline degree of cellulose and hemi-cellulose is different between different specimens. The crystalline degree is different within one specimen when the moisture content is changed. The crystalline degree variation will

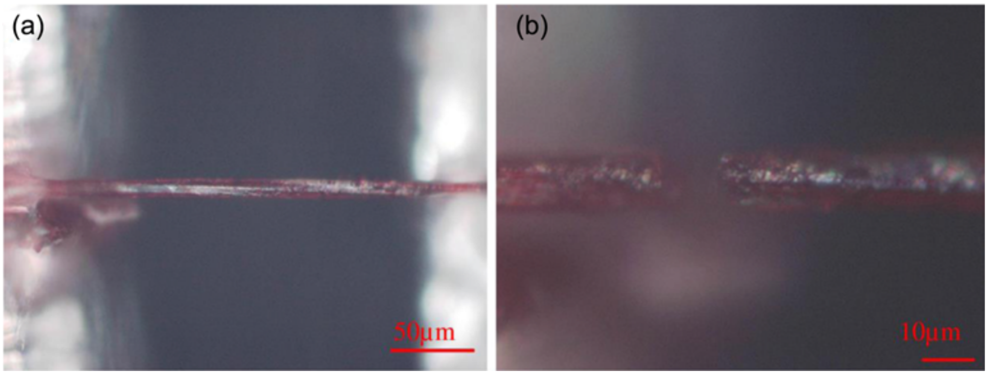

Figure 7. Optical picture of fibril undergoing micro-tension; (a) the aligned and fixed fibril and (b) local fracture.

have a remarkable effect on the mechanical and physical properties of bamboo fibers and fibrils [3,12,14,18]. (4) There are several different lamellas inside the fibril wall. The cellulose, hemi-cellulose, lignin contents and micro cellulose angle distribution is different within the lamellas, causing different mechanical and material properties. The lamellas thickness and the diameters of fibrils are also different. (5) The natural environment (temperature, relative humidity, wind seasons, nutrition of lands) and the bamboo species are diverse in different regions [18-20]. (6) The mechanical properties of bamboo will change remarkably with age [20]. The cell wall thickening of bamboo fibers cells during the culm elongation and early maturation will continue for several years. Liese and Weiner [21] have shown that the development of bamboo fibers occurs in two main phases. The main phase happens during the first 2 years and leads to the development of fibers with lignified cell walls. The second phase follows several years later and additional lamellae are formed during this period. Such lamellae are initially un-lignified and are laid down onto an already lignified secondary wall. Eventually these new lamellae also become lignified themselves. Research findings indicate that the strength of bamboo increases with age and attains an optimum value at 2.5-4 years and then decreases after maturity [22].

Conclusion

The hierarchical microstructures of bamboo are characterized with SEM, and the functionally graded mechanical properties of bamboo fiber are studied with tensile experiments. In order to further understand the mechanical properties of bamboo at micro scale, bamboo fibrils are fabricated through chemical processing, and the corresponding mechanical properties are tested with homemade in-situ micro-tension setup. The results suggest that the mechanical properties of fibril are superior to fiber. The bamboo fiber may be regarded as the composite of fibrils and matrix, and the bamboo fibril shows a high degree of microstructure-closely related crystalline nature which has very high level of crystalline character and orientation effect properties.

Acknowledgments

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References

1. J. P. Cottingham, *J. Acoust. Soc. Am.,* **136**, 2283 (2014).
2. B. Sharma, A. Gatóo, M. Bock, and M. Ramage, *Const. Build. Mater.,* **81**, 66 (2015).
3. A. K. Ray, S. Mondal, S. K. Das, and P. Ramachandrarao, *J. Mater. Sci.,* **40**, 5249 (2005).
4. S. C. Burgess and D. Pasini, *J. Eng. Des.*, **15**, 177 (2004).
5. S. A. S. Zainathul Akhmar, M. Z. Nurul Aizan, A. Mohd Muhiddin, J. Siti Sarah, and Z. Nor Hazwani, *Adv. Mater. Res.,* **812**, 53 (2013).
6. C. Hong, Y. Yan, T. Zhong, Y. Wu, Y. Li, Z. Wu, and B. Fei, *Cellulose*, **24**, 333 (2017).
7. X. Zhou, L. Chen, S. Huang, G. Su, and Y. Yu, *Tran. Chin. Soc. Agr. Eng.,* **30**, 287 (2014).
8. J. Xie, J. Qi, T. Hu, C. F. De Hoop, C. Y. Hse, and T. F. Shupe, *J. Mater. Sci.,* **51**, 7480 (2016).
9. S. Amada and S. Untao, *Compos. Part B-Eng.,* **32**, 451 (2001).
10. L. Zou, H. Jin, W. Y. Lu, and X. Li, *Mater. Sci. Eng. C,* **29**, 1375 (2009).
11. S. Yang, X. Liu, B. Fei, Z. Jiang, X. Yang, and H. Shan, *Chin. For. Sci. Technol.,* **3**, 70 (2012).
12. N. S. V. Gupta, K. V. S. Rao, and D. S. A. Kumar, *IOP Confer. Ser. : Mater. Sci. Eng.,* **149**, 012093 (2016).
13. Y. Wang, G. Wang, H. Cheng, G. Tian, Z. Liu, Q. F. Xiao, X. Zhou, X. Han, and X. Gao, *Text. Res. J.*, **80**, 334 (2010).
14. L. Ma, H. He, C. Jiang, L. Zhou, Y. Luo, and D. Jia, *J. Macromol. Sci. B*, **51**, 2232 (2012).
15. H. Chen, Y. Yu, T. Zhong, Y. Wu, Y. Li, Z. Wu, and B. Fei, *Cellulose*, **24**, 333 (2017).
16. W. Wu, X. Li, and L. Liu, *Rev. Sci. Instru.,* **80**, 085107 (2009).
17. E. P. S. Tan, C. N. Goh, C. H. Sow, and C. T. Lim, *Appl. Phys. Lett.,* **86**, 073115 (2005).
18. R. Krishnaprasad, N. R. Veena, H. J. Maria, R. Rajan, M. Skrifvars, and K. Joseph, *J. Polym. Environ.,* **17**, 109 (2009).
19. P. K. Kushwahak and R. Kumar, *J. Reinf. Plast. Comp.,* **30**, 73 (2011).
20. B. Lybeer, J. Van Acker, and P. Goetghebeur, *WoodSci. Technol.,* **40**, 477 (2006).
21. W. Liese and G. Weiner, *Wood Sci. Tech.,* **30**, 77 (1996).
22. S. M. Yang, Z. H. Jiang, H. Q. Ren, B. H. Fei, and X. E. Liu, *Spectrosc. Spect. Anal.,* **30**, 3399 (2010).