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Nanoscale structural and mechanical characterization of the cell wall of bamboo fibers

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ABSTRACT

Bamboo is a natural biological composite with superior mechanical strength and toughness. What is the secret recipe that Mother Nature uses to fabricate bamboo? Here we report discovery of cobble-like polygonal cellulose nanograins with a diameter of 21–198 nm in the cell wall of bamboo fibers. These nanograins are basic building blocks that are used to construct individual bamboo fibers. Nanoscale mechanical tests were carried out on individual fiber cell walls by nanoindentation. The nanograin-structured bamboo fibers are not brittle in nature but somewhat ductile. The bamboo fiber reinforcing mechanisms are discussed with reference to the hierarchical structure and mechanical properties of individual bamboo components.

1. Introduction

Being a typical natural biological material with unique multiscale structure and superior mechanical properties, bamboo has long been fascinating scientists to take it as one of the most extensively referenced models for biomimetic design of composites [1,2]. It is well known that bamboo is one kind of functionally gradient fiber-reinforced composite and its excellent mechanical strength and toughness are attributed to its fibers [3–6]. What is the secret recipe that Mother Nature uses to fabricate bamboo? What roles does the multiscale structure play in strengthening and toughening of bamboo? Can we learn from this to produce bamboo-like composites? Here we report the nanoscale structure in the cell wall of bamboo fibers and its mechanical properties that are significant for understanding fiber growth and maturation, and for promoting the development of biomimetic materials.

Nature has evolved highly complex and elegant mechanisms for materials design and synthesis. Bamboo, as one of the most important natural biological materials, has served humanity, especially in Asia for thousands of years [7]. It has long been widely used for constructional purposes as well as for the pulp and paper in industry [8,9]. It is well known that the superior mechanical properties of bamboo are mainly attributed to its unidirectionally oriented fibers which account for 40% of a culm by volume [10]. Bamboo fibers are distributed in the internodes of vascular bundles as fiber caps or sheaths surrounding the conducting elements (including vessels, sieve tubes, and companion cells) [10]. How do these sparsely distributed fiber sheaths contribute to the strength and toughness of bamboo culm? Like many natural biological materials, such as bone, nacre, deep-sea sponges, and wood, bamboo possesses a hierarchical structure from the molecular scale to the macroscopic level. At the microscale level, it has proven that the spindle-like short tiny fibers with a length of 1.9 mm and a diameter of 15.3 μm tapered at both ends are intercalated longitudinally among one another to form the structure of the fiber caps. For each individual fiber, the fiber cell wall has a polylamellate structure with alternating broad and narrow lamellae [9–11]. The mechanical properties of bamboo fibers are still lacking in literature. Although much work has been focused on bamboo fiber maturation [2–14], the correlation between bamboo fiber structure and mechanical properties as well as bamboo growth mechanisms are poorly understood.

To date, structural and mechanical characterization of bamboo has mainly been carried out at the macro/microscopic level [10,15,16]. Very little has been reported on the nanoscale structure and mechanical properties of individual bamboo constituents such as fibers [17–20]. Existing strengthening and toughening mechanisms as well as simulation and computational studies cannot explain entirely the ultra-high strength and toughness of bamboo. This suggests that there are unrevealed structural secrets that significantly contribute to the strength and toughness of bamboo. Here we limit our focus to bamboo fiber cell wall. In this study, the nanoscale structure of the cell wall of

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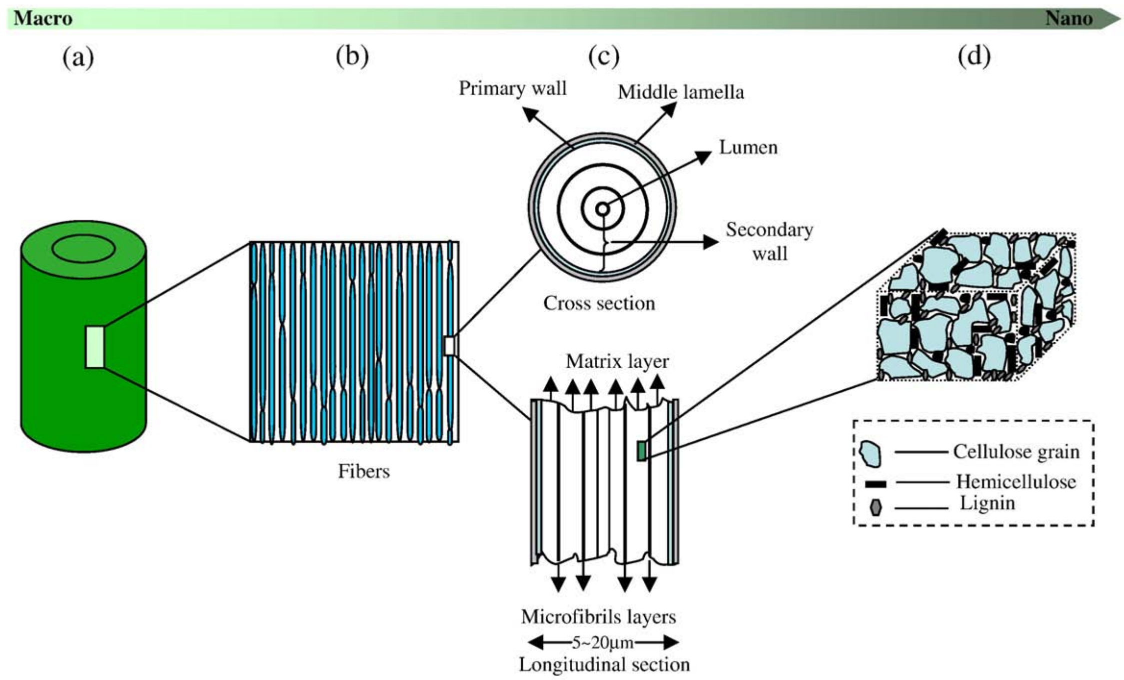

Fig. 1. Hierarchical organization of bamboo fibers over different length scales. (a) Bamboo culm, in which bamboo fibers are distributed longitudinally along the culm. (b) The spindle-like short tiny fibers, tapered at both ends, are intercalated longitudinally each other along the culm. (c) The fiber cell wall exhibits a polylamellate structure with alternating broad and narrow lamellae. The middle lamella is the outer-most layer, followed by primary wall, and the secondary wall, as shown in the upper schematic in (c). The narrow layers consist of unidirectional microfibril layers, alternatively in transverse and longitudinal lamellae, with orientation 2–20°/85–90°; the broad layers are matrix, as shown in the lower schematic in (c). (d) Nanoscale cellulose grains with random orientation.

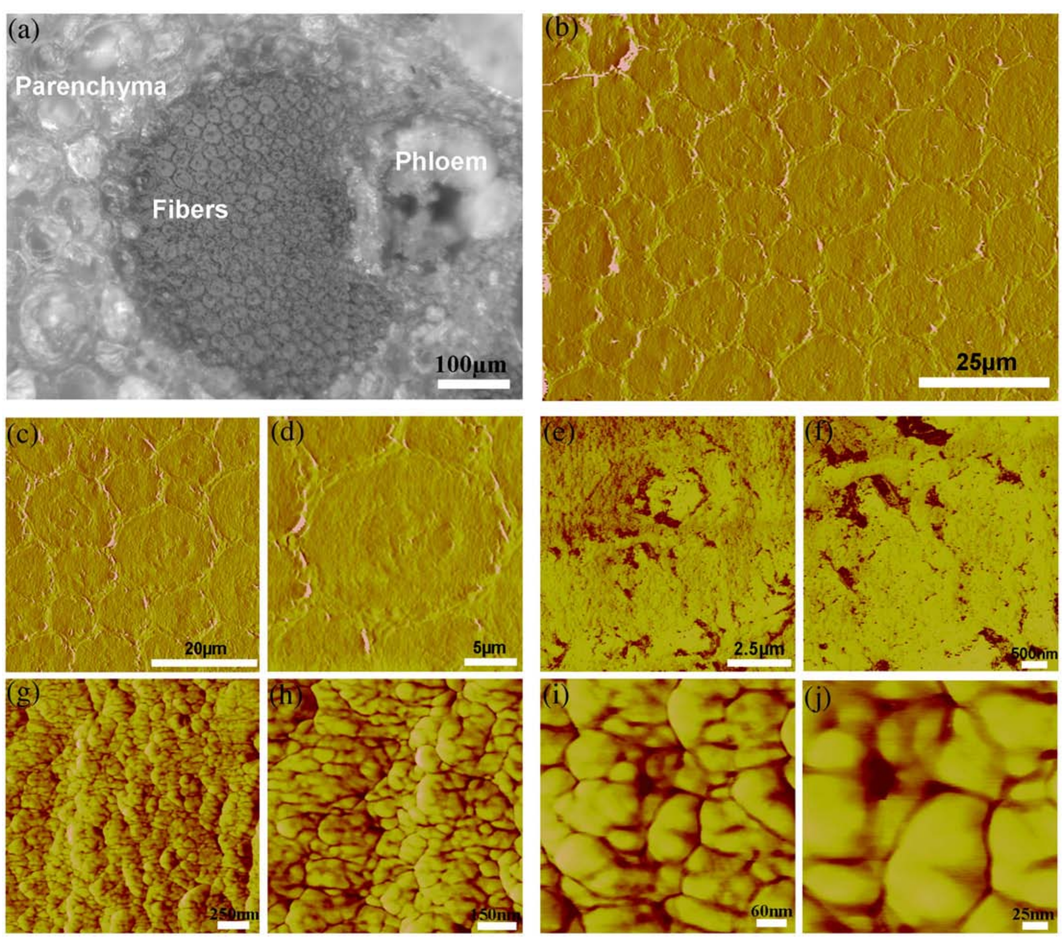

Fig. 2. Cross-sectional micrographs of a phloem fiber cap in a vascular bundle of a bamboo culm. (a) Optical micrograph of a fiber cap. (b)–(d) AFM phase images of bamboo fibers. (e)–(j) AFM phase images of the nanoscale structure in the fiber cell wall.