Composites Science and Technology 157 (2018) 126–133

Contents lists available at ScienceDirect

Composites Science and Technology

journal homepage: http://www.elsevier.com/locate/compscitech

Flexural deformation and fracture behaviors of bamboo with gradient hierarchical fibrous structure and water content

Guowei Chen [a, b], Hongyun Luo [a, b, c, *], Sujun Wu [a, b, c], Juan Guan [a], Jun Luo [a, b], Tianshu Zhao [a, b]

[a] School of Materials Science and Engineering, Beihang University, Beijing 100191, China
[b] Beijing Key Laboratory of Advanced Nuclear Materials and Physics, Beihang University, Beijing, China
[c] The Collaborative Innovation Center for Advanced Aero-Engine (CICAAE), Beihang University, Beijing, China

ARTICLE INFO

Article history:
Received 19 December 2017
Received in revised form
14 January 2018
Accepted 21 January 2018

Keywords:
Fracture
Debonding
Acoustic emission
Fractography

ABSTRACT

Natural gradient fibrous bamboo bended from two opposite directions (divided as Type I and Type II samples) showed pronounced asymmetric flexural performances as the water contents gradually increased (0%, 6%, 22% and 35%). The real-time flexural deformation and fracture behaviors were detected and analyzed with the aid of acoustic emission (AE). Results indicated that there were three kinds of mechanical behaviors during the flexural deformation and fracture process of bamboo: matrix (parenchyma cells) failure, fiber interfacial dissociations (fiber/matrix and fiber/fiber wall dissociations) and fiber breakage. They showed different sequences within the Type I and Type II samples, which were caused by the gradient fibrous structure. The AE energy was dramatically declined and the fiber interfacial dissociations showed exponential-like growth as the water content increased. Upon certain content of water, the gradient hierarchical fibrous structures were toughened through detailed mechanisms of micro-fiber pull-out, debonding and bridging, laminar debonding, local cell wall buckling and micro wart swelling. The study provides critical experimental evidences on the effects of gradient fibrous structure and water content on the flexural performance and fracture behaviors of the natural bamboo.

1. Introduction

Bamboo, as a kind of natural fibrous composites, has been widely used in many daily used commodities [1,2] since the ancient times. Recent progresses in bamboo research suggested its great potentials as structural components for automobiles, aerospace structures and electrodes [3–6]. The gradient fibrous structure of bamboo has drawn studies in the last few decades [7–10], and the hierarchical structure would make great differences on their flexural performances [11–16]. The asymmetry in the flexural behaviors of bamboo and its underlying mechanisms were studied by Lu, et al. [11,15], which indicated that the gradient distribution of the fiber bundles across the thickness was mainly responsible for the asymmetry. However, as natural fibrous materials with multi-scaled structures, knowledge about the natural bamboo's real time flexural deformation and fracture behaviors were far from enough; especially the coupling effects of the gradient hierarchical structures and water contents were seldom reported.

As multi-scaled fibrous bamboo, effects of the microstructures on the mechanical properties can not be ignored [10,17–19]. Bamboo fibers are mainly composed of cellulose microfibers as cores and cross-linked lignin and hemicellulose as cell walls [20,21]. Molecular models were introduced by Youssefian, et al. [20], which figured out that the hydrogen bond and intermolecular forces were the keys to the mechanical strength and stiff of bamboos. As natural fibrous cellulosic materials, mechanical properties of either the raw bamboo or the bamboo-made scrimbers are quite sensitive to the moisture effects [22–26], given that there are large numbers of hydrophilic groups (e.g. hydroxyl) exposed at the macromolecule surfaces [20]. For the dry bamboo, fiber pull-out, bridging and crack deflection have been widely recognized as the main toughening mechanisms [11,27,28], but as the water was introduced in, things may be different.

Acoustic emission (AE) has been widely applied in the non-destructive detection of damage within the fibrous composites [29–31]. The micro deformation and fracture behaviors [32] could

---

* Corresponding author. School of Materials Science and Engineering, Beihang University, Beijing, China.
E-mail addresses: lhy@buaa.edu.cn, Luo7128@163.com (H. Luo).

https://doi.org/10.1016/j.compscitech.2018.01.034
0266-3538/

be recorded by AE during the fracture processes. There are mainly three kinds of fracture behaviors within the artificial fibrous composites detected by AE, which were matrix breakage, fiber dissociation and fiber breakage [30,31,33]. However, the real-time flexural fracture behaviors within the gradient hierarchical bamboo were rarely detected by AE. Here, AE was used to investigate the flexural deformation and the fracture behaviors within bamboo. The influences of gradient hierarchical structure and water contents on the flexural performances and fracture behaviors were discussed. As water was introduced in, the toughening mechanisms within the gradient hierarchical fibrous bamboo were studied in details.

2. Materials and methods

2.1. Materials

The Moso bamboos (Phyllostachys heterocycla (Carr.) Mitford cv. Pubescens) were collected and bought from a plantation located in the south central Hunan province, China. Raw materials were all mature (5 years old), sectioned from the stalks ~1.5 m high from bottom, and kept at room temperature and relative humidity of 55%–70%. The outer and inner skins were removed and the gradient fibrous structure was achieved, as can be seen in Supplemental Fig. 1 [34,35]. Samples with varied water contents (0%, 6%, 22% and 35%) were achieved by dehydration and exposed in the ambient air or soaked into the distill water for different hours [26]. For each at least 5 samples were selected for the later tests.

2.2. Flexural performance test

To evaluate the flexural fracture behaviors of bamboo, samples ($160 \times 20 \times 5$ mm^3) were prepared for the three-point bending tests. They were performed on a mechanical test machine (SANS, MTS Industrial System Co. Ltd., China) with a bending speed of 0.5 mm/min. There were two types of specimens (Type I: the fiber content varies from high to low along the bending force direction; Type II: fiber content varies from low to high along the bending force direction). The flexural strains studied herein were all nominal strains. Both types of samples were bent to a total fracture when a stress drop reached over 90% and the nominal strain was defined as the “total fracture strain”.

2.3. Flexural fracture behaviors characterization

The flexural deformation and fracture process were recorded by an optical video microscope from the side views. AE signals were recorded and analyzed by a digital signal processor with an AEwin v2.19 AE system (Physical Acoustic Corporation, USA). The three-point bending and the *in situ* observation/detection are displayed in Fig. 1(a). More details can be seen in Supplemental Information.

The fracture morphologies were observed by an optical microscope (OM, KH-3000, HIROX, Japan) and a field-emission environmental scanning electron microscope (FESEM, Qutanta FEG 450, FEI, USA), with low vacuum and an accelerating voltage of 15 kV.

3. Results and discussions

3.1. Pronounced asymmetric flexural performance

The flexural performances of the two types of samples with gradient water contents are shown in Fig. 1(b and c) and Supplemental Fig. 2. As the bending force was applied from high fiber content to low, Type I samples with different water contents showed sharp fracture behaviors as shown in Fig. 1(b). Air dry samples (6%) and the absolutely dry (0%) samples shared the similar failure strains, which were just over 0.01. Samples with water content of 22% and 35% had much lower strength than the dry samples, but they showed delayed failure at strains close to 0.02, almost twice of the dry counterparts. As the bending force was loaded upside down from low fiber volume to high, Type II samples with different water contents showed more rounded stress-strain

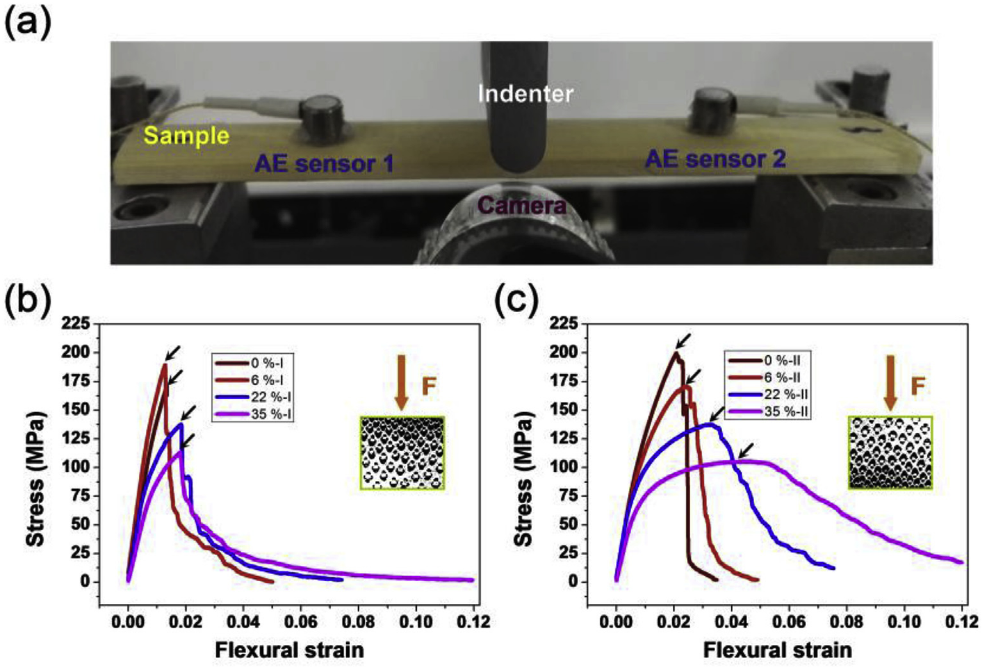

Fig. 1. (a) Three-point bending and the *in situ* observation/AE detecting diagrams; (b) Flexural performance of the Type I samples with gradient water contents; (c) Flexural performance of the Type II samples with gradient water contents. The stress maximum points (failure strains) were indicated by black arrows in (b) and (c).