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Fracture and mixed-mode resistance curve behavior of bamboo

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ABSTRACT

Bamboo is a natural composite abundantly available in the world, and is a source of inspiration for design of new construction materials and structural composites for many applications. The microstructure of this Functionally Graded Material (FGM) evolves through its thickness in response to wind-induced stresses that arise in the plant during its lifetime. This paper presents the results of an experimental study on the structure and toughening mechanisms in Moso culm bamboo. The hierarchical and multi-scale structure of bamboo and the distribution of micron scale fibers are revealed via optical microscopy. Four-point bend fracture experiments are performed where the applied crack-driving forces are computed as a function of crack length. This experimental data are incorporated within a finite element framework in order to understand the fracture and deformation mechanisms of bamboo, and compute the Resistance-curves (*R*-curve)s. The resistance-curve behavior is shown to be dependent on the orientation of the fibers. In cases where the fibers are perpendicular to the crack growth toughening is observed to occur via crack bridging. Intermediate shielding levels are observed when toughening occurs by crack deflection for crack growth along the fiber orientation.

1. Introduction

In recent years, there has been increasing interest in the use of bamboo, the fast growing naturally occurring bio-composite material, as an eco-friendly structural material [1–4]. This interest is due to the bamboo's attractive combinations of relatively high strength-to-weight ratio, stiffness-to-weight ratio and shape factor [3–8]. Such unique properties has resulted in structural applications of bamboo in bicycles and housing in rural and urban environments [9]. In countries such as China, bamboo has been used as structural material for centuries [10]. Bamboo has also been used to fabricate structural elements and as alternative to steel in reinforced concrete [11].

Excluding the outer layer (epidermial layer) of bamboo stalk, its structure consists of fibers and vascular bundles that are surrounded by parenchyma cells. Researchers attribute the outstanding mechanical properties of bamboo to the presence of the fibers which are non-uniformly distributed in the cross section of bamboo [12,13]. The structure of the fibers in which cellulose fibrils are surrounded by a matrix of mainly lignin and hemicellulose has also been previously investigated [14–17]. Between 20% and 30% of the cross-sectional area of the stalk is made of longitudinal fibers which are heavily concentrated near the exterior layer [18]. The non-uniform distribution and the orientation of these fibers makes bamboo an orthotropic material with high strength along the fibers, and low strength transversal to the fibers [19–21]. Moreover, due to this structure, bamboo is a representative of a natural Functionally Graded Material (FGM) [22–27].

FGMs may be characterized by their variation in composition and structure over volume. This variation results in corresponding changes in the properties of the material in a continuous manner which may reduce the stress concentration and increase bonding strength [28–30]. However, in spite of its structural application, there have been very few mechanistic studies of the toughening mechanisms in bamboo [7]. There have also been no such studies that clearly show the resistance-curve behavior of bamboo. Instead, most of the prior studies have involved the use of topology optimization in the understanding of deformation, and studies of mechanical properties [31,32].

There are many experimental studies on bamboo, including measuring strength, Young's modulus of matrix and fiber, and through analysis of microstructures and fiber distribution [33–36]. In a recent study by Dixon et al., the flexural properties of Moso bamboo in the axial direction, along with the compressive strengths

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in the axial and transverse directions were measured. Based on the microstructural variations and solid cell wall properties, analytical models of mechanical properties of bamboo which describe the experimental results were developed [5]. Numerical methods such as the finite element method (FEM) can be useful in understanding the mechanical behavior of composite materials in general [37,38]. Considering that bamboo is an inhomogeneous orthotropic material, complex methods were used to investigate its properties numerically [6,7,39,40]. Moreover, in order to estimate how the microstructure influences the effective properties of these materials, multiscale methods such as homogenization can be used [41–44]. Another approach to model bamboo is to employ a homogeneous, averaged value of Young's modulus, allowing comparisons and demonstrating the limitations of simplified procedures.

This paper presents the results of a combined experimental and theoretical/computational study of the resistance-curve behavior of Moso Culm bamboo. In this study, the hierarchical structure of bamboo is described using multi-scale images of structure between the micro- and macro-scales. This is followed by a section in which the experimental fracture resistance-curve measurements are described. Then, the experimental results are elucidated before presenting theoretical/computational models for the estimation of resistance-curve behavior. Hence, the main goal of this study is to explain the basic deformation and toughening mechanisms for mixed mode fracture of bamboo using experimental and numerical methods. The implications are described and the conclusions can be used as a guide to design and make bio-inspired fracture-resistant composites.

2. Materials and methods

The specific material studied in this paper is Moso Bamboo. Samples of the bamboo were obtained to study the microstructure, the fracture properties and crack resistance behavior. The bamboo samples were approximately five years old. The samples were cut from a bamboo culm with the following dimension: width, $W = 8.0$ mm; height, $H = 8.0$ mm and length, $L = 56.0$ mm.

Microstructural information is pivotal in understating the fracture properties and toughening mechanisms in composite materials. Thus, sections of bamboo specimens were cut with Beuhler dimond cutter and polished down to a 1 μm surface finish with Beuhler polisher and aluminium carbide abrasive (course to fine grit sizes). Then the samples were cleansed by acetone and menthol. The prepared samples were viewed under the optical microscope. In addition, image analysis was performed in order to characterize the mesoscale distribution of fiber bundles across the bamboo culm wall thickness.

Fig. 1 shows the structures of the bamboo obtained by optical microscopy. These images show bamboo structure consisting of bundles of vascular fibers in a matrix of primarily parenchyma cells. Most significantly, the microstructure is highly graded in that the volume fraction of the fibers increases from the inside to outside, the latter being the part that is exposed to the atmosphere or environment. The volume fraction of fibers across the thickness of the bamboo culm from the outer surface to the inner surface is computed from the optical images and presented in Fig. 2. These three regions can be classified as high fiber density region (at and near the outer surface of the culm), low fiber density region (at and near inner surface of the culm) and the medium fiber density region (in between the two).

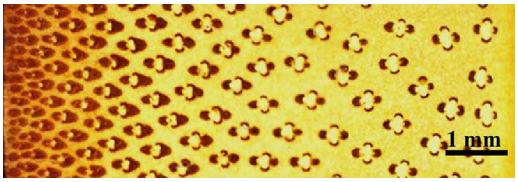

Fig. 1. Optical microscopy image of the functionally graded microstructure of bamboo.

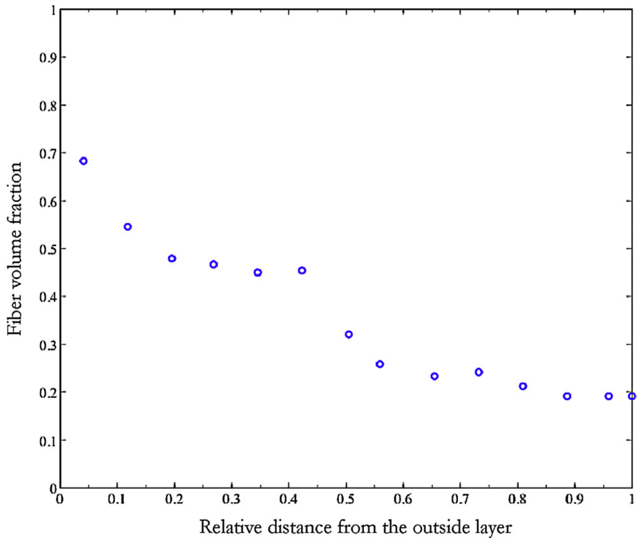

Fig. 2. Dependence of fiber volume fraction on radial distance from the outer bamboo wall.

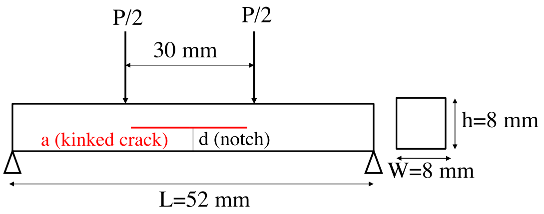

Fig. 3. Schematic of the setup and beam cross-section for the four-point bending experiment.

2.1. Crack–resistance curve

2.1.1. Experimental procedure

Constant moment crack growth resistance tests were performed on single edge notched bend (SENB) specimens of dimensions 8.0 mm × 8.0 mm × 56.0 mm. The specimens were notched at the center with initial notch/height ratio, $d/h = 0.25$. The specimens were characterized into two categories, according to the placement of the notch. Specimens notched in the outer side of Longitudinal(L)/Tangential (θ) orientation are hereby referred to as outside cracked, while those notched on inside part of the L/θ orientation are referred to as inside cracked.

Tests were carried out under four-point-bending using an Instron 8871 servo-hydraulic testing machine under constant loading rate. The outer and inner sample spans were 52.0 mm and 30.0 mm, respectively. Fig. 3 shows the schematic diagram of the test setup, sample and the loading condition. Testing was done under loading control. For each test peak loads were selected and loading ramped at a loading rate of 1 N/s. At each peak load, the crack extension/position was measured by a Quester Brandon High-Resolution Camera. This experimental setup is of particular interest, since the crack microstructure interaction can be observed readily with the microscope. Experimental data of applied loads and crack extensions were recorded for the analysis of the resistance-curve behavior of bamboo.

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