Theoretical and Applied Mechanics Letters 5 (2015) 236–243

Contents lists available at ScienceDirect

Theoretical and Applied Mechanics Letters

journal homepage: www.elsevier.com/locate/taml

Letter

Effects of humidity on shear behavior of bamboo

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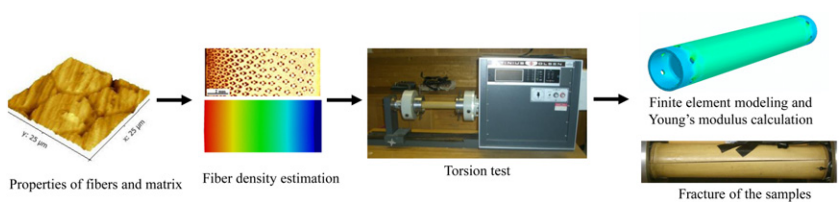
HIGHLIGHTS

- A functionally graded orthotropic model of bamboo is proposed.
- Bamboo with 60% environmental humidity demonstrated the highest shear modulus.
- The optimal humidity of the samples for highest strength is between 60%–80%.
- Similar to wood, bamboo, a grass, exhibits more ductility under torsion as the humidity of the samples increases.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 20 September 2015
Accepted 14 November 2015
Available online 28 November 2015
*This article belongs to the Biomechanics and Interdiscipline

Keywords:
Bamboo
Torsion test
Humidity
Finite element analysis

ABSTRACT

Bamboo is a naturally occurring biological composite, however its microstructure and hence its properties are very complex compared to the manmade composites. Due to optimization, it can be assumed that the variation in properties along the thickness of the culm be a smooth transition for better bonding strength between layers and to prevent non uniformity in stress concentration. As a consequence, biological structures are complicated and functionally graded. Hence, a realistic model that can capture the mechanical performance of bamboo is valuable in future design of robust multifunctional composites. This paper presents the results of experimental and numerical studies on the torsional (shear) properties of bamboo. The hierarchical and multi-scale structure of bamboo and the distribution of micro-scale fibers are revealed via laser scanning and atomic force microscopy. This information was incorporated into a finite element model to analyze the mechanical behavior of bamboo under torsion and to estimate the shear modulus of bamboo along the fibers. Moreover, the effects of humidity and therefore water content on the mechanical properties of bamboo were evaluated by performing torsion tests on samples maintained in environments with different humidities. Increasing the humidity does not cause a drop in the shear modulus, however, a jump in the shear modulus did occur at around 60% humidity. Results of this study indicate that the highest strength values in samples occurred in environments with humidity levels between 60% and 80% and undergo a significant drop after that. In higher humidities, the samples behave more ductile.

Bamboo is one of the oldest building materials used by mankind. There are signs in far east, for instance, where Chinese writings and drawings refer to bamboo that date back from 1600 BC to 100 BC [1,2]. Bamboo has been used to fabricate structural elements and also as an alternative to steel in reinforced concrete [3]. Sustainability and the practice of using environmentally friendly

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http://dx.doi.org/10.1016/j.taml.2015.11.007

materials is continually gaining momentum in both developed and underdeveloped parts of the world [4–6]. This is largely due to the decreasing supply of available timber around the world. Natural materials all around us exhibit fascinating properties that are typically multifunctional and optimal for the construction purposes [7]. Bamboo is a very favorable sustainable material for the construction industry. Bamboos attractive combination of strength-to-weight ratios, stiffness-to-weight ratios, and shape factors make it an ideal candidate for construction materials and many other applications [5–11].

Most bamboo culms are cylindrical and hollow, with diameters ranging from 0.25 in. to 12 in. (1 in. = 2.54 cm). Bamboo is considered a composite made up of non-uniformly distributed longitudinal fibers [12–14]. Separating the culms are evenly spaced nodes with internal diaphragms (knots). The main constituents of bamboo culms are cellulose, hemicellulose and lignin, which amount to over 90% of the total mass [15–18]. The minor constituents of bamboo include resins, tannins, waxes and inorganic salts. As an orthotropic material, the density of the bamboo changes through the cross-section, ranging from 500 kg/m^3 to 800 kg/m^3, with the higher density located at the outside face. The unique fiber–matrix ratio and distribution give bamboo exceptional strength characteristics [19–21]. To prevent non-uniformity in stress concentration and increase bonding strength between layers, the variation in the properties along the thickness of the culm should be modeled using a smooth transition [22–24]. There are many variables that affect the strength of bamboo, including maturity, season when it is harvested, and the treatment applied after the bamboo harvest. Previous studies have shown that the optimum maturity period is about 3–4 years to provide optimum strength [25]. Following this period of time the strength and density of bamboo begins to decay. At the optimum maturity period, bamboo has shown tensile strengths greater than spruce and equal to or greater than steel per unit weight.

Few studies treating the modeling of natural fibers have been found in the literature due to the complexity of the microstructure [14,26]. However, there are many experimental studies on bamboo measuring strength, Young's modulus of matrix and fiber, and through the analysis of its microstructure and fiber distribution [20,26–34]. In a study of Dixon and Gibson (2014) [8], the flexural properties of Moso bamboo in the axial direction, along with the compressive strengths in the axial and transverse directions were measured, and based on the microstructural variations and extrapolated solid cell wall properties of bamboo, analytical models which describe the experimental results were developed. Another approach used to estimate how the microstructure influences the effective properties of bamboo is to model these materials through the use of homogenization, or the extraction of the microstructure properties that can then be introduced to the section as a whole [35–37]. Employing a homogeneous, averaged value of Young's modulus can also be used, allowing comparisons and demonstrating the limitations of simplified procedures. However, considering that bamboo has complicated shapes and material distribution inside its domain with many important details, the numerical methods such as the finite element method (FEM) can be useful tools for understanding the mechanical behavior of these functionally graded materials (FGMs) [9,27–30,38–41] and many composite structures in general [42,43]. Molecular dynamics (MD) is another effective tool to study the properties of composite materials [18,44,45].

In spite of its structural application, there have been no prior mechanistic studies on the role of water content with regard to the mechanical performance of bamboo. Many studies have been conducted on other biological materials such as nacre and bone. As an example, the existence and role of water in the structure of nacre has been investigated by many researchers. It has been mentioned that the effect of water acts to increase the ductility of nacre and increase the toughness [46,47]. The conductivity of bamboo and effect of absorbed water was investigated in a study conducted by Shiji et al. [48]. However, more multiscale investigation is needed to understand the effect of water content or humidity on the mechanical performance.

The goal of this study is to experimentally and numerically investigate the mechanical behavior of bamboo in torsion. While other studies have estimated the modulus and stiffness, very few studies have investigated the torsional properties and shear modulus of bamboo. In this study a new method of modeling was used to estimate the shear modulus of bamboo. Additionally, the effect of humidity on the torsional behavior of bamboo was investigated. The results of this study can be used as a guide to improve the properties of bamboo in different applications, take advantage of effect of water on natural materials, and to design and make bioinspired composites with remarkable mechanical properties.

Samples from the Phyllostachys species of bamboo were used for the torsional experiments conducted in this study. The bamboo samples were approximately five years old. The bamboo was kiln dried and stored in a ventilated warehouse for at least a year followed by storage within the lab. The storage assured that only gradual moisture changes took place and ensured that cracks in the bamboo did not form prior to testing. The experiment in torsion was conducted using a Tinius Olsen Model 290 torsion testing machine (Fig. 1) with a maximum torque of 10000 lb·in (1 lb = 0.454 kg). The onboard load display was bypassed with the use of LabView software platform with a custom written program to record load, rotation, and strains. Two fixtures were fabricated out of mild steel with six 3/8 in.-24 thread bolts in each for securing the bamboo sample.

Kiln dried Phyllostachys bamboo was cut to 14 in. in length. The specific length of 14 in. was chosen due to the limitation of the testing machine having a maximum specimen length of 20 in. in addition to the bamboo node spacing. With the specimen having a node spacing of approximately 12 in., the fittings could be clamped within one inch of a node on each end of the 14 in. specimen. The average diameter of the bamboo was about 2.25 in. with a 1/4 in. wall thickness.

An important factor in a torsion experiment is to prevent slippage between the specimen and the fixture for accurate rotation recordings measurements. Preliminary tests of the fixture system resulted in the bolts slipping on the bamboo surface at a torque of approximately 800 lb·in. Additional tightening of the bolts would pose additional damage to the specimen and larger concentrated loads at the location of the bolts. As a result, a new system was developed by precisely drilling 9/32 in. holes where the fitting bolts would normally meet with the bamboo. A series of one inch wide washers bent to the outside curvature of the bamboo along with 3/4 in. washers bent to the inside curvature are used in conjunction with 1/4 in. bolts and matching nuts, one inch in length to create the mounting setup. In addition, 80 grit drywall sandpaper was sandwiched between the outside washer and bamboo to provide increased friction. A completed bamboo specimen setup is shown in Fig. 1.

By orientating the bolt heads parallel to the longitudinal fiber direction, the heads can bear the applied transverse load. The specimen was mounted into the fitting with the fitting bolts tightened onto the washers and bearing on the bolt head. Using the 9/32 in. hole through the bamboo and large washers distributed the load evenly and prevents excessive concentrated loads at the hole locations. Using the setup, the experiment proved to be successful with no slippage and failure occurring in between the mounting holes, showing that excessive concentrated loads are not taking place at the holes. Loading occurred at five degrees per minute until the specimen reached failure. Throughout the experiment