Construction and Building Materials 131 (2017) 574–584

Contents lists available at ScienceDirect

Construction and Building Materials

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

Edge bearing tests to assess the influence of radial gradation on the transverse behavior of bamboo

Richard Moran [a], Kelly Webb [b], Kent Harries [c], José Jaime García [a,*]

[a] *Escuela de Ingeniería Civil y Geomática, Universidad del Valle, Cali, Colombia*
[b] *Department of Civil Engineering, Architecture and Building, Coventry University, United Kingdom*
[c] *Department of Civil and Environmental Engineering, University of Pittsburgh, United States*

HIGHLIGHTS

- Edge bearing tests, DIC, and finite element simulations to characterize bamboo circumferential behavior.
- Three circumferential modulus distributions were proposed for three bamboo species.
- Circumferential failure stresses and strains were determined.
- Typical and atypical failures are described in standard edge bearing test.

ARTICLE INFO

Article history:
Received 31 May 2016
Received in revised form 15 November 2016
Accepted 22 November 2016

Keywords:
Bamboo
Digital image correlation
Finite element method
Circumferential elastic modulus
Functional graded material

ABSTRACT

Bamboo is a sustainable material with high potential for structural applications. The aim of this study was to use edge bearing tests, digital image correlation analysis, and finite element simulations to research about the distribution of the circumferential elastic modulus through the wall and the associated failure strain and stress. Studied bamboo species were *Phyllostachys edulis* (Moso), *Bambusa stenostachya* (Tre Gai) and *Guadua angustifolia* (Guadua). Using the edge bearing tests, the effective circumferential moduli under compression were similar to those obtained under tension. Mean effective moduli were 1358.5 MPa, 662 MPa, and 862 MPa for bamboo Moso, Tre Gai, and Guadua, respectively. Linear, exponential and parabolic functions that were proposed to represent the circumferential modulus provided a relatively good fitting of the experimental results. Due to the radial gradation, the circumferential moduli at the outer position were 2.3, 1.9, and 2.6 higher than those at the inner location for Moso, Tre Gai, and Guadua, respectively. Mean circumferential failure strains and stresses in the inner culm surface were: 6693 $\mu\varepsilon$ and 7.6 MPa; 13137 $\mu\varepsilon$ and 12.1 MPa; and 5948 $\mu\varepsilon$ and 3.7 MPa for Moso, Tre Gai and Guadua respectively.

1. Introduction

Bamboo is a variety of giant grass widely available in tropical zones around the world [1]. Bamboo has shown great potential as a sustainable material, due to its fast growth and maturation, and its capacity to sequester CO_2 and regulate water cycles [2,3]. Furthermore, bamboo has excellent potential as a structural material because of his tubular shape and the fact that its axial strength is similar to that of low carbon steel [4,5].

Bamboo culms consist of hollow cylindrical internodes reinforced with transverse diaphragms dispersed along their length. The internodes behave mechanically as a hollow cylinder reinforced with axially oriented cellulose fibers embedded in a weak matrix of lignin [5]. Thus, mechanical properties are highly anisotropic, with large strength and stiffness in the axial direction and poor properties in the transverse directions [6,7]. In addition, bamboo is a heterogeneous material as the fiber density increases from the inner to the outer wall faces of the internode cross-section. For this reason, bamboo is often referred to as a functionally graded material [8,9].

Despite its attributes, the use of bamboo in construction remains limited primarily to 'non-engineered' or vernacular structural forms. This is due in part to the considerable dimensional and mechanical property variation among culms and even along the

* Corresponding author.
E-mail addresses: richard.moran@correounivalle.edu.co (R. Moran), webbk6@uni.coventry.ac.uk (K. Webb), kharries@pitt.edu (K. Harries), josejgar@gmail.com (J.J. García).

http://dx.doi.org/10.1016/j.conbuildmat.2016.11.106
0950-0618/

length of a single culm. In addition, due to the unidirectional fiber-reinforced structure of the material, longitudinal splitting is a typical failure mode in bamboo members [5,10–12]. Splitting failures are often critical at structural joints, where high localized shear and tensile circumferential stresses are generated, due for example to the presence of holes in bolted connections [12]. The splitting mode of failure is also present, and often is dominant, in bending [5] and even in compression.

One the main challenges in bamboo construction is the development of efficient connections, which are difficult to build due to the hollow cylindrical shape of the culms. In order to design efficient and inexpensive connections for bamboo members, an understanding of the failure modes and stress distribution in critical regions is necessary. However, this can only be achieved using constitutive models that can accurately capture the anisotropic and heterogeneous behavior of the material. In this regard, most experimental studies focus on axial property characterization [9,13–16], while transverse properties remain poorly understood, even though most bamboo failures are initiated within the fiber planes due to the transverse components of the stress tensor.

Few studies have been carried out to determine transverse mechanical properties of bamboo. Torres et al. [17] proposed an edge bearing test and a transverse isotropic law to calculate the effective circumferential elastic modulus of *Phyllostachys edulis* (Moso) and *Guadua angustifolia* (Guadua) rings. Sharma et al. [10] tested thin-walled Moso and thick-walled *Bambusa stenostachya* (Tre Gai) rings using the edge bearing test to determine strain profiles and the effective circumferential elastic modulus. Circumferential strength results were compared with split-pin transverse tension tests in which a fracture mechanics approach was used to investigate the splitting failures [18]. However, no distribution of elastic modulus was proposed, and it was recognized that more research is necessary to determine the influence of fiber gradation through the culm wall thickness on the mechanical transverse behavior of bamboo.

Lee et al. [19] developed a test arrangement using bamboo rings under internal pressure. To analyze the variation of the circumferential elastic modulus through the culm wall thickness, linear, power and exponential distributions were used to fit the inner and outer strain measurements. Based on this study Lee et al. [19] proposed an exponential distribution for the circumferential modulus. Lee et al. [19] did not report the species used although a review of available literature [20] indicates that through-wall modulus distribution is species dependent.

Thus, the goal of this study was to investigate the variation of the circumferential Young's modulus of bamboo with radial position. The circumferential compression, or 'edge bearing' test was used together with digital image correlation (DIC) and finite element (FE) models to assess the distribution of circumferential elastic modulus of three bamboo species. Additionally, circumferential failure strains and stresses were determined.

2. Methods

2.1. Material

Rings were extracted from internode zones of three species of bamboo: *Phyllostachys edulis* (Moso), *Bambusa stenostachya* (Tre Gai) and *Guadua angustifolia* Kunt (Guadua). These are commercially viable species in China, Southeast Asia, and South America, respectively. All rings came from borax salt treated culms [6,7,10]. Rings were extracted from four different culms of Tre Gai and Moso and five different culms of Guadua, although location along the culm of the rings was not available for any bamboo species. Specimens were labeled as X-YYZ, where the first letter (X) was used to identify the species (M for Moso, T for Tre Gai and G for Guadua), and the following three numbers were used to identify the culm number (YY) and the specimen number from the culm (Z).

Moisture content was measured in eight locations for every test specimen using a test probe (EXTECH Moisture Meter 0220), the average moisture values measured were: 12.4% (COV = 0.06) for Moso, 14.4% (COV = 0.17) for Tre Gai and 11.6% (COV = 0.05) for Guadua.

All rings were marked at four quadrants (N, E, S and W). Diameters (D) were measured across N-S and E-W positions, while thickness (t) and ring specimen length (L) were measured at each quadrant. Average dimensions of tested specimens for each species and load type (described subsequently) are reported in Table 1.

For the compression tests, L/D ring ratios were 0.59 (COV = 0.09), 0.58 (COV = 0.03), and 0.41 (COV = 0.03) for Moso, Thre Gai, and Guadua, respectively. For the tension tests, L/D ratios were 0.48 (COV = 0.2), 0.15 (COV = 0.08), and 0.41 (COV = 0.05) for Moso, Thre Gai, and Guadua, respectively. A lower L/D ratio for the Thre Gai rings under tension was necessary to be able to test these thick-walled rings in the tension fixture described below.

2.2. Edge bearing test

The edge bearing or transverse compression test has been used to characterize transverse effective properties of bamboo rings [10,17]. In this test, specimens are loaded across their diameter (load points are designated N and S) and the load and vertical or horizontal displacement (Δv or Δh) are recorded (Fig. 1).

Under the assumption of the material as homogeneous and transverse isotropic, each displacement Δv or Δh of Fig. 1 can be determined in terms of the load P, the effective circumferential elastic modulus E_ϕ, and the geometrical parameters of the ring by using the Castigliano's theorem described in texts of solid mechanics [21]. These formulas are presented in Ref. [22]. As the vertical displacement Δv was measured in the compression experiment, the circumferential modulus was calculated as,

$$E_{\varnothing} = \frac{12PR^3}{Lt^3\Delta_v} * \left(\frac{\pi k_1}{4} - \frac{2k_2^2}{\pi}\right). \tag{1}$$

On the other hand, as the horizontal displacement Δ_h was measured in the tension experiment, the elastic modulus was calculated using,

$$E_{\varnothing} = \frac{12PR^3}{Lt^3\Delta_h} * \left(\frac{k_1}{2} - k_2 + \frac{2k_2^2}{\pi}\right). \tag{2}$$

where k_1 and k_2 are correction factors equal to:

$$k_1 = \left(1 - \frac{t^2}{12R^2} + \frac{FEt^2}{12GR^2}\right), \quad \text{and} \tag{3}$$

$$k_2 = \left(1 - \frac{t^2}{12R^2}\right) \quad \text{for thin rings, and} \tag{4}$$

$$k_2 = \left(\frac{t}{Rln\frac{R_o}{R_i}}\right) \quad \text{for thick rings.} \tag{5}$$

In which R is the mean radius of the ring ($D/2 - t/2$), R_o and R_i are inner and the outer radii, respectively, and t is the culm wall thickness. Finally, considering a transverse isotropic model the ratio E/G is assumed to be $2(1 + \nu)$, where the Poisson's ratio, $\nu = 0.22$ [6] and the shape factor $F = 1.2$ for a rectangular section