Composites Part B 79 (2015) 374–382

Contents lists available at ScienceDirect

Composites Part B

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

Mechanical performance of laminated bamboo column under axial compression

Hai-tao Li [a, *], Jing-wen Su [a], Qi-sheng Zhang [a], Andrew John Deeks [b], David Hui [c]

[a] *Collage of Civil Engineering, Nanjing Forestry University, Nanjing 210037, China*
[b] *College of Engineering and Architecture, Dublin University, Dublin, Ireland*
[c] *Department of Mechanical Engineering, University of New Orleans, LA 70148, USA*

ARTICLE INFO

Article history:
Received 25 February 2015
Accepted 16 April 2015
Available online 24 April 2015

Keywords:
A. Laminates
B. Buckling
C. Finite element analysis
D. Mechanical testing

ABSTRACT

This study investigated the mechanical performance of 120 laminated bamboo column specimens under axial compression. Experimental and computational investigations were conducted on axially loaded laminated bamboo columns. The load-deflection and load-strain relationships were obtained from column tests, and the detailed failure modes for all specimens are reported. Squashing or crushing failures were observed for the short columns, and bearing capacity of for the short columns is found to be determined mainly by the compressive strength of the material. However, buckling failures were observed for the longer columns, and the failures involved significant lateral deflection. Deflection caused by initial defects influences the bearing capacity of the specimens more and more obviously as the slenderness ratio increases, and the bigger the slenderness ratio, the bigger the lateral deflection corresponding with the peak load. The variation of ultimate lateral strain and longitudinal strain versus slenderness ratio was also studied. Comparison between the test results, theoretical calculations, and FEM analysis results are reported. An equation for calculating the stability coefficient φ of laminated bamboo columns is proposed. The loading capacities obtained from the equation gives good agreement with the test results.

1. Introduction

As resource availability declines and resource demands increase in today's modern industrialized world, it is becoming increasingly necessary to explore opportunities for new, sustainable building materials [1,2]. Both wood and bamboo have recently gained popularity in the green building community because of their environmentally beneficial characteristics: they are promoted as renewable, biodegradable, sequestering carbon from the atmosphere, low in embodied energy, and creating less pollution in production than steel or concrete [1,2]. However, usable bamboo can be harvested in 3–4 years from the time of planting, as opposed to traditional timbers which need decades between planting and harvesting [3–6]. Not only is bamboo fast-growing, but it is also highly efficient in comparison to other structural materials [7]. Compared with other common building materials, bamboo is stronger than timber, and its strength-to-weight ratio is greater than that of common wood, cast iron, aluminum alloy, and structural steel [7].

Although bamboo is a promising wood substitute, structural forms in which it can be used are limited by the diameter of the bamboo culm and the low rigidity of the bamboo. To solve the limitation of member size and to enhance dimensional consistency, strength, and uniformity, the bamboo culm can be disassembled into thin flat laminae and then laminated together with adhesive to form certifiable structural members. The composite material is called laminated bamboo [7]. The mechanical properties of laminated bamboo compare favorably with those of common wood, and so laminated bamboo rectangular structural members are competitive with commonly used building materials, whilst also having renewable characteristics [8–11]. Much research work have been done on wood [1,12–15] but less on laminated bamboo lumbers [16–30], so more work needs to done on this kind of new building material.

The majority of studies into the properties of laminated bamboo have been concerned with boarding rather than structural members. Effects of layer structure, bamboo species, oil treatment, and glue type on the mechanical properties of laminated bamboo

---

* Corresponding author.
E-mail address: lhaitao1982@126.com (H.-t. Li).

http://dx.doi.org/10.1016/j.compositesb.2015.04.027
1359-8368/

boarding have all been studied [12–19]. Verma et al. [12–14] performed tensile, compressive and bending tests on specimens of layered laminate bamboo composite (LLBC), looking at the effect of orientation of the laminate layers on the strength. LLBC is primarily used for flooring board and the specimens used were very small, having a cross-section of 16 mm × 10 mm.

In terms of structural members, an early study by Lee et al. [20] examined the bending properties of 24 laboratory-manufactured laminated bamboo beams. A recent study by Wei et al. [21] examined the failure of laminated bamboo beams in detail, and concluded that the cross-sectional stiffness was the control condition for design load. Arijit Sinha et al. [22] characterized the structural performance of laminated bamboo lumber (LBL) and bamboo glulam beams (BGBs). There is potential to use LBL in structural framing applications. However, certain issues need to be addressed and researched before LBL and BGB can find wide acceptance in the construction marketplace. Yeh and Lin [23] investigated the finger joint performance of structural laminated bamboo members in bending, tension, compression and shear. The study of Li et al. [24] showed that the short laminated bamboo columns (with the cross section of 100 mm × 100 mm) in compression display a significant amount of plastic behaviour before crushing, and also showed that the stress-strain relationship in compression could be represented using a tri-linear model with an elastic portion, and elasto-plastic portion and a purely plastic portion.

Xiao-hong Lv [25] has examined the mechanical performance of five groups of GluBam column with the cross section of 56 mm × 56 mm, including the influence of slenderness ratio upon the ultimate load. Some researchers [26–29] have studied the buckling performance of the original bamboo culms, but it is difficult to find papers addressing the performance of laminated bamboo columns. To the authors' knowledge, most of previous studies of laminated bamboo in compression have used specimens of small scale. Few studies have been performed using full size structural members. The behaviour of structural members could be significantly different from the behaviour of small specimens, as the cross-section is built up of bamboo strips of cross-section approximately 20 mm × 5 mm. This study aims to examine the compression behaviour of laminated bamboo structural members with realistic cross-sections.

To achieve these objectives, the study examines in detail the behaviour of full size structural members (with the design cross section of 100 mm × 100 mm) constructed from laminated bamboo with different slenderness ratio. Based on the experimental and computational investigations, the formula for calculating stability factors will be proposed for the columns.

2. Materials and test methods

The source Moso bamboo (Phyllostachys pubescens, from Jing-an county in the Jiang-xi province) was harvested at the age of 3–4 years. Bamboo strips from the lower growth heights of a 2100 mm tall culm were selected. The culms were then split into 20 mm–24 mm wide strips, and the outer skin (epidermal) and inner cavity layer (pith peripheral) were removed using a planer. All the culm strips were then dried and charred. Final thicknesses of 8 mm for the flat strips from the lower (G) growth portions were obtained, and the final strip widths were 21 mm. Finally the strips were made into laminated bamboo lumbers by Yuan-nan Co. Ltd.

Phenol glue was used to manufacture the laminated specimens. Single layers were made first, and these were then were pressed together to form the blocks. A pressing temperature of 140 ± 5 °C was used. A transverse compression of 1.82 MPa was applied for both the sheets and the blocks, and a confining pressure of 4.74 MPa was used when manufacturing the sheets. The final moisture content was 7.6% and the density was 635 kg/m^3 for the laminate sourced from the lower portion. According to the compressive tests, the compression strength for the laminated bamboo was 58.68 MPa, with the modulus of elasticity of 9643 MPa, ultimate compression strain of 0.02.

Fifty groups of specimens were constructed with the same design cross section of 100 mm × 100 mm. Each group consisted of eight identical specimens. Specimens from the different groups are shown in Fig. 1a. The lengths ranged from 400 mm to 1800 mm with increments of 100 mm. The cross-sectional structure of the laminated bamboo can be seen in Fig. 1b.

The test arrangement is illustrated in Fig. 2. The displacement for the quarter points, including the mid-span deflection were measured by three Laser Displacement Sensors (LDS type: Keyence IL-300) respectively. Two strain gauges were pasted on each middle side surface of the specimens, as shown in Fig. 2. The load was applied along the central axial line. The test was performed using a microcomputer-controlled electro-hydraulic servo universal testing machine (Fig. 3) with a capacity of 1000 kN, and an LDS Data Acquisition System was used.

3. Test results and analysis

3.1. Failure modes and mechanism analysis

Typical failure modes can be seen from Fig. 4 to Fig. 5. Fig. 4 shows the final pictures for the short column whose failure is strength failure. The specimen crushed at the top, with the outer laminations on four sides being pushed outwards in the top surface pictures, as shown in Fig. 4b. A squashing or crushing failure always happened for the short column specimens. However, in contrast to the short specimens, Fig. 5 shows the final pictures for a long column where the failure is through buckling. The ultimate strength for the long column specimens is smaller than the material strength of the laminated bamboo. Buckling failure always happened for the long column specimens.

Typical load-longitudinal strain curves can be seen from Fig. 6 to Fig. 7. Fig. 6 shows how four strains on the middle side surfaces change with the axial implying load for the short column, while Fig. 7 shows that for the long columns. The four measured strains are consistent in the elastic stage both for specimen 500-2 and 900-1. However, the two groups of curves differ during the non-linear stage, particularly after the peak load point, consistent with the different failure modes. Buckling failure occurs for specimen 900-1, and that is why strain C reverses after the peak load point in Fig. 7.

3.2. Influence of slenderness ratio upon load and deflection

Fig. 8 plots typical load vs middle lateral deflection curves for specimens with various slenderness ratios (λ). In the initial phase the lateral deflection is very small and increases linearly with axial load. After the peak load point, the lateral deflection increases suddenly. The load decrease while the lateral deflection keeps increasing until failure happens.

As can be seen from the Fig. 8, the rate at which the lateral deflection increased before achieving the ultimate load accelerated with the increase of slenderness ratio. Deflection caused by the initial defects influences the bearing capacity of the specimens more and more obviously as the slenderness ratio increases, and the bigger the slenderness ratio, the bigger the lateral deflection occurring at peak load. After peak load, the load decreased more and more slowly with increase of slenderness ratio. This indicates that the mode of failure is becoming closer and closer to elastic