Experimental Research on the Compressive Performance of Raw Bamboo Materials along the Grain

Liu Pengcheng¹, Zhou Qishi*, Zhang Hai¹, Tian Jiefu¹

¹School of Civil Engineering, Central South University, Changsha 410075, China
Corresponding author’s email: qishizhou@csu.edu.cn

Abstract: This paper carried out a compression test along the grain of the raw bamboo material, analyzed the failure process and failure form of the specimen, studied the relationship between the compression strength along the grain and the elastic modulus and the density, and initially explored the raw bamboo based on the reliability analysis Design value of compressive strength along the grain of the material. The research results show that the compressive load-displacement curve of bamboo along the grain can be divided into elastic, elastoplastic and descending segments, and the specimens show obvious ductile failure characteristics; the compressive strength and elastic modulus along the grain are positively correlated with the density; raw bamboo The standard value of compressive strength along the grain of the material is 48.83MPa, and the design value is 8.71MPa.

1. Introduction

Bamboo is a natural composite material with a wide range of distribution, fast growth, and excellent mechanical properties [1]. Due to the development of industrialization and urbanization, natural aggregates used in construction are gradually depleted. Therefore, it is necessary to develop sustainable building materials and recyclable building resources, and bamboo is a high-quality green building material that meets the development trend and requirements of the times.

In recent years, a series of results have been achieved in the research of bamboo. Tian Genlin [2] systematically studied the mechanical properties of bamboo fibers and their influencing factors; Tian Ke [3] studied the flexural performance of the original bamboo frame lightweight material composite floor; He Ziqi et al. [4] studied the double-limbed bamboo with different connection methods The compression performance of the members was experimentally studied; Wu Songlin [5] studied the structural joints of raw bamboo buildings. In addition, in the past few decades, bamboo structures have been increasingly used in various countries. However, the design value of bamboo strength is still lacking.

This paper carried out a compression test along the grain of the raw bamboo material, analyzed the failure process and the failure form of the specimen, studied the relationship between the compression strength along the grain and the elastic modulus and the density, and preliminarily explored the design value of the compressive strength of the raw bamboo material along the grain.

2. Materials and methods

2.1. Selection of bamboo material and preparation of specimens

The original bamboo material studied in this paper was taken from Chenzhou City, Hunan Province, China, and the bamboo species was Phyllostachys pubescens. In the bamboo forest, bamboo stalks...
with a bamboo age of about 4 years, a diameter at breast height of about 100mm and a good shape and straight growth were selected for random felling, and the number of felling was 160. After air-drying, the test piece is made, and the height-diameter ratio of the small test piece along the grain with pressure-resistant clear material is 1.

2.2. Compressive strength test along the grain
Refer to the standards JG/T 199-2007 [6] and LY/T 2564-2015 [7] to carry out the compression test of bamboo along the grain, a universal testing machine was used for loading (Figure 1). The test was first loaded to 800N and held for 1.5min, then the stress was loaded to 6MPa at a rate of 150N/s, and then cyclically loaded 3 times in the stress range from 6MPa to 15MPa at a loading rate of 0.01mm/s to analyze along the grain Compressive elastic modulus, finally loaded to failure at a rate of 0.01mm/s. The formula for calculating the compressive strength and elastic modulus along the grain is formula (1-2).

\[
UCS = \frac{P_{\text{max}}}{A} \quad (1)
\]

\[
UCE = \frac{20\Delta P}{A\Delta l} \quad (2)
\]

Where, UCS is the compressive strength along the grain (MPa), \( P_{\text{max}} \) is the failure load (N), \( A \) is the force area (mm\(^2\)), UCE is the compressive elastic modulus along the grain (GPa), and \( \Delta P \) is the upper and lower limit load. The difference (N), \( \Delta l \) is the difference between the deformation values of the specimen under the upper and lower limit loads (mm).

![Figure 1. Loading of test pieces](image1)

![Figure 2. Typical failure mode of specimen](image2)

![Figure 3. Typical load-displacement curve of specimen](image3)

2.3. Water content adjustment
Take a small sample with a size of about 20mm×20mm to test the moisture content and density. Since the moisture content has a significant impact on the physical and mechanical properties of bamboo, the physical and mechanical properties are uniformly adjusted to the value under the standard moisture content (12%) during the study. The adjustment formula is as follows [6-7]:

\[
\rho_{12} = \rho_w[1-0.01\times(1-K)\times(W-12)] \quad (3)
\]

\[
UCM_{12} = K_wUCM_w \quad (4)
\]

where, \( \rho_{12} \) is the air-dry density at 12% moisture content (g/cm\(^3\)), \( \rho_w \) is the air-dry density (g/cm\(^3\)) when the moisture content is W, K is the volume shrinkage coefficient, and W is the moisture content (%). UCM\(_{12}\) is the along-grain compressive strength or elastic modulus of the specimen under standard moisture content (12%); UCM\(_w\) is the along-grain compressive strength or elastic modulus when the
moisture content is \( W \); \( K_W \) is the moisture content correction coefficient.

### 2.4. Strength design value analysis method

According to the bearing capacity failure limit state equation \( Z = R - S = 0 \), the relationship between the reliability index and the resistance partial index is derived from the center point method as equation (5) [8].

\[
\beta = \frac{K_R\gamma_R (\gamma_G + \gamma_Q \rho) - (K_G + K_Q \rho)}{\sqrt{(K_R\gamma_R)(\gamma_G + \gamma_Q \rho)\delta_R}^2 + (K_Q \delta_Q)^2}
\]  

Where: \( \beta \) is reliability index; \( K_R \) is resistance uncertainty; \( \delta_R \) is resistance variation coefficient; \( \gamma_R \) is resistance partial coefficient; \( \gamma_G, \gamma_Q \) are permanent load partial coefficients and variable load partial coefficients; \( K_G, \delta_G \) are permanent load uncertainty coefficient and variation coefficient; \( K_Q \) and \( \delta_Q \) are variable load uncertainty coefficient and variation coefficient; \( \rho \) is the ratio of variable load and permanent load effect standard value.

### 3. Results and discussion

#### 3.1. Destruction process and destruction form

The failure process and failure mode of the node and internode along the grain compression specimens are roughly the same. During the loading process, the test piece gradually bulged, and the bulging parts included the middle and the end. Most of the test pieces had end bulge (Figure 2). In the extreme state, the test piece had longitudinal cracks. Figure 3 shows the typical load-displacement curve of bamboo along the grain compression test. The curve can be divided into elastic section, elastoplastic segment and descending section. Bamboo timber has obvious ductile failure characteristics along the grain compression test.

#### 3.2. The relationship between mechanical properties and density

The Linear function, Exponential function, and Power function are used to fit the relationship between the compressive strength and elastic modulus of bamboo along the grain and the density to obtain the fitting curve shown in Figure 4-5. It can be seen from the curve that the compressive strength and elastic modulus of bamboo along the grain are positively correlated with density. The best fitting relationship between the compressive strength, elastic modulus and density of bamboo along the grain is equation (4-5).

\[
\text{UCS} = 146.98\rho^{1.94} \quad (R^2=0.368) 
\]  

Figure 4. UCS and \( \rho \) relationship curve  

Figure 5. UCE and \( \rho \) relationship curve
UCE=17.058ρ^{1.071} (R^2=0.434) \quad (7)

3.3. Discussion on strength design value

One hundred and fifty four bamboo stalks with a diameter at breast height of about 100mm and a length of 3m were subjected to a compression test along the grain. The average strength of the small specimens of clear wood at both ends of the bamboo stalk represents the strength of a bamboo stalk. The statistical results of characteristic values are shown in Table 1. Generally, the strength value corresponding to the 5% quantile value under the 75% confidence level is defined as the standard strength value of the material. The standard value of the compressive strength of bamboo along the grain calculated in this paper is 43.83MPa (Table 1).

| Item | Number | Average value/MPa | Standard deviation/MPa | Coefficient of Variation | Standard value UCSk/MPa |
|------|--------|-----------------|----------------------|-------------------------|-----------------------|
| Value | 154    | 54.04           | 6.83                 | 0.13                    | 43.83                 |

The resistance and load statistical parameters of raw bamboo materials are detailed in the timber structure design code [9]. Because the raw bamboo and the log are similar in composition, the statistical parameters of resistance can not be adjusted based on the log coefficient [10]. Consider dead load + live load on residential floor (D+R), dead load + live load on office floor (D+O), dead load + wind load (D+W) and dead load + snow load (D+S) Four load combinations and seven load ratios such as 0, 0.25, 0.5, 1.0, 2.0, 3.0, 4.0. The structural safety level is considered according to the second level, and the target reliability index of bamboo along the grain compression is β_0=3.2. According to the analysis of formula (5), the relationship curve between the raw bamboo material reliability index β and the resistance sub-factor γ_R and the load ratio ρ under dead load + residential floor live load (D+R) is shown in Figure 6-7. The curves under other load combinations are similar to Figure 6-7. It can be seen from Figure 6-7 that with the increase of resistance sub-factor γ_R and load ratio ρ, the reliability index β shows an increasing trend; the resistance sub-factor γ_R is the largest when the load ratio ρ=0 under the same reliability index β.

![Figure 6. Relationship curve between β and γ_R (D+R)](image)

![Figure 7. Relationship curve between β and ρ (D+R)](image)

When the target reliability β_0=3.2 and the load ratio ρ=0, the maximum value of the resistance component coefficient under each load combination is 1.55. This is used to calculate the design value of the bamboo along the grain compressive strength. The calculation formula is as follows:

\[
UCS_d = \frac{UCS_i K_p K_A K_0}{\gamma_R} \quad (8)
\]

Where, UCS_d is the design value of bamboo strength (MPa); K_p is the equation accuracy factor; K_A
is the geometric parameter uncertainty factor; \( K_0 \) is the reduction factor converted from the strength of the small specimen to the strength of the member. After calculation, the design value of the compressive strength along the grain of the original bamboo material is 8.71MPa.

4. Conclusion
(1) As the loading process progresses, the compression test piece along the grain gradually bulges, most of which are end bulges. When the load reaches the limit state, the test piece produces longitudinal cracks. The load-displacement curve of the specimen is divided into elastic section, elastoplastic section and descending section, and the specimen exhibits obvious ductile failure characteristics.

(2) The compressive strength and elastic modulus of bamboo along the grain are positively correlated with density. The linear function is used to fit the relationship between the compressive strength and elastic modulus and density of bamboo.

(3) The standard value of raw bamboo material strength calculated by using 5% quantile value under 75% confidence level is 48.83MPa. The reliability index of bamboo material increases with the increase of the resistance sub-factor and load ratio. The maximum value of the resistance sub-factor under the target reliability index is 1.55. Based on this calculation, the design value of the compressive strength of the raw bamboo material along the grain is 8.71MPa.

Acknowledgements
The work described in this paper is supported by grants from the National Key R&D Program of China (Grant No. 2017YFC0703500).

References
[1] Sharma B, Gatoo A and H M 2015 Ramage.Effect of processing methods on the mechanical properties of engineered bamboo Construction and Building Materials, 83:95-101.
[2] Tian G 2015 Study on the main influencing factors of bamboo fiber mechanical properties Chinese Academy of Forestry (in Chinese)
[3] Tian Y 2016 Research on flexural performance of light bamboo composite floor slab with original bamboo skeleton Xi’an University of Architecture and Technology (in Chinese)
[4] He Z, Zhou X, Xiao S and Wang J 2018 Experimental study on the performance of Moso bamboo compression members Journal of Building Structures, 39 (S2): 233-241.(in Chinese)
[5] Wu S 2018 Research on Structural Nodes and Design Expressions of Original Bamboo Buildings Nanjing University (in Chinese)
[6] JG / T199-2007, Test method for physical and mechanical properties of bamboo for construction (in Chinese)
[7] LY/T 2564-2015, Test method for physical and mechanical properties of round bamboo. (in Chinese)
[8] Zhang Y, Lu Y, Zhao Y, Zhou Y and Zhang Q 2018 Partial resistance coefficient of PTFE coated fabrics Journal of Building Structures, 39(S2): 351-359.(in Chinese)
[9] GBJ 5-1988, Design Code for Wood Structures.(in Chinese)
[10] Xiao Y, Yang R, Shan B, She L and Li L 2012 Experimental study on mechanical properties of glued bamboo for structure[J]. Journal of Building Structures, 33(11): 150-157.(in Chinese)