

Article

Axial Compression Behaviors of Columns Fabricated from Bamboo Oriented Strand Boards

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Abstract: Due to the low specific strength of bamboo oriented strand boards compared with the commonly used wooden building materials, reasonable and novel cross-section designs of bamboo columns fabricated from bamboo oriented strand boards as structural members were investigated. An axial compression experiment was carried out on full-scale bamboo columns to characterize the ultimate behaviors under a concentric load. The ultimate bearing capacities of solid, hollow and five-core columns of the same height were not obviously different from each other. The columns with a larger slenderness ratio showed lower ultimate loads and higher axial deflections. The short columns experienced failure due to material crushing, and the long columns experienced a combination of material crushing and inelastic buckling. The empirical equations for predicting the ultimate bearing capacity for wooden columns showed applicability for bamboo columns. Non-linear finite element modeling analyses were carried out to validate the experimental results, and a satisfactory agreement was found in the failure modes and ultimate bearing capacity.

Keywords: bamboo; column; bamboo oriented strand board; axial compression; cross-section design



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1. Introduction

Bamboo is abundant in China, and it has the advantages of a short growth cycle, high toughness and high strength. It is an ideal substitute for wood to be used as a construction and building material [1–3]. The design and use of structural bamboo products allow for the great demands of this renewable resource [4]. Bamboo scrimber [5,6], laminated bamboo lumber [7], bamboo–wood veneer composites [8], bamboo fiberboard [9] and bamboo oriented strand boards [10,11] are the main engineered bamboo products. Bamboo oriented strand boards have the advantages of a high utilization rate of materials, a high automation level and stable performance [12,13]. It was reported that the density and modulus of rupture and the modulus of elasticity of bamboo oriented strand boards were 0.7–0.85 g·cm^{−3}, 70–85 MPa and 8–11 GPa, respectively. Their density and modulus of rupture were higher than those of Douglas fir and southern pine, but their modulus of elasticity was similar to the two woods [11,14–16]. Due to their high strength and controllable performance, bamboo oriented strand boards could be used in the field of structural construction [17]. Recently, related studies focused mainly on the manufacturing, processing and basic mechanical properties of bamboo oriented strand boards; the boards are mainly used for container flooring and furniture, but less attention was paid to the application of the boards as architectural structure components [18,19].

Columns are major structural components that significantly affect a building's overall performance and stability [20,21]. The design and axial compression performance of columns constructed from bamboo-based composites were reported in some previous studies. Li et al. [22] investigated the axial compression of laminated bamboo columns and reported that non-linear finite element modeling analyses could be applied for theoretical calculations of the column bearing capacity. They also found that the compression of short

laminated bamboo columns displayed remarkable plastic behavior before crushing. The axial compression test on bamboo scrimber columns with three types of cross sections was studied by Su [23], and the results showed that the failure mode was related to the type of columns. Inelastic bulking occurred on solid columns, while splitting failure was found on square hollow columns and I-shaped columns. Karyadi et al. [24] studied the axial compression of hollow columns constructed from laminated Asian bamboo lumber with a small slenderness ratio, and reported that the average ultimate stress was 59.08 MPa, which exceeded that (46.3 MPa) of hollow columns constructed from southern pine sawn timber [25]. Furthermore, all of these studies suggest that the mechanical properties of columns constructed from bamboo-based composites compare favorably with those of common wood, and the axial compression is qualified for structural purposes. However, these studies were performed on columns constructed from laminated bamboo lumber or bamboo scrimber. Few research reports have been investigated to optimize usage of bamboo oriented strand boards for structural element components.

Compared with the commonly used wooden building materials, bamboo oriented strand boards have low specific strength due to their high density. Therefore, it would be helpful to prepare a bamboo column with high strength and less material through a reasonable cross-section design. A column section with a larger gyration radius is more resistant to buckling. In this paper, three different designs of bamboo columns constructed from bamboo oriented strand boards were prepared to explore the rationality of the structure. Through a full-scale axial compression test on the bamboo columns, the failure modes and ultimate bearing capacities of the three types of columns of different heights were studied. The objective of this study was to characterize the compression behavior of full-scale structural members constructed from bamboo oriented strand boards. Based on empirical equations and finite element modeling analyses, the theoretical ultimate bearing capacity of the columns was predicted.

2. Materials and Method

2.1. Sample Design and Preparation

Four- to six-year-old bamboo (*Dendrocalamus giganteus* Munro) culms were selected from Mangshi, Yunnan, China. The bamboo strands were prepared with a length of 140–145 mm (longitudinal), a width of 5–60 mm (tangential) and a thickness of 0.8 mm (radial). The moisture content of the dried strands was 5%. The mass fraction of the emulsion polymer isocyanate for the bonding strands was 6%, according to the oven-dry strand mass. The produced bamboo orientated strand board specification was 2440 mm × 1220 mm × 28 mm at the beltline scale and its target density was 0.9 g·cm⁻³. The following two different orientation types were designed: (1) bamboo fibers oriented mainly along the length of the board (BOSL); (2) a special three-layer structure with strands parallel to the length of the board on both skin layers and orthogonal strands in the central layer (BOSB). The weight ratio of the BOSB's face–core–back layer was set to 1:2:1. The moisture content of the two boards was 10% after conditioning in an environment of 20 ± 6 °C and 65% ± 5% relative humidity.

Figure 1 shows the fabrication process of the bamboo columns. The boards (BOSB and BOSL) were first sawed and sanded into component units of the columns. The units were then glued and laminated into 3 types of columns (Figure 2a–c), including square solid (S), hollow (H) and five-core columns (F), using a 290 g·m⁻² adhesive application at a pressure of 2 MPa for 4 h. Resorcinol–phenol–formaldehyde, purchased from Beijing Dynea Chemical Industry Co., Ltd. (Beijing, China), was used for the adhesion of the bonding units. The height ratio of the base and the hardener was 100:15. The three types of columns had relatively equal cross-sectional areas but different radii of gyration of the critical buckling axis. Each kind of column had two heights (1000 mm and 2800 mm). All three types of columns with a height of 2800 mm were finger-jointed using the resorcinol–phenol–formaldehyde adhesive and stagger-jointed due to the limit of the board dimensions, as shown in Figure 2e,f. The three 1000-mm-high columns were not finger-jointed. However,

to investigate the effect of finger joints on the compression behavior of short columns, five-core columns with a height of 1000 mm (F1000-Finger) were also finger-jointed and stagger-jointed, as shown in Figure 2c,d. The specimens were conditioned for 14 days in an environment of 20 ± 5 °C and $65\% \pm 5\%$ relative humidity.

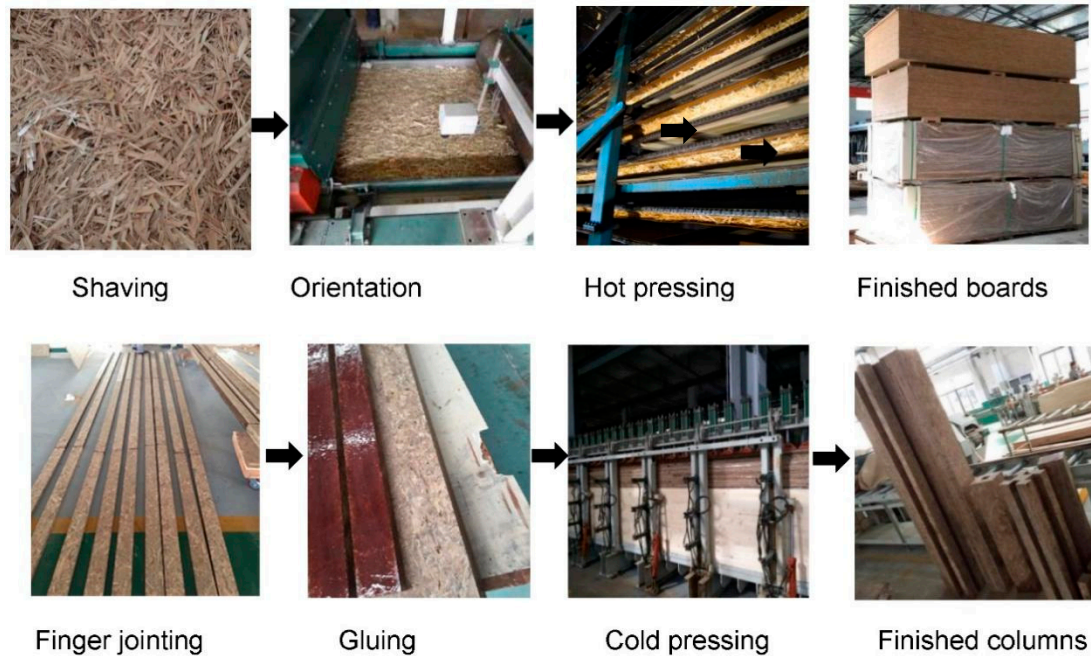


Figure 1. The fabrication process of the bamboo columns.

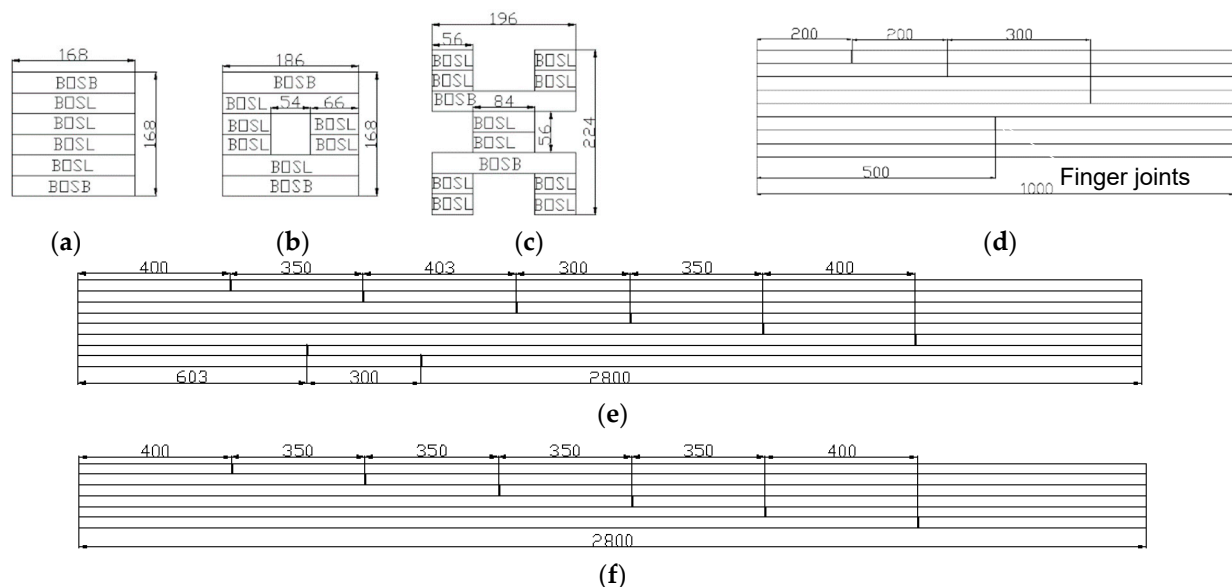


Figure 2. Details of the bamboo columns as follows: (a–c) cross section of the solid, hollow and five-core columns, respectively; (d,e) assembling joint gaps for the five-core columns with a height of 1000 mm and 2800 mm, respectively; (f) assembling joint gaps for the solid and hollow columns with a height of 2800 mm.

2.2. Test Setup

Based on the Chinese standard GB/T50329 [26], the axial compression load was applied to the column. As illustrated in Figure 3, the end condition was fixed-pinned, theoretically resulting in a column effective length factor (K) equal to 0.80. The axial load and the corresponding axial displacement were recorded with a constant loading speed

($1.5 \text{ mm} \cdot \text{min}^{-1}$) using an electro-hydraulic servo universal testing machine with a capacity of 1000 tons. Six linear voltage displacement transducers (LDS) were installed on the two adjacent sides of each specimen to measure the lateral deflections of the quarter and the mid-span points for the X–X (i.e., DX1, DX2 and DX3) and Y–Y axes (i.e., DY1, DX2 and DY3) of the columns, as shown in Figure 3. Moreover, eight strain gauges were attached on the four sides at the mid-length of each specimen to measure the longitudinal (i.e., SL1–SL4) and transverse (i.e., ST1–ST4) strains, as shown in Figure 3b. The deflection and strain data were recorded synchronously by a DH3816 static strain testing system with a sampling frequency of 1 Hz (Donghua Testing Technology Co., Ltd., Taizhou, China). In addition, the axial loading tests were conducted according to ASTM D 198 [27] on 300-mm-long columns collected from the same test specimens to determine the compressive strength parallel to the surface strand orientation of the test materials, and the values of the solid, five-core and hollow columns were 49.68 MPa, 44.8 MPa and 45.2 MPa, respectively. These values will be used for the theoretical ultimate stress calculations and finite element modeling analyses.

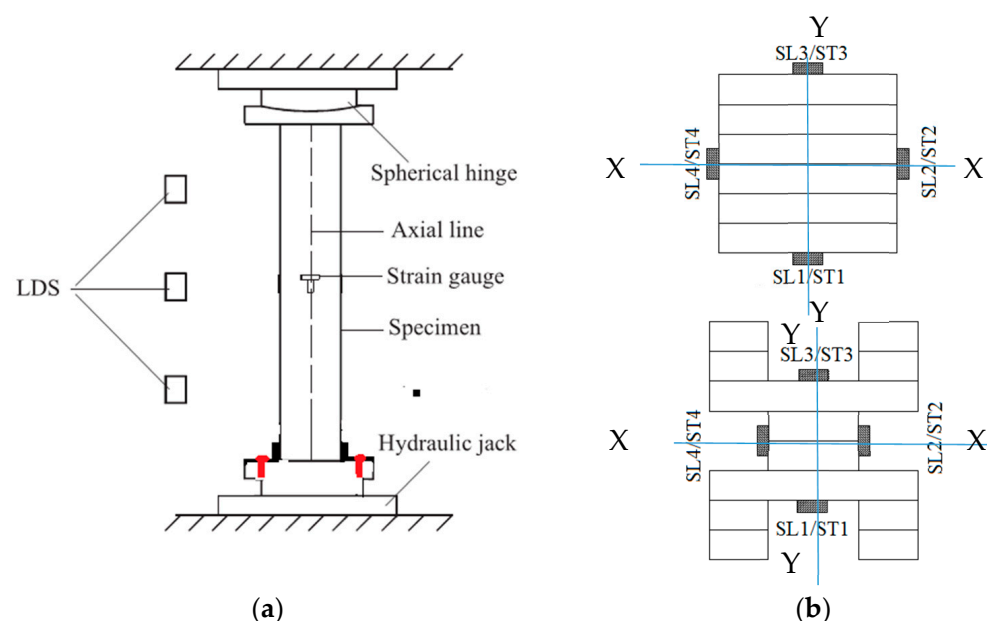


Figure 3. Details of the column experiment assembly. (a) Experiment setup; (b) strain gauge layout for the solid and five-core columns. The strain gauge layout of the hollow columns is the same as the solid columns.

3. Results and Discussions

3.1. Failure Modes

Figure 4 shows failures of the three column types with heights of 1000 mm and 2800 mm. The 1000-mm-high solid column (S1000) had a wedge split at the top of the column. The failure of the hollow columns with a height of 1000 mm (H1000) was generally a combination of shearing and splitting, which was mainly caused by internal defects in the sample. The 1000-mm-high five-core column (F1000 and F1000-Finger) showed a shear rupture at the top of the column. The three column types with heights of 1000 mm failed by crushing due to material failure without obvious lateral deflections. This could be explained by the fact that for the column with a relatively small slenderness ratio failure occurred once the stress exceeded the elastic limit of the column material [28]. Shear fracture failure occurred at the bottom of the 2800-mm-high five-core (F2800) and hollow columns (H2800). For the 2800-mm-high solid columns (S2800), inelastic buckling occurred at the middle due to the second-order bending moment, and cracks developed at the tension zone located in the middle of the columns. The columns with a height of 2800 mm mainly experienced material crushing or inelastic buckling. With the increase in the load, the lateral deflection and the additional bending moment would continue to increase. As a result of mutual

influence, the long column would be damaged under the joint action of the axial force and bending moment.

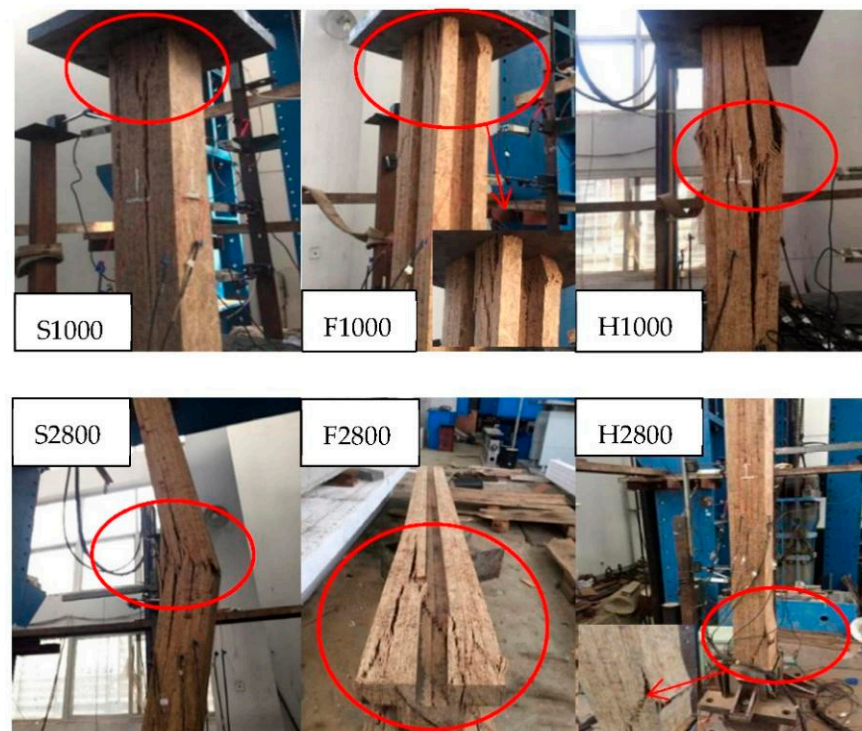


Figure 4. Failure modes of the three types of columns with different heights after a compression test.

3.2. Analysis on Ultimate Bearing Capacity

As shown in Table 1, the higher columns, which had a larger slenderness ratio, showed lower ultimate loads and higher axial displacements. The ultimate loads of H2800, S2800 and F2800 were 6.53%, 17.33% and 20.69%, respectively, which are lower than those of H1000, S1000 and F1000. These may be caused by the eccentricity in the loading and irregularities in the column material of the higher columns. For columns of the same height, the lower slenderness ratio usually results in a higher ultimate bearing capacity. However, in this study, although the slenderness ratios of the hollow and five-core columns were smaller than those of the solid columns, the ultimate bearing capacities of the three columns obtained in this study were similar, with a difference of around 10%. This could be caused by gaps in the hollow and five-core columns and eccentricity in the loading, which may stress the concentration on part of the column's cross section. Besides, the ultimate loads of F1000 and F1000-Finger were very close, with a difference of less than 2%. This illustrated that the appropriate assembling joints would not affect the ultimate bearing capacity of the columns.

Table 1. Results of the axial compression test on the bamboo columns.

Sample	Column Height (mm)	Slenderness Ratio	Ultimate Load (kN)	Axial Displacement (mm)	Ultimate Stress (F_c) (MPa)
S1000	1000	21	1298	10.88	44.65
S2800	2800	59	1073	18.25	36.91
F1000	1000	17	1209	10.51	41.85
F1000-Finger	1000	17	1188	9.50	41.12
F2800	2800	47	959	18.62	33.19
H1000	1000	20	1179	9.92	40.51
H2800	2800	56	1102	18.15	37.87

3.3. Column Lateral Deflection and Strain

Figure 5 plots the typical load curves and the corresponding lateral deflections. For all of the specimens in the initial phase, the lateral deflections were very small and increased with the axial load. Once the ultimate loads approached, the lateral deflections increased substantially until failure happened. In general, the lateral deflections in the X–X axis were less than those in the Y–Y axis. This is attributed to the higher flexural rigidity in the X–X direction of the bamboo orientated strand board, which is a kind of anisotropic material. Zhou et al. [29] drew a similar conclusion on square solid columns constructed from laminated bamboo lumber.

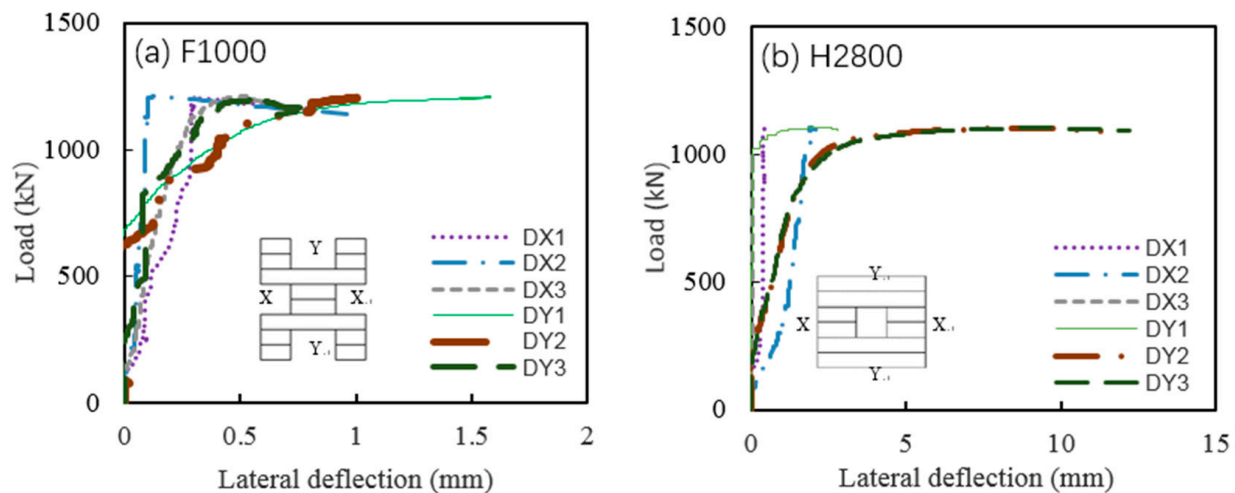


Figure 5. Typical curves of the load and the lateral deflection. (a) F1000; (b) H2800.

Similar load–strain curves were found in all of the specimens except for S2800. For the solid columns, the maximum longitudinal strain of the high one (S2800) was larger than that of the short one (S1000) (Figure 6), which is consistent with the conclusion reported by Lv [30]. For S2800, as shown in Figure 6b, SL3 reversed after the peak load, while SL1, which was measured on the opposite side of SL3, showed a dramatic increase in negative value. This was in accordance with the failure mode of S2800, as shown in Figure 4, which showed a large lateral deflection due to its high slenderness ratio. This result was mainly due to the interaction of tensile stress caused by a second-order bending moment and compressive stress caused by the axial compressive load [21,30]. The positive values (expansion) of the transverse strain were caused by the contraction in the longitudinal direction.

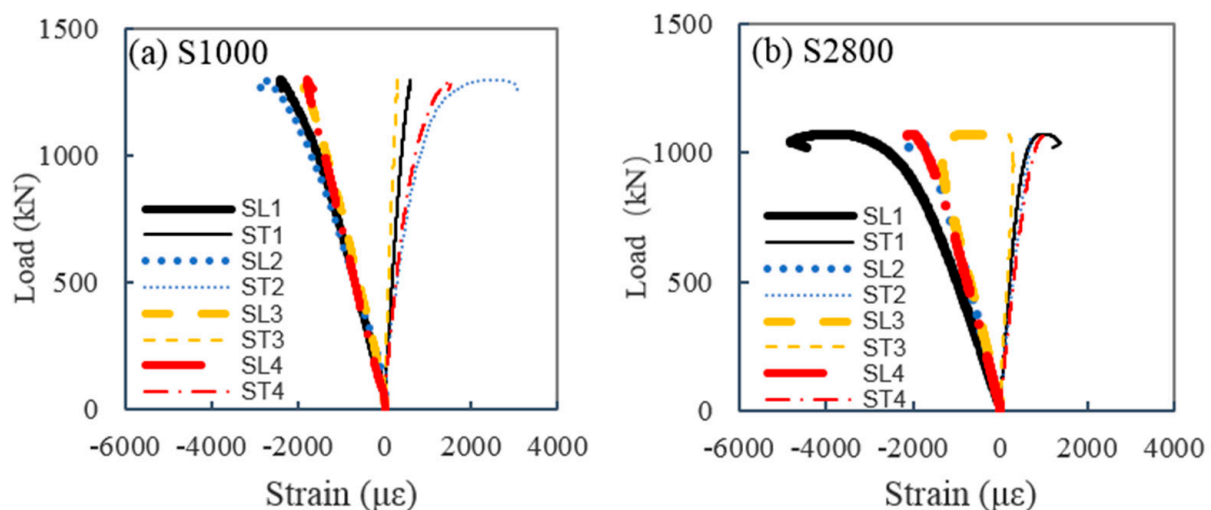


Figure 6. Load–strain curves of S1000 (a) and S2800 (b).

3.4. Empirical Theoretical Calculation

There is a set of wooden column design equations for determining the allowable compressive stress, but there are still no empirical design equations for bamboo columns. In this study, the theoretical calculation of bamboo columns was referred to the design standards of wooden columns.

Referring to the Chinese standard GB 50005-2003 [31], Equation (1) was used to calculate the theoretical ultimate stress (F'_c) as follows:

$$F'_c = F_c^* \times c_p \quad (1)$$

$$c_p = \frac{1}{1 + \left(\frac{\lambda}{80}\right)^2} \quad (2)$$

where F_c^* is the compressive strength of the material and c_p is the column stability factor, which is calculated using Equation (2) when the slenderness ratio (λ) is less than 75; $\lambda = l_e/i$, $l_e = Kl$ (mm) where l is the height of the test piece, $K = 0.8$ in this paper, i is the radius of gyration; $i = \sqrt{I/A}$, where I is the section inertia modulus (mm^4) and A is the cross-sectional area (mm^2).

The American standard NDS-2015 [32] comprehensively considered the influence of the elastic modulus (E), compression strength and column height on the ultimate stress of columns. Accordingly, the preceding ultimate stress equation was simplified as follows:

$$F'_c = F_c^* \left[\frac{1 + \left(\frac{F_{ce}}{F_c^*}\right)}{2c} - \sqrt{\left[\frac{1 + \left(\frac{F_{ce}}{F_c^*}\right)}{2c} \right]^2 - \frac{F_{ce}/F_c^*}{c}} \right] \quad (3)$$

where c is the buckling and crushing interaction factor of the columns, $c = 0.9$ for the glued laminated timber and structural composite lumber and F_{ce} is the Euler critical buckling stress for the columns; $F_{ce} = \pi^2 EI / (l_e)^2$, where E is the reference modulus of the elasticity associated with the axis of buckling, $E = 9.33$ GPa (details are presented in Section 3.5).

Table 2 shows the comparison between the test results and the calculation results by Equations (1) and (3), respectively. The overall error between the test results and the calculation results was below 15%, which indicates that the calculated ultimate stress was in good agreement with the experimental ones. The errors could be caused by the empirical calculation equations, which were more applicable for wooden columns than for bamboo columns. However, overall, these equations for wooden columns can be adopted for calculating the ultimate stress of bamboo columns.

Table 2. Comparison between the test results and theoretical calculations by NDS and GB50005.

Column Length (mm)	<i>d</i> -NDS (%)			<i>d</i> -GB50005 (%)		
	F	S	H	F	S	H
1000	6.40	7.96	9.45	4.59	6.73	8.04
2800	14.54	−5.31	−11.10	11.07	8.75	−2.64%

Note: The error, $d = (F'_c - F_c) / F_c \times 100\%$.

3.5. Finite Element Modeling

In this study, the ANSYS software (ANSYS Inc., America) was used to simulate the axial compression test of the bamboo columns. An element (SOLID185) was used to model the three types of columns. The elastic constants of the materials for the analysis were determined through testing according to ASTM D1037 [33] and are summarized in Table 3. The testing coupons for the elastic constants of the materials were cut from solid column testing specimens. For the bamboo columns, L, T and R represent the three principal axes

with respect to the surface-oriented strand direction, as shown in Figure 7, and RT, LR and LT are the horizontal, radial and tangential sides, respectively.

Table 3. Elastic constants of the bamboo column.

Material	E-L (GPa)	E-R	E-T	G-LT (GPa)	G-RT	G-LR	v-LT	v-RT	v-LR
Bamboo column	9.33	2.6	3.99	1.44	0.52	0.54	0.27	0.08	0.4

Note: E means modulus of elasticity; v means Poisson's ratio; G means shear modulus; L, R, T, RT, LR and LT are explained in the text.

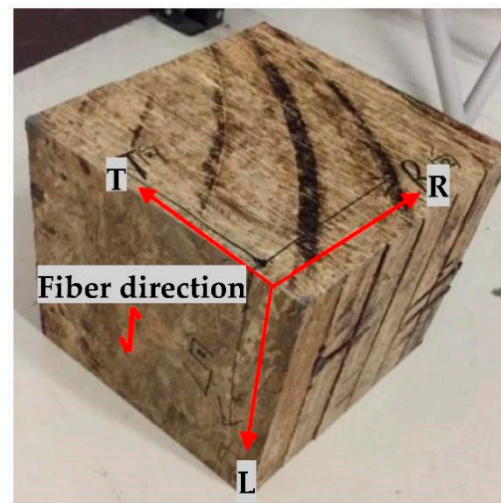


Figure 7. The three axes of the column relative to the fiber direction.

The two approaches in ANSYS, i.e., eigenvalue analysis and non-linear elastic analysis, were used to establish the buckling response of such structures. By eigenvalue buckling analyses, the critical buckling load of an ideal elastic structure can be predicted. There are two steps to gaining the critical buckling load. Firstly, a static solution for an initially applied load was obtained and the stress stiffness matrix $[K_{NL}]$ was calculated. Secondly, the eigenvalue analysis was conducted in accordance with the following generalized eigenvalue equation:

$$([K] + \lambda_i [K_{NL}])u_i = 0 \quad (4)$$

where $[K]$ is the stiffness matrix, λ_i is the i th eigenvalue (used to multiply the generated stress stiffness matrix $[K_{NL}]$) and u_i is the i th eigenvector of the displacements. Finally, the critical buckling load is calculated as follows:

$$P_{cr} = (\lambda_i)_{\min} P \quad (5)$$

where $(\lambda_i)_{\min}$ is the minimum eigenvalue and P is the total applied load [34]. In the non-linear analysis, the total load applied to the finite element model was divided into a series of load increments. The Newton–Raphson method was used to solve the non-linear equations. A relatively large displacement was applied to the structure, and the automatic load step dichotomy method was used for the non-linear analysis. The non-linear analysis was achieved based on a presumed imperfection [35]. Here, an initial imperfection equal to 1/500 of the column specimen height was introduced at middle height in the first mode shape of the non-linear analysis. By drawing the load–displacement curve, the ultimate stress of the columns could be obtained.

It was found that the stress nephogram distribution characteristics of the different columns of the same height were similar. Figure 8 shows two typical examples. The stress at the mid-upper part and bottom of F1000 was large, which may be caused by the

loading on top and the fixed condition at the bottom of the column. According to the stress nephogram of H2800, it showed that the complete buckling failure of the column should appear in the middle, but it also showed that the stress on the bottom side was large. If there were eccentricities in the loading or irregularities in the column material, the initial failure probably occurred at the bottom of the column before the buckling failure. Overall, the failure modes from the finite element modeling analyses were in agreement with the experimental failure modes.

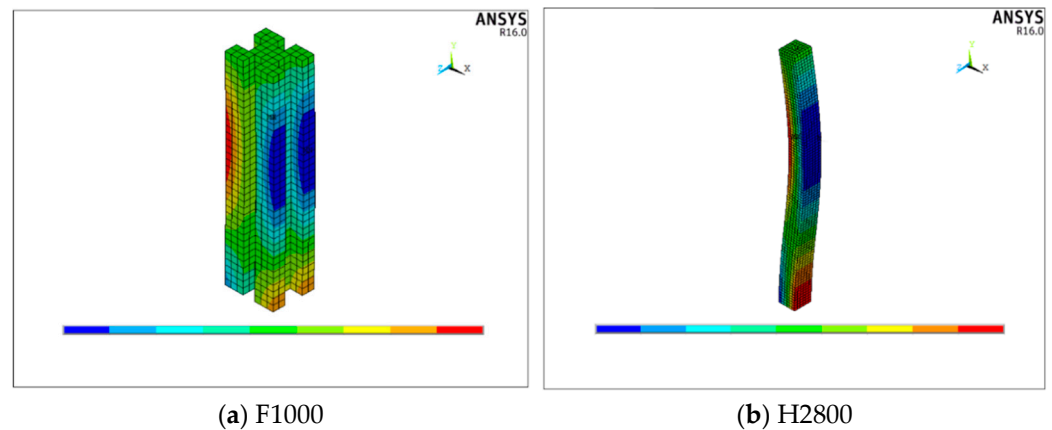


Figure 8. Stress nephogram of the bamboo columns F1000 (a) and H2800 (b).

Table 4 shows the errors of the test results and theoretical calculations from the finite element modeling analyses for the pinned-fixed bamboo columns. Overall, the calculation values from the eigenvalue analysis were significantly larger than the experimental values. This was because the eigenvalue buckling analysis had not considered the influence of the material non-linearity and geometric non-linearity. Moreover, through the eigenvalue buckling analysis, the errors of the columns with a low slenderness ratio were obviously larger than those of the columns with a high slenderness ratio. This was mainly because the damage of the columns with a lower slenderness ratio was mainly determined by the compressive strength of the material. The non-linear analysis showed a better agreement with the test results, and the error was less than 10%. The non-linear buckling analysis accounted for the geometric non-linear and large deflections of the structure. Li et al. [21] reported similar conclusions for the laminated bamboo columns.

Table 4. Errors of the test results and theoretical calculations by finite element modeling analysis.

Column Length (mm)	<i>d</i> -Eigenvalue Analysis Stress (%)			<i>d</i> -Non-Linear Buckling Analysis (%)		
	F	S	H	F	S	H
1000	372.10	435.87	406.05	9.76	1.35	3.51
2800	104.02	35.28	46.93	9.62	8.13	−0.36

4. Conclusions

Through axial compression tests on the bamboo columns, the failure modes and ultimate bearing capacities of three columns at different heights were studied. The following conclusions can be drawn.

The short columns (1000 mm) failed by crushing without obvious lateral deflections due to material failure. The high columns (2800 mm) experienced material crushing or inelastic buckling. The height and cross-sectional structures of the columns affected the failure mode of the columns.

The columns with a larger slenderness ratio showed a lower ultimate bearing capacity and a larger lateral deflection under the influence of eccentricity in the loading and irregularities in the column material. In addition, the ultimate bearing capacities of the three column types of the same height were not obviously different from each other.

The empirical equations for predicting the ultimate bearing capacity of wooden columns showed applicability for bamboo columns. The failure modes obtained by finite element modeling analyses were consistent with the observations from the test. The calculated ultimate bearing capacity values by eigenvalue analyses were significantly larger than the experimental values. The non-linear analyses gave better agreement with the test results, and the error range was less than 10%.

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Data Availability Statement: Data available on request due to privacy/ethical restrictions.

Conflicts of Interest: The authors declare no conflict of interest.

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