Article

Flexural Properties of Multiple Bamboo Beams with Connection Joints

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Abstract: Bamboo is a natural material widely used in buildings and bridges that has good mechanical properties. However, the longitudinal connection of bamboo culms is a major problem for the bamboo industry. In this study, sleeve-nailed bamboo specimens were produced, which contained three bamboo pieces. Two bamboo pieces with similar diameters were longitudinally joined by inserting a short bamboo culm with a smaller diameter, fixed with nails. The flexural performance of single beams and two-culm beams were studied. The load-displacement curves and fracture behavior of the specimens were investigated. The results show that the flexural bearing capacity of the single connected bamboo specimen was relatively smaller than that of an unconnected one, while the flexural bearing capacity of the two-culm beam was improved significantly. It can be seen that the lateral connection of bamboo specimens can improve the bearing capacity of the combined bamboo culms. This study provides a basis for promoting the application of sleeve-type nailed connections for bamboo.

Keywords: bamboo; multiple-culm beams; longitudinal joint

1. Introduction

Bamboo is a fast-growing plant that is eco-friendly and renewable [1]. It has good mechanical properties, a high strength, and good flexibility. It can absorb lots of energy in earthquakes [2–4] and is widely used in buildings, bridges, trusses, and scaffolds. The tension, compressive, bending, and other properties of bamboo have been studied [5–8], which are important for the application of bamboo materials in construction.

Bamboo has a long history as a building material, such as early bamboo scaffolding [9], temporary buildings, and low-rise bamboo buildings, connected by lashings, straight nails, etc. [10]. With the development of bamboo applications, it is no longer only used for decoration and temporary buildings, but also used for permanent buildings. However, the connection joint is a major problem and important for bamboo, which can affect the service life of a bamboo building. Bamboo connection joints have been studied by many researchers [11–15], such as mortise-tenon joints, filler reinforced joints, bolted joints, steel member and steel plate joints, etc. [16,17]. The sleeve-type joint has been researched in recent years, including sleeve-bolt, sleeve-cement, sleeve-bolt-cement, sleeve-gypsum, and so on. Brittle failure usually occurs due to the weak shear interface at holes [18–21].

The roof of the Bamboo and Rattan Pavilion of the Beijing Expo in 2019 is a 35 m-long circular bamboo arch structure. To lengthen the bamboo for making long purlins, two bamboo culms with similar diameters were longitudinally joined by inserting a short bamboo culm with a smaller diameter inside those two bamboo culms, in which the
smaller-diameter bamboo culm acted as a connector between the two larger bamboo culms. Then, the three bamboo culms were fixed by nails. This method of connection is convenient and does not require bolts. To widen bamboo for making large-diameter pur- lins, multiple bamboo culms were combined with each other using bolts [22–24]. These two connection methods have lots of advances, are convenient, and result in little crack- ing. However, they need to be further studied if widely used in building. Therefore, a single connected culm and two-culm beams with sleeve-nailed joints were studied in this paper. The flexural properties and fracture behaviors were analyzed. The results of this study provide theoretical data for the design of bamboo buildings.

2. Materials and Methods

2.1. Materials

Hong bamboo (*Phyllostachys iridescens* C. Y. Yao et S. Y. Chen) was obtained from Anji county, Zhejiang Province, China. It was 3–4 years old, with a breast height diameter of 4 cm. All bamboo culms were carbonized. The carbonization conditions were 0.22 MPa of press pressure, 100 °C for the press temperature, and 30 min of pressing time. The bamboo culms before and after the carbonization are shown in Figure 1. Then, the bamboo culms were stored in air-drying conditions for 1 month with a moisture content of 10%–12%.

![Figure 1. The bamboo culms before and after carbonization.](image)

The bamboo culms were divided into two groups. One group was used as the outer bamboo, which had a diameter of 40 mm and a thickness of 5 mm. The other group was utilized as the inner casing, which had a diameter of 30 mm and a wall thickness of 4 mm. The density was 0.79 g/cm³ and the linear mass was 0.58 g/mm. All small-diameter bam- boos were micro-carbonized. The moisture content was 10%–12%.

2.2. Preparation of Specimens

Two groups of bamboo specimens were prepared for the experiments. One was the original round bamboo culm, and the other was the group of bamboo with sleeve-nailed joints.

1) The bamboo-sleeve group: Each group consisted of three bamboo specimens: two specimens of D₄₀ and one of D₃₀. The two D₄₀ bamboo specimens were connected with D₃₀ specimens and fixed by nails. The air nail gun used was Meite F32F. The length of the nails was 15 mm. The nails were staggered up and down, which can prevent bamboo beams from cracking. The spacing of the nails was about 30 mm. The length of D₄₀ was 750 mm, and the length of D₃₀ was 400 mm. The process is presented in Figures 1 and 2.

2) The control group (original round bamboo culm): The control group of bamboo specimens had no connection. The length was 1500 mm and the diameter was 40 mm. The details are shown in Figure 2.
2.3. Preparation of Sleeve-Nailed Specimens

The sleeve-nailed specimens were a group of bamboo culms in which two bamboo culms with similar diameters were longitudinally joined by inserting a short bamboo culm with a smaller diameter, and the smaller-diameter bamboo culm acted as a connector between the two larger bamboo culms.

The process details are shown in Figures 2 and 3. All specimens were connected and reinforced with straight nails.

2.4. Preparation of Specimens for Flexural Test

Five groups were tested in flexural tests. The results can be seen in Table 1. Group I was a single sleeve-nailed bamboo specimen. Group II was a single original round bamboo culm. Five samples from each group were tested in the flexural tests.

Groups III, IV, and V were two-culm bamboo beams. Group III consisted of a single original bamboo culm and a sleeve-nailed culm. The two specimens were connected in the transverse direction by bolts and nuts. The diameter of the screws was 8 mm. To avoid the two specimens sliding during the flexural test, a rectangular wooden strip was used between the bolt connections of the two bamboo columns. Group IV also contained two parts, which were composed of two sleeve-nailed culms. Group V consisted of two original bamboo culms that had no joint. There were five specimens in each group. The details are presented in Table 1.

Table 1. Description of the five groups of bamboo specimens.

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Number</th>
<th>Figure</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Single sleeve-nailed bamboo specimen</td>
<td>5</td>
<td><img src="image1" alt="Figure 2" /></td>
</tr>
<tr>
<td>II</td>
<td>Single complete bamboo specimen</td>
<td>5</td>
<td><img src="image2" alt="Figure 2" /></td>
</tr>
<tr>
<td>III</td>
<td>One was a sleeve-nailed bamboo specimen; the other was a</td>
<td>5</td>
<td><img src="image3" alt="Figure 3" /></td>
</tr>
</tbody>
</table>
2.5. Strain Measurement

The distribution of the strain gauge at the tensile and compressive sides of the bamboo specimens are shown in Table 1. The strain gauge distributed at the upper side was used to measure the compressive side strain, which was odd-numbered. The strain gauge distributed at the lower side was used to measure the tensile side strain, which was even-numbered. The data were collected by the static strain test system.

2.6. Test Method and Equipment

Based on the forestry industry standard of China LY/T 2564-2015 [25] and ISO 22157-2019 [26], the bending properties of all specimens were tested. The ambient temperature was 28 °C and the relative humidity was 60%–80%. The Jinan Test gold WDWE100 mechanical testing machine was used for four-point loading. The test loading speed was 20 mm/min, and the loading method was monotonous static loading. The test device is shown in Figure 4. The flexural strength was calculated using Equation (1) and the modulus was calculated using Equation (2).

\[ \sigma = \frac{F_{\text{max}} \times L \times D_{\text{min}}}{12 \times I} \]  

Here, \( \sigma \) is the flexure strength (MPa), \( F_{\text{max}} \) is the maximum total load (N), \( L \) is the span between the center supports (mm), \( D_{\text{min}} \) is the minimum diameter at the loading points (mm), and \( I \) is the moment of inertia (mm\(^4\)).

\[ E = \frac{23 \times \Delta F \times L^3}{1296 \times \Delta \delta \times I} \]  

Here, \( E \) is the modulus of elasticity (MPa), \( \Delta F \) is the difference value between the upper (40%) and lower (20%) loads (N), and \( \Delta \delta \) is the difference value of the deformation between the upper and lower deformations (mm).

\[ P_{\text{max}} = \frac{M_{\text{max}}}{W} \]  
\[ M_{\text{max}} = \frac{F_{\text{max}} \times a}{2} \]  
\[ W = \frac{\pi D^3}{32} (1 - a^4) \]  

Here, \( P \) is the stress (MPa), \( M_{\text{max}} \) is the ultimate bending moment (N·mm), \( W \) is the section modulus in bending, and \( a \) is the difference value between the outside diameter and insider diameter of the bamboo culms.
3. Results and Discussion

3.1. The Bending Properties of Single-Culm Specimens

A summary of the load capacities of the specimens tested is shown in Table 2. It can be seen that the average value of the maximum load of the sleeve-nailed bamboo specimens was 0.73 kN, which was 63.87% lower than that of the control group. The flexural strength of the sleeve-nailed bamboo specimens was 32.49 MPa and the elastic modulus was 9.58 GPa, which were 59.49% and 18.68% lower than that of the control group, respectively. Therefore, the flexural strength of the sleeve-nailed bamboo specimens was relatively lower than that of the control bamboo specimens.

Table 2. Test results for flexural performance of single specimens.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Type I</th>
<th>Type II</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P max/MPa</td>
<td>F max/kN</td>
</tr>
<tr>
<td>Mean</td>
<td>54.48</td>
<td>0.73</td>
</tr>
<tr>
<td>SDV</td>
<td>12.28</td>
<td>0.22</td>
</tr>
<tr>
<td>COV</td>
<td>22.53%</td>
<td>29.66%</td>
</tr>
</tbody>
</table>

Note: SDV is standard deviation. COV is coefficient of variation.

Figure 5 shows the typical load-displacement curve of the sleeve-nailed bamboo specimens (Type I) and the original bamboo specimens (Type II). As can be seen from Figure 4, the two groups of specimens showed a three-stage development law:

(1) In the initial stage of the curve, the load-displacement curve basically showed a linear change from the beginning to 40% of the total segment. At this stage, the specimen experienced elastic deformation, which could be recovered if the load was removed.

(2) In the second stage, the curve showed a nonlinear trend from 40% to the maximum point. The deformation increased rapidly compared to the initial stage.

(3) After that, the displacement continued to increase, while the load decreased rapidly. The curve showed a serrated trend and macrocracks appeared in the bamboo tube until failure.
The failure modes of the sleeve nail-connected bamboo specimens were analyzed, and they can be classified into three typical failure modes (Figure 6):

(1) Failure model I: One of the outer bamboo pieces split and was damaged due to the small bamboo piece that was inserted. Cracks appeared in the outer bamboo, beginning from the connecting interface. It could be seen that the bamboo fibers were slowly tearing. When the load increased, the cracks gradually expanded until reaching the end of the specimen. The straight nail at the bottom of the specimen was pulled off the outer bamboo culms (Figure 6a). This meant that the outer bamboo determined the total ultimate bearing capacity of the group.

(2) Failure model II: Cracks first appeared at the nail hole of the specimen. When the load increased, the cracks became larger until the specimen failed (Figure 6b). The ultimate bearing capacity was slightly smaller due to the shear failure of the nail hole.

(3) Failure model III: During the loading process, small cracks appeared at the nail hole and passed through, then extended along the direction of the long axis of the nail hole. They extended until big cracks appeared at the joint between the outer and inner bamboo culms, and then failure occurred. (Figure 6c).

Figure 6. Three typical failure modes of single-culm specimens. (a). Failure model I; (b). Failure model II; (c). Failure model III.

The ultimate bearing capacity was affected by the stiffness of the outer bamboo and the shear failure of the straight nail holes. The connected joint was the weak part of the sleeve-nailed bamboo specimens. At the beginning, the outside of the bamboo specimens carried the majority of the load. When the load increased, the inner bamboo began to carry the load and apply force on the outer bamboo. At the same time, smaller cracks appeared along the nearby nail and extended, resulting in larger cracks sometimes, and then failure occurred.

The failure modes of Type II specimens are shown in Figure 7. Longitudinal cracking was observed. The results are similar to those of previous research involving horizontal bending tests of bamboo [27,28]. One of the researchers observed that longitudinal cracking drove the failures of major bamboo specimens, in which the shorter-span specimen
was at least 1.5 times that of the larger-span specimen [28]. In this study, the span was about 10 times that of the diameter according to the standard, which was shorter than 16D, 24D, or 30D in the previous study. A shorter standard flexural test showed the better shear-dominant behavior of the full-culm bamboo.

There are several previous studies of bamboo culm with pin joint, gusset plate joint, wood joint and so on [27,28]. Comparing with five joint connection methods previously discussed, the bending strength of the sleeve-nailed joint in this paper was moderate; it was lower than the mortar-filled joint specimens (85.1 MPa) and higher than other four joint specimens, such as pin joint (8.8 MPa), gusset plated joint (23.6 MPa), steel tube joint (14.9 MPa) and wood joint (31.7 MPa). This means that the sleeve-nailed joint connection is a good joint method.

3.2. Two-Beam Specimen Test Result Analysis

3.2.1. Test Results

The results for the load capacities of the specimens are shown in Table 3. It can be seen that the maximum load of Type V was the largest of the two-culm beams, with an average value of 3.62 kN. The maximum load of Type III was the second largest, with a value of 2.93 kN. The maximum of Type IV was the smallest, with a value of 1.62 kN. As shown in Table 2, the maximum loads of Types I and II were 0.73 kN and 2.02 kN, respectively. Compared with the single connected bamboo specimens, the ultimate load of Types III and V increased. Therefore, the bearing capacity of multiple-beam bamboo was better than that of the single specimens.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Stress (MPa)</th>
<th>Maximum Load (F/kN)</th>
<th>Displacement X/mm</th>
<th>Stiffness/N·mm⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>TA Type III</td>
<td>Mean 160.81</td>
<td>2.93</td>
<td>50.88</td>
<td>83.07</td>
</tr>
<tr>
<td></td>
<td>SDV 20.55</td>
<td>0.33</td>
<td>10.66</td>
<td>10.47</td>
</tr>
<tr>
<td></td>
<td>COV 12.78%</td>
<td>11.20%</td>
<td>20.94%</td>
<td>12.61%</td>
</tr>
<tr>
<td>TB Type IV</td>
<td>Mean 120.86</td>
<td>1.62</td>
<td>43.12</td>
<td>42.36</td>
</tr>
<tr>
<td></td>
<td>SDV 15.37</td>
<td>0.29</td>
<td>11.92</td>
<td>7.49</td>
</tr>
<tr>
<td></td>
<td>COV 12.71%</td>
<td>17.94%</td>
<td>27.64%</td>
<td>17.69%</td>
</tr>
<tr>
<td>TC Type V</td>
<td>Mean 211.8</td>
<td>3.70</td>
<td>65.73</td>
<td>96.25</td>
</tr>
<tr>
<td></td>
<td>SDV 24.76</td>
<td>0.64</td>
<td>7.70</td>
<td>16.96</td>
</tr>
<tr>
<td></td>
<td>COV 11.70%</td>
<td>17.21%</td>
<td>11.71%</td>
<td>17.62%</td>
</tr>
</tbody>
</table>

The stiffnesses of the single- and two-culm beams were calculated and the results are shown in Figure 8. The stiffness of Type V was the largest, with an average value of 96.25 N·mm⁻¹, while that of the Type III specimens was the second largest, with a value of 83.07
The stiffness of Type IV was the smallest, with an average value of 42.46 N·mm⁻¹. The average stiffnesses of the Type I and Type II specimens decreased sharply, which were 33.85 N·mm⁻¹ and 47.32 N·mm⁻¹, respectively. This was due to the connection joint, which is the weakest part of bamboo specimens. It could be seen that the stiffness of Type V, which had two full culm specimens without joints, was almost two times that of Type II, which had a single culm. However, the stiffness of Type IV, which had two sleeve-nailed specimens, was not two times that of Type I, which had a single sleeve-nailed specimen. This means that the stiffness of bamboo-joint specimens does not increase sharply. The weak loading points should be staggered up and down a multi beam. Type III, which had one full culm and one sleeve-nailed culm, was more than twice the stiffness of Type I. Therefore, the sleeve-nailed connection of the bamboo specimens had a certain effect on improving the bearing capacity of the combined specimen, which needs the better design of a multi beam based on the capacity of joints with bamboo culms and nails.

![Figure 8. Initial stiffness of five types of round bamboo.](image)

3.2.2. Load-Displacement Curve Analysis of the Two-Culm Bamboo Columns

The load-displacement curve of the two-culm bamboo columns is shown in Figure 9. At the beginning of the curve, the displacement increased linearly with an increase in the load. At this stage, the speed of the load increased sharply. As the load gradually increased, after the yield point, the load increased slowly and the displacement showed a nonlinear trend. When the ultimate load was reached, the fiber appeared to be teared and the curve then showed a ladder-shaped trend. Then, the curve reached the maximum bearing capacity and decreased sharply until the specimen was completely destroyed.
3.2.3. Analysis of Damage Form of the Two-Culm Bamboo Columns

The failure forms of three types of the two-culm beams are shown in Figure 10. The failure mode of Type III was that the bamboo specimen with the sleeve-type joint was destroyed at first. Cracks appeared in the joint with a splitting sound, and then several cracks were generated at a nearby joint when the load increased. The cracks extended along the grain direction and gradually expanded until the bamboo culm failed. Then, the other original bamboo culm carried the total load. The failure mode of this specimen was similar to that of the single original bamboo specimen.

The connected joint was also the main weak point of Type IV, which had two connected specimens. Cracks appeared at the connection interface and extended until failure occurred. The failure mode of the Type V specimen was similar to that of the single original bamboo specimen. The bamboo was crushed at the two loading points first, which resulted in several longitudinal cracks. Then, the cracks extended along the grain direction, and always ended at two thirds of the length.

Figure 9. Load-displacement curves of two-culm bamboo columns ((a) TA Type III; (b) TB Type IV; and (c) TC Type V). Five specimens were tested and showed at the curve of 1–5.
3.2.4. Load-Strain Curve Analysis of the Two-Culm Bamboo Columns

The load-strain curves of all groups are shown in Figure 11. Tensile strain is shown by a positive value, while compressive strain is shown by a negative value. The load-strain curves of each measuring point showed linear trends, whether at the compression surface or the tension surface. Type III contained two bamboo culms fixed by bolts and nuts at both ends. One was a full culm without a joint, and the other was a single beam with a bamboo joint. The maximum compressive strain at the loading point (3172) of the complete culm was lower than that of the connected one (4534), while the maximum tensile strain (6090) of the original culm was larger than that of the connected one (3398). Type IV contained two bamboo pieces, with both connected longitudinally with an inserted smaller piece of bamboo. The maximum compressive strain was 1378 for 1#, which was at the loading point, while the maximum value was 1234 for 2# at mid-span. The maximum tensile strain was 1035 for 1#, which was between the loading point and the supporting point, while the other was 1084 for 2# at the loading point. This shows that the strain of Type IV was relatively smaller than that of Type III due to the connection joint.
4. Conclusions

In order to evaluate the flexural properties of sleeve-nailed bamboo columns, bending tests were carried out. The conclusions are showed below:

1. The single sleeve-nailed bamboo specimens always cracked at the joints. They appeared to undergo brittle failure with shear splitting due to the inserted bamboo culm. The original bamboo appeared to undergo longitudinal splitting and local crushing.

2. The bending maximum load of the single sleeve-type nailed specimen was relatively small, which was 63.87% lower than that of the complete single bamboo specimen, while the bending capacity of the two-culm beams increased more significantly than the single one. Type V had the largest flexural bearing capacity, followed by Type III, and Type IV had the smallest one. Compared with the maximum load of the single specimen, Type III increased by 75.09%, while Type IV increased by 54.94%.

3. The stiffnesses of the single bamboo specimen for Types I and II were 33 N·mm⁻¹ and 47 N·mm⁻¹, respectively. The stiffnesses of the two-culm beams of Types III, IV, and V were 83.07 N·mm⁻¹, 42.46 N·mm⁻¹, and 96.25 N·mm⁻¹, respectively. The stiffnesses of Types III and V were higher than that of the single one.

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