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EFFECTS OF NODE DISTRIBUTION ON BENDING DEFORMATION OF BAMBOO

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Bamboo has attracted increasing interest for its promising application and usage in sustainable structural purposes. Bamboo node is crucial in improving stiffness and stability of bamboo under wind load. However, the structural role of node distribution in bending deformation has not yet been fully understood. This paper studied the effects of node distribution on bamboo outer diameter compression both theoretically and experimentally. A loaded bamboo model was set up to deduce the formula for its calculated compression. One loaded bamboo (*Phyllostachys pubescens*) with 42, 11 or 0 node was measured to obtain the measured compression values. The calculated and the measured compressions showed that the outer diameter compression of the bamboo with 42 nodes was lower than the bamboo with 11 nodes, and much lower than that without node. Bamboo nodes effectively reduced the outer diameter compression, and the more nodes, the smaller the compression value. Nodes also kept compression from 0.16 to 2.04 mm. Bamboo nodes played a vital role in avoiding strong bending deformation under wind load. This work could provide insights to help the bio-inspired design of advanced structures with desired bending deformation.

Keywords: Bamboo node, outer diameter compression, *Phyllostachys pubescens*, calculated and measured compression values

INTRODUCTION

In recent years, there has been increasing interest and research in the use of bamboo as biological material in a wide range of applications. In its natural habitat, bamboo acts as a cantilever beam with fixed support in the earth and is subjected to its own weight and wind load (Tan et al. 2011). Many researchers have been attracted to produce light weight designs based on the hollow cylinder, good flexibility and tough character of bamboo, which are mainly due to the longitudinally reinforced fibres and discretely distributed nodes (Shigeyasu & Sun 2001). Mechanical properties of bamboo fibres have been widely investigated, with limited efforts on bamboo nodes. Even these only analysed the mechanical properties of bamboo nodes such as stiffness, strength and toughness. Mechanical properties (shear, compression and tensile) of bamboo at nodes and internodes increased from bottom to top (Gusti et al. 2014). The bamboo culm stiffness, strength and toughness are low at the nodes (David et al. 2015). Bamboo node improves stiffness and stability of bamboo culm during growth (Shao et al. 2010) and prevents local buckling (Kappel et al. 2004). Geometry of the wild bamboo is a consequence of self-adaptive control under natural conditions (Hiroyuki et al. 2016). According to authors, cross-section of bamboo changes from round to oval as a result of deformation. Fibres in the node become entangled in a complicated manner to produce nodes with isotropic properties that provide additional reinforcement for the culm (Shigeyasu et al. 1997).

The objective of the present study was to investigate how node distribution affected bamboo bending deformation. Using theoretical and experimental data, we set up a loaded bamboo model and deduced the formula for its calculated compression. We measured the compression values of loaded bamboo having 42, 11 and 0 nodes. The model and data will be helpful to design advanced structures with the required bending deformation.

MATERIALS AND METHODS

Calculating compression process

To calculate compression values, load capacity was calculated using equation 1 (in the Appendix) and reference data. The elastic modulus of tensile strength parallel to grain E was adopted as 14 Gpa and compression strength E', as 4 Gpa (Xian & Xian 1990). The calculated compression values of outer diameter was determined using equations 2–4 (Appendix).

Measuring compression process

Sample preparation

Bamboos (*Phyllostachys pubescens*) were collected from Hunan province in China. Fifty mature bamboos (5 years old) were randomly collected and measured for outer diameter in air-dry condition. The outer diameters ranged from 41.6 to 123.2 mm. One bamboo sample with average outer diameter was selected as sample. A length of 10 m (containing 42 nodes) was cut from the bottom of the bamboo to the top.

Measuring tools

Diameter was measured using a pair of vernier callipers with a measuring range of 0–1000 mm and accuracy of up to ± 0.02 mm. Wall thickness and node thickness were measured using callipers with a measuring range of 0–150 mm with ± 0.05 mm accuracy. Internodal length was measured using tape with a measuring range 0–5000 ± 1 mm.

Measuring process

As the measured compression is obtained by subtracting the loaded from the unloaded outer diameter, the outer diameters of the sample bamboo at different heights were firstly measured in its original state before loading. The node outer diameter, wall thickness, node thickness and the internodal length were also measured before loading. After that, to facilitate measurement, the sample bamboo was evenly divided into two parts. The first part was from the bottom to 5-m height, and the second part was from 5 to 10 m. In order to demonstrate the existence or non-existence of node, both parts were cut in half along its length (Figure 1). Half of the first part was kept and labelled as A and half of the second part as B. To simulate natural loading, wind load acted on the culm was taken as equivalent to the load acted on one cantilever beam. Load capacity was calculated using equation 1 (Appendix). Since we kept half of the culm, the load was also halved. For both specimens A and B, the thicker end was fixed, and the thinner end was loaded with 50 and 12.5 N respectively using metal plates (Figure 2), after which the outer diameters were measured. In the first measurement, two specimens were measured with a total of 42 nodes (Figure 2). In the second measurement, for every three nodes one node was kept. A total of 31 nodes were removed by mechanically planing the external ridges and machining out the internal diaphragms, leaving the specimens with 11 nodes. For the third measurement, the 11 nodes were also removed in the same way, so specimens A and B were measured without nodes. Finally, we subtracted the loaded from the unloaded values to get the measured compression values.

Reference data

In order to achieve accuracy in the results, it was necessary to adopt the following reference data: basic wind velocity, $v_0 = 7$ m s^{-1}, height variation coefficient of wind pressure, $\mu_z = 1.0$ (cutting

(a) 42 nodes (b) 11 nodes (c) 0 node

Figure 1 Specimens with the different number of nodes

Figure 2 Measurement of the outer diameter of the 42-node loaded bamboo

height was under 10 m), coefficient of wind load system, $\mu_s = 0.6$, and wind vibration factor $\beta_z = 1.45$ (MOHURD 2012).

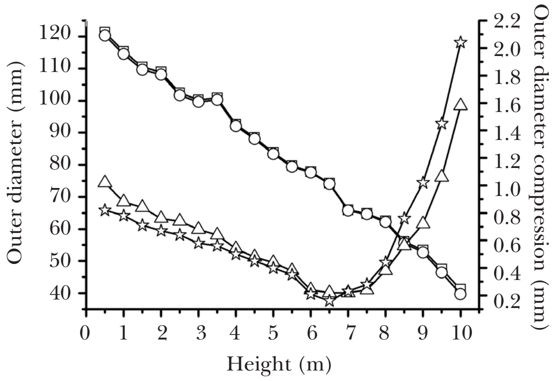
RESULTS AND DISCUSSION

Model verification

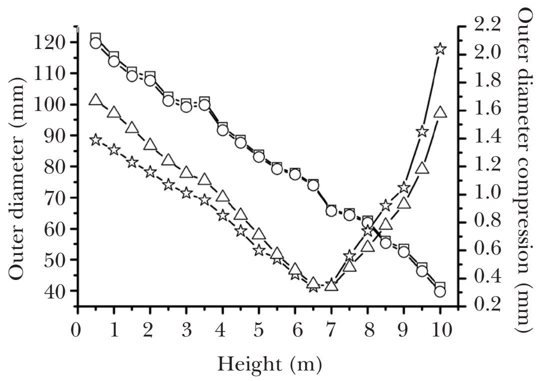
For measured compression, the bamboo with 42 and 11 nodes showed decreasing measured compression from the bottom to 6 m, little changes from 6 to 7.5 m and increasing values from 7.5 to 10 m (Figures 3a and b). The bamboo without nodes had decreased measured compression from bottom to top (Figure 3c). The corresponding calculated compression values were almost similar and the little difference was due to similar material properties of the bamboo used. For the calculated results, the material parameters were quoted from the literature which were similar to the measured bamboo material. The measured and calculated values were very close, and this verified the loaded bamboo model.

Compression of measured outer diameter

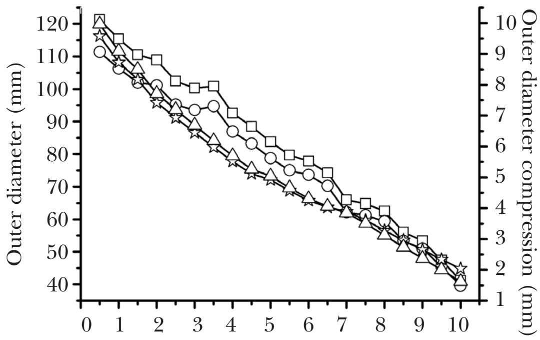
Compression of the 0-node bamboo showed outer diameter compression slowly decreasing as height increased (Figure 3c). It reached maximum value 9.97 mm at the bottom and minimum, 1.62 mm at the top. Compression of the 42-node bamboo started from 0.98 mm at the bottom, decreased slowly to its minimum value of 0.22 mm around 7 m height and then increased sharply to 1.57 mm at the top. For the 11-node bamboo, compression was maximum (1.67 mm) at the bottom, minimum (0.34 mm) around



(a) 42-node bamboo



(b) 11-node bamboo



(c) 0-node bamboo

Figure 3 The variation trends of the outer diameters and the compressions; □ unloaded outer diameter, ○ loaded outer diameter, △ measured compression, ☆ calculated compression

7 m after which it increased sharply at the top (1.59 mm) (Figures 3a and b). In comparison, the compression values at the bottom and middle of the 42-node bamboo were 41.3 and 35.3% lower respectively than the 11-node bamboo. These values were much lower than the bamboo without nodes (by 90.2 and 94.3% at the bottom and middle respectively). Compression values at the top were similar for all bamboo (Figure 4). Compression of the 0-node bamboo varied widely (range 1.62–9.97 mm), while the 42- and 11-node bamboo had less variation (0.22–1.57 and 0.34–1.67 mm respectively).

Compression of calculated outer diameter

Compression of the 0-node bamboo showed a slowly decreasing trend (Figure 3c). It reached maximum 9.58 mm at the bottom and minimum 2.04 mm at the top. Compression for bamboo with 42 and 11 nodes reduced greatly with values of only 0.82 mm and 1.39 mm respectively at the bottom. The values decreased gradually and reached minimum values of 0.16 and 0.34 mm respectively around 6.5 m. This was followed by a sharp increase until the maximum value of 2.04 mm at the top. Compression values at the bottom and middle of the 42-node bamboo were 41 and 53% lower than the 11-node bamboo at the same positions. Correspondingly, the values were much lower than the bamboo without nodes, i.e. by 91.4 and 96%. Compression values at the top were the same for all three samples (Figure 4). Compression of the 0-node bamboo varied greatly (range 2.04–9.58 mm), while the 42- and 11-node bamboo showed less variation (0.16–2.04 and 0.34–2.04 mm respectively).

CONCLUSIONS

Compression of the 42-node bamboo was lower than the 11-node bamboo and it was much lower than the 0-node bamboo. Compression of the 0-node bamboo varied widely compared with the other two samples. Nodes can effectively reduce the outer diameter compression of bamboo at all layers but is more obvious at the bottom. The more nodes there were, the smaller the outer diameter compression. Nodes can control compression within a certain range and cause the compression at different heights to change only slightly, resulting in a more uniform deformation. Findings and the numerical model obtained from this study will be useful for the biomimicking purposes in processing structures similar to cantilever beam with desired bending deformation.

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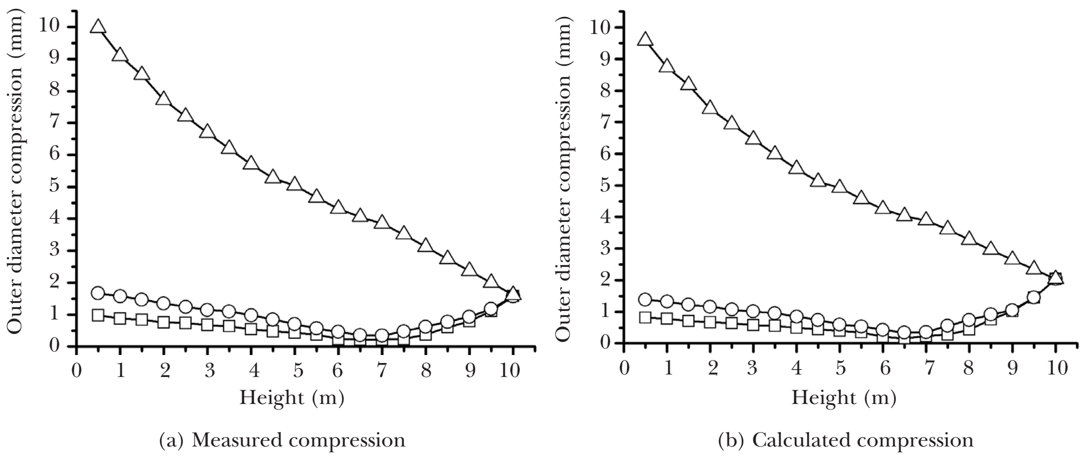

(a) Measured compression

(b) Calculated compression

Figure 4 Variation trends of the outer diameter compressions; □ 42 nodes, ○ 11 nodes, △ without nodes

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Appendix

Loaded bamboo model

The formulas for reaction force are as follows (refer to Figure A1):

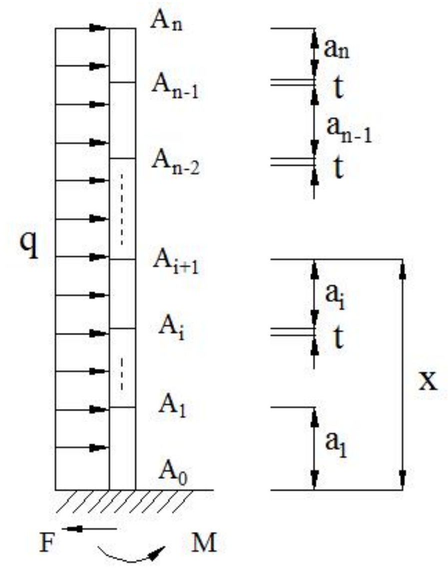

Figure A1 Loaded bamboo structure; q = instantaneous wind load intensity, a_1, a_2, ... $a_n - 1$, a_n = internodal lengths from bottom to top, A_1, A_2, ... $A_n - 1$, A_n = nodes, F = shear force, M = bending moment, t = node thickness

$$F_n = -\frac{1}{2}\pi\rho v_0^2\beta_x\mu_s\mu_x r\left(nt + \sum_{i=1}^{n} a_i\right) \tag{1}$$

$$M_n = -\frac{1}{4}\pi\rho v_0^2\beta_z\mu_s\mu_z r\left(nt + \sum_{i=1}^{n} a_i\right)^2 \tag{2}$$

where ρ = air density, v_0 = basic wind velocity, μ_x = height variation coefficient of wind pressure, μ_s = coefficient of wind load system, $ß_x$ = the wind vibration factor at the height of x, r = bamboo radius, n = number, t = node thickness

Its rotating angle θ_x equation is as follows:

$$\theta_x = \frac{\partial w_x}{\partial x} = -\frac{16M_x}{E\pi\left(D_{xr}^4 - d_{xr}^4\right)}\left\{v_{12}z^2 + 2\left[x - (k-1)t - \sum_{i=0}^{k-1} a_i\right]\right\} + \sum_{i=1}^{k-1}\frac{\partial w_{ir}}{\partial x} + \sum_{i=1}^{k-1}\frac{\partial w_{ic}}{\partial x} \tag{3}$$

where D_{xr} = outer diameter at the height of x, d_{xr} = inner diameter at the height of x, E = elastic modulus of the grain and v_{12} = Poisson ratio

Cross-section changes from round to oval (Hiroyuki et al. 2016) as a result of deformation. A_xB_x is compressed into A'_x B'_x. So the outer diameter compression ΔD_x can be expressed as:

$$\Delta D_x = D_x - \frac{x - u_x}{\sin\theta_x}\left(1 + \frac{1}{\sin\theta_x}\cdot\sin\frac{x - u'_x}{x - u_x}\theta_x\right) \tag{4}$$

where u_x = tensile displacement of bamboo outside at the height of x and u'_x= compression displacement of bamboo inside at the height of x.