Variability of macroscopic dimensions of Moso bamboo

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Abstract: In order to the macroscopic geometry distributions of vascular bundles in Moso bamboo tubes. The circumference of bamboo tubes was measured, used a simple quadratic diameter formula to analyze the differences between the tubes in bamboo culm, and the arrangement of vascular bundles was investigated by cross sectional images of bamboo tubes. The results shown that the vascular bundles were differently distributed in a bamboo tube. In the outer layer, the vascular bundles had a variety of shapes, and were aligned parallel to each other. In the inner layers, the vascular bundles weren't aligned but uniform in shape. It was concluded that the vascular bundle sections arranged in parallel should be separated from the non-parallel sections for the maximum bamboo utilization.

Keywords: Bamboo tube, uniformity, taper, mathematical formulation.

INTRODUCTION

Bamboo, which was a natural material, was useful to mankind in numerous ways. Humans had used different parts of bamboo plant for centuries and were finding the new uses. Bamboo had the potential to be used in the production of consumer goods. However, the structure and mechanical properties should be investigated. Simultaneously, bamboo was a complex biological material with homogeneous and non-homogeneous properties. Bamboo culm was composed of a number of bamboo tubes, each of a different size (Zehui, 2002). To accurately grasp the microscopic and macroscopic properties of bamboo, the geometric uniformity of bamboo tubes should be determined (Le *et al*, 2003; Tan *et al*, 2011).

The distribution of vascular bundles in bamboo was determined the bamboo macroscopic mechanical properties. Xingjuan *et al* (1990) reported that bamboo with thick-walled fibers arranged in an ordered way had a specific stiffness. Wenji *et al* (2002) found that the vascular bundles affect the bamboo mechanical properties, the number of vascular bundles per unit area, the bamboo fiber alignment direction and the strength of fibers were also the important factors for the strength of bamboo. Lili *et al* (2011) studied that the vascular bundles determined the bamboo mechanical properties and were an important link connecting microscopic and macroscopic bamboo properties. Gutu (2013) concluded the strength properties of bamboo are higher than most of the soft and hard woods. To determine the stability of macroscopic geometries in bamboo culms, the geometry arrangement of vascular bundles was investigated in bamboo tubes.

MATERIALS AND METHODS

4-year-old Moso Bamboo (*Phyllostachys pubescens*) was collected from Huangshan forest. Bamboo was dried naturally. Bamboo culm (fig. 1) was composed of many internodes, which were separated for tubes (Le *et al*, 2014). The distance between two neighboring internodes was the tube length. Bamboo characteristics were shown in table 1. Fig. 2 shown the picture of bamboo tube. No. 1 and No. 2 culm had the diameter 113.5mm and 113.0mm with the length of 14.86m and 15.3m, respectively. The longitudinal direction was defined as the Z-axis, and 0 marks the middle position on this axis. The down-direction was defined as ^{-}Z, and the up-direction was ^{+}Z. The circumference of tube was measured at 2 cm intervals along the Z-axis.

Table 1: Tube of bamboo culm

Culm ID	Section length/m	Tubes' Number	Tube ID
1	0-6	24	1-1,1-2,…,1-24
2	0-6	25	2-1, 2-2,…, 2-25

A tape was used to measure the circumference of bamboo tube, and the Vernier caliper was used to measure the wall thickness and diameter of each bamboo tube.

To obtain cross-sections of bamboo, the 1.0 cm × 1.0 cm (width × height) bamboo blocks were softened and then used a sliding microtome to smooth them. No scratches occurred on the bamboo blocks. Bamboo block was scanned by a color HP Scanjet G4050 scanner.

RESULTS

Fig. 3 described the changes in circumference (Ci,j) with z in bamboo tubes from No.1 and 2 culms. Figs. 4 to 6 represented the change of ai,j, bi,j and ci,j with bamboo tubes. And the cross-section images of the bamboo blocks from tube 18 of No.1 culm was shown in fig. 7. Above the red line in fig. 7(a) the vascular bundles were aligned

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parallel to each other. Figs. 8 and 9 depicted the arrangement of vascular bundles in the outer and inner layer of bamboo tube 1-18, respectively.

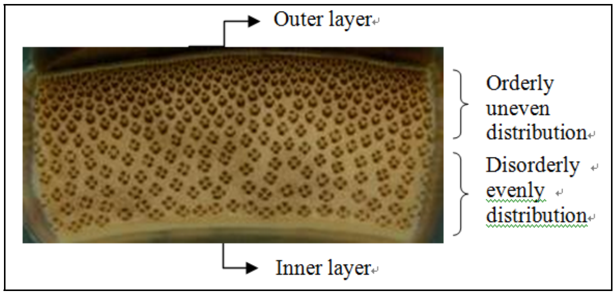

Fig. 1: Vascular bundle distribution in bamboo cross-section.

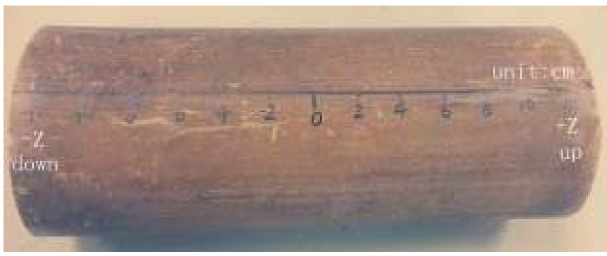

Fig. 2: Bamboo tube sample.

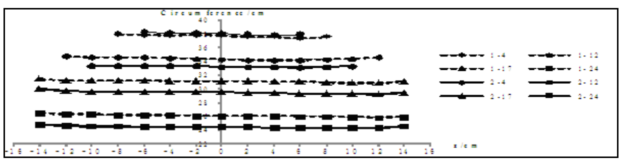

Fig. 3: Circumference of bamboo tubes.

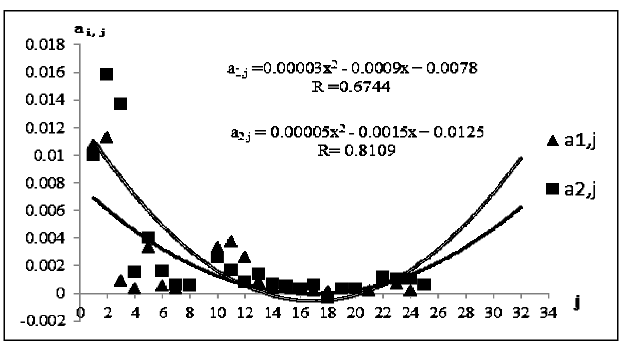

Fig. 4: Circumference equation $a_{i,j}$ values in bamboo tubes.

DISCUSSION

In each tube, the circumference $C_{i,j}$ varied along the Z-axis as follows:

$C_{i,j}=a_{i,j}z^2+b_{i,j}z+c_{i,j}$, (1)

i-ID number of culm, i = 1,2; j -ID number of bamboo tube; j = 1,2,3, ..., 25; $a_{i,j}$ - curvature of bamboo culm; z - circumference measurement location in 2 cm intervals along tube; $b_{i,j}$ - tapered degree of bamboo culm; $c_{i,j}$ - value of bamboo tube circumference in middle tube.

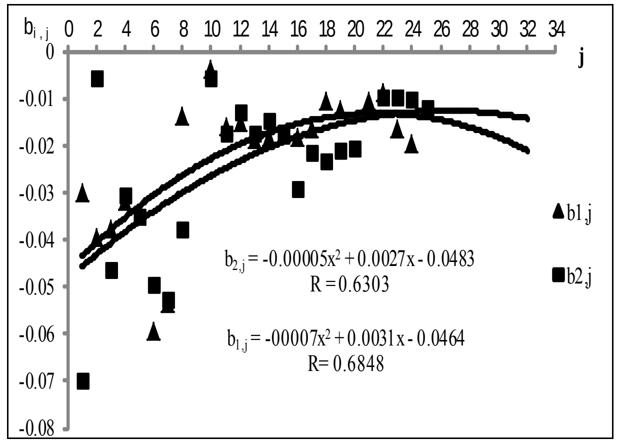

Fig. 5: Circumference equation $b_{i,j}$ values in bamboo tubes.

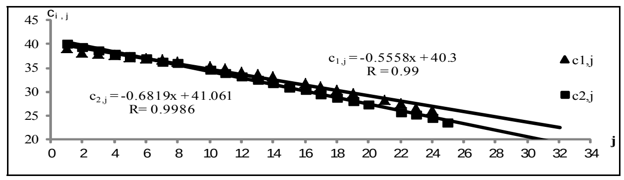

Fig. 6: Circumference equation ci, j values in bamboo tubes.

Fig. 3 showed that the circumference of tube 1-4 was 38 cm, and tube 1-24 is 24.5 cm. It resulted that there was more than 10 cm difference in tube circumferences of a 6-m high bamboo culm. In one bamboo tube, there was the little difference in circumference (as shown by the fairly straight lines). The circumference lines of tubes 1-4 and 1-24 were parallel. In a bamboo culm, the circumference and tapering greatly varied. It was a non-uniform material. In a bamboo tube, however, the circumference and tapering didn't vary, and then a bamboo tube was uniform.

As could be seen from table 2, the R-values of bamboo tubes were more than 0.8, and the equation represented variations in tube circumferences. The $a_{i,j}$ values were very small about 10^{-4}, indicating a small curvature in the bamboo tubes. The $b_{i,j}$ values were negative and close to zero, indicating that the bamboo circumference at the bottom was bigger than at the top, and the tapering was small.

According to the fig. 4, $a_{i,j}$ values were mostly close to 0, indicating that the degree of bamboo surface bend was small (Huaqiang, 2003). $|a_{i,j}|$ values leaded to the wider parabolas. The $a_{i,j}$ values of these two bamboo culms were higher for tubes 1 to 12. The distribution of $a_{i,j}$ values in bamboo tubes 12 to 24/25 fluctuated close to 0. And the curvature of bamboo tubes 1 to 12 was larger than that in bamboo tubes 12 to 24/25.

Table 2: Values in tube circumference equation

Tube ID	Tube height /m	Circumference equation	R Value
1-4	0.4	$C_{1,4} = 0.0003z^2 - 0.0317z + 37.725$	0.8967
2-4	0.3	$C_{,24} = 0.0015z^2 - 0.0304z + 38.076$	0.9407
1-12	2.2	$C_{1,12} = 0.0026z^2 - 0.0148z + 34.294$	0.9087
2-12	2.3	$C_{2,12} = 0.0008z^2 - 0.0127z + 33.261$	0.7830
1-17	3.6	$C_{1,17} = 0.0002z^2 - 0.0164z + 31.159$	0.9081
2-17	3.3	$C_{2,17} = 0.0006z^2 - 0.0213z + 29.479$	0.9180
1-24	6.0	$C_{1,24} = 0.0002z^2 - 0.0193z + 26.10$	0.9567
2-24	5.7	$C_{2,24} = 0.001z^2 - 0.0098z + 24.446$	0.9194

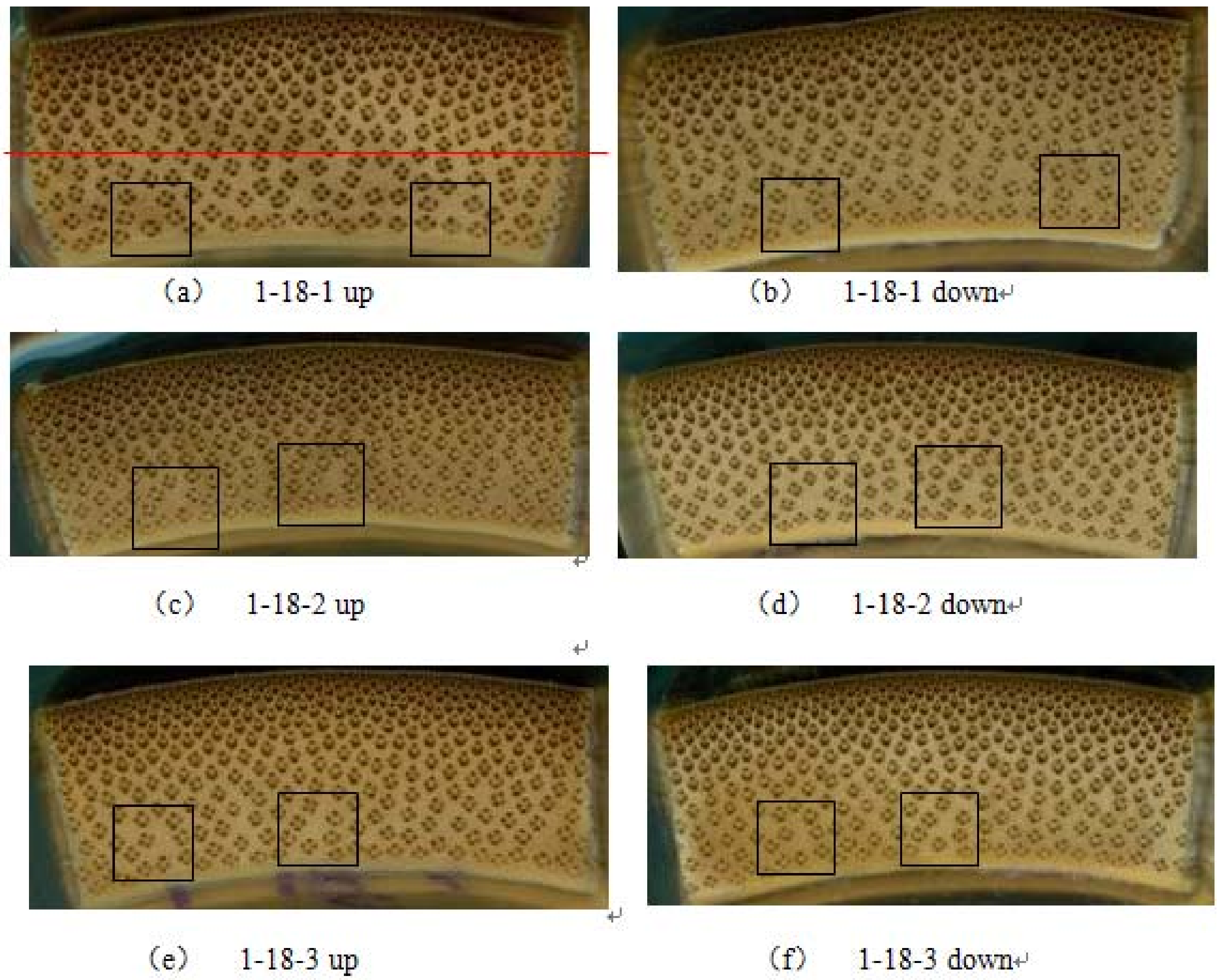

Fig. 7: Cross–sections of bamboo blocks from bamboo tube 1-18

Fig. 5 shown that tubes 1 to 12 (in the lower half of the bamboo culms, i.e., heights lower than 2m) were greater circumference variability than tubes 12 to 24/25 (range 2-5 m). As seen from fig. 5, all $b_{i,j}$ values, which followed a quadratic function, were negative. The coefficient meant the tangent point of the curve intersects with the y-axis. It proved that the circumferences of lower tubes were larger than upper tubes. The closer $b_{i,j}$ values were to 0, and the tapering was in bamboo culm. The tapering in bamboo culms stabilized to a near constant value in tubes 12 to 24/25.

In fig. 6. There was a linear relationship between the middle circumference and the tube ID number. The circumference in the culm decreased linearly with height. Amada *et al* (1997) also reported that bamboo tube circumferences and wall thick nesses decreased linearly with bamboo height. The outside diameter of the bamboo culm was inversely proportional to the height.

Fig. 7 shows the cross-section images of the bamboo blocks from tube 18 from No.1 culm. The upper cross sections are labeled “up” and the lower cross sections are labeled "down". The vascular bundles in the upper cross sections were also presented in the lower cross sections (fig. 7). In a bamboo tube, the circumferences varied slightly from top to bottom (fig. 3), but the number of vascular bundles didn't vary, indicating that the bamboo slope was parallel to grain changes (Cramer *et al*, 1989).

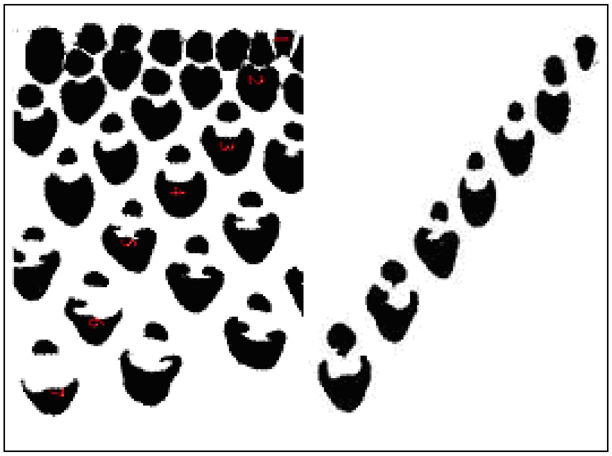

Fig. 8: Vascular bundles in outer layer of tube 1-18

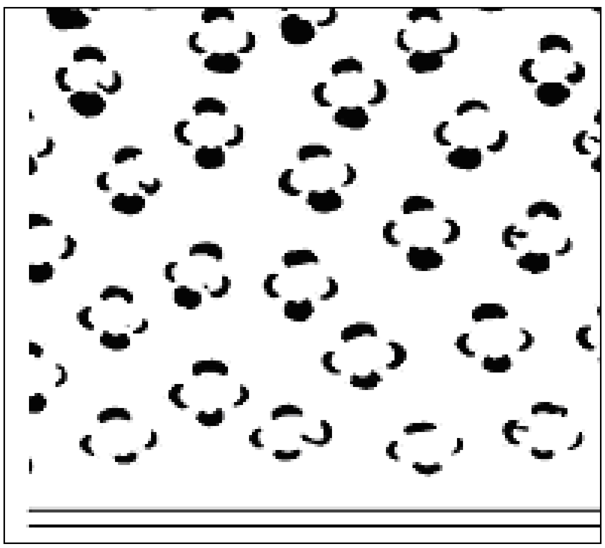

Fig. 9: Vascular bundles in inner layer of tube 1-18

The vascular bundles numbered 1-7 in fig. 8 (right image) illustrated the parallel alignment (left image). Vascular bundle 1 was smaller and more spherical than vascular bundle 7 which had an elongated shape. And the shape of the vascular bundles varied when they were aligned in parallel (Wenji *et al*, 2002). The part under the red line in fig. 7 (a) was the inner layer. The arrangement of vascular bundles in inner layer (fig. 9) were different to that in the outer layer. In the layer, the vascular bundles weren't aligned and were disordered, but were uniform in shape. The different arrangements of vascular bundles in the outer and inner layers resulted the different mechanical properties (Amada *et al*, 1996).

It was concluded that there is a good linear relationship between the height of bamboo culm and tube circumference. The tube circumference was low in tubes at the top of bamboo culm compared with the tubes at the bottom of culm. Although there were large differences in the macroscopic geometry of a whole bamboo culm. Each bamboo tube showed only slight variations in circumference. In each bamboo tube, the vascular bundles were succeeded in dividing into two parts: the inner layer in which vascular bundle distribution was disordered but the vascular bundle shape was uniform, and the outer layer in which vascular bundle distribution was ordered and the shape was non-uniform. Vascular bundles were aligned parallel to each other in bamboo tubes, and each vascular bundle run throughout the length of the bamboo tube.

CONCLUSION

The vascular bundles were uniformly distributed. Bamboo could be considered as a composite material composed of parenchyma cells as a matrix and reinforced by vascular bundles. The above results concluded that there was a good linear relationship between the height of bamboo culm and tube circumference. The tube circumference was in tubes at the top of culm lower than at the bottom. In each bamboo tube, the vascular bundles could be succeeded and divided into two parts: the inner layer where vascular bundle distribution was disordered and its shape was uniform, and the outer layer where vascular bundle distribution was ordered and its shape was non-uniform. Vascular bundles were aligned parallel to each other in bamboo tubes, and each vascular bundle run throughout the length of bamboo tube. In the future research, the effect vascular bundles on macro-mechanical properties of bamboo tubes should be deeply investigated.

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