INDENTATION COEFFICIENT AND INDENTATION BEHAVIOR OF BAMBOO[1]

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Abstract. Bamboo hardness test standards are not available. The study aimed to develop a new method of testing bamboo indentation hardness. With the V-shaped prismatic head, bamboo rings with different lengths were tested. The V-shaped indentation coefficient (IC) was defined. The results showed that the IC had a good correlation with compression strength. The V-shaped IC increased with the increase in the longitudinal height of the bamboo pole, and the variance analysis showed significant differences in different axial directions of the same bamboo ring. In addition, the correlation between density and IC is good. The V-shaped IC can be applied in bamboo grading.

Keywords: Moso bamboo, indentation behavior, indentation coefficient, grading.

INTRODUCTION

Bamboo is a common material in China and has many advantages, such as abundant resources, low energy consumption, and fast growth rate.

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Round bamboo is the basic form of bamboo material and has the good compression, tensile and flexural properties, and toughness. However, round bamboo is a heterogeneous material with an elliptic, thin-walled, hollow, vascular island-type gradient distribution. First, it has the irregular geometric dimensions, including the difference in the cross section and vertical dimensions. Second, circular bamboo showed the nonuniformity in the radial dimension (Janssen et al 2002; Chung and Yu 2002; Yu et al 2003). Therefore, the application of round bamboo as structural material is limited. In recent years, the mechanical properties of round bamboo have been extensively explored for the nondestructive testing of round bamboo.

In 2004, the international standard for evaluating the physical and mechanical properties of round bamboo was issued. This standard stipulates the testing methods of longitudinal compressive, longitudinal shear, transverse tensile, and tensile properties of round bamboo and provides a more reliable basis for the utilization of round bamboo (ISO/TR 22157-2 2004). According to the ISO standard, the variations of bending, shearing, and compressive properties of *Phyllostachys pubescens* were studied and the radial mechanical properties of *Phyllostachys pubescens* under different conditions were explored with the biaxial compression, uniaxial compression, and ring stiffness methods (Wang et al 2010; Zhang 2012; Zhang et al 2013).

Longitudinal grain compression is important in the application of round bamboo as structural materials. In the study on the parallel compression of bamboo (Shao 2004), the yield limit of bamboo is three times the transverse limit because vascular bundles provide high strength as the main body of axial compression load. However, the dynamic failure process or mechanical behavior of parallel compression of the circular bamboo tube, or the reverse axial local compression of circular bamboo, was seldom explored. The material characteristics are not well explored.

In the study, we explored the V-shaped indentation at a longitudinal end of round bamboo and found the indentation load had a good linear relationship with the area. Therefore, the indentation coefficient (IC) was defined as the linear elastic constant of the indentation at the longitudinal end surface of round bamboo. The IC is related to mechanical properties, so it achieved the rapid classification of mechanical properties of round bamboo by establishing a rapid detection method of IC.

MATERIALS AND METHODS

Materials

From Xinchang town, Zhejiang Province, China, 200 4-yr-old moso bamboo (*Phyllostachys pubescens*) culms with a total height of ~13 m and a diameter at the breast height of 9-15 cm were harvested, and 20-mm-long bamboo rings were obtained at the breast height for the indentation test. The upper and lower circles of the rings were absolutely parallel to each other and perpendicular to the axial direction of bamboo. The heights at four points of each bamboo ring were measured, and the measurement error was controlled within 5%.

The specimens of bamboo rings at different heights of the same plant were obtained according to the following procedure. After removing the root from a fresh bamboo, 20-mm-long bamboo rings were collected in the middle of each internode. A total of 29 bamboo rings from bottom to top were collected, and the average MC in the specimens was about 69%.

Test Instrument

Indention hardness tests were performed on an universal mechanical testing machine equipped with a load cell with a capacity of 10 KN (Fig 1). The V-shaped pressure head used in the indentation test is a straight line–shaped compression head. A three-dimensional schematic diagram and the section size are shown in Fig 1. The V-shaped compressing head was fixed on a compress platen. The height of the head was 3 mm.

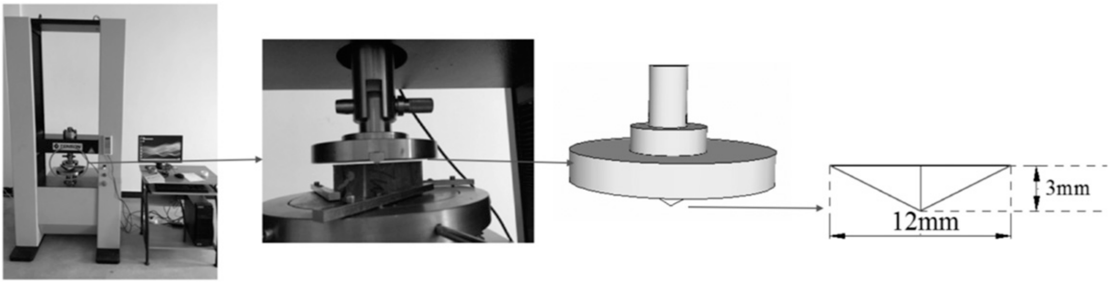


Figure 1. Schematic diagram of round bamboo indentation test equipment.

Test Methods

Two performance indices of bamboo were tested: V-shaped IC and compression strength in the longitudinal direction at E and F positions (Fig 2). First, the AB axis and the CD axis were used in the indentation test with the V-shaped compression head. The dimensions of the specimens used in the compression strength test was 20 mm (longitudinal) × 20 mm (tangential) × t mm (radial), and the specimens were obtained at E and F positions after indentation hardness tests. Compression strength was tested according to GB/T 15780-1995.

Before the tests, the height and thickness of bamboo rings at the points (A, B, C, and D) were measured. The longitudinal, tangential, and radial dimensions of compression strength specimens were measured.

In IC tests, specimens were put on the bottom platen and fixed by the centering device. The specimens were loaded at a displacement rate of 3 mm/min until the head was completely embedded into the culm wall. The corresponding load and displacement in the process were recorded.

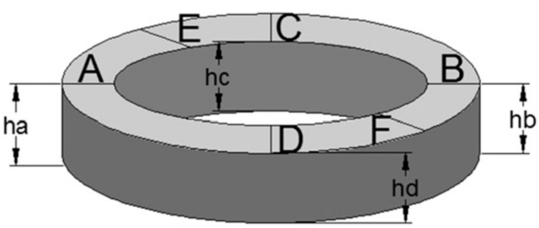


Figure 2. Height measurement of a bamboo ring.

In compression strength tests, small specimens were set on the center of the bottom platen and compressed by the top smooth platen. The specimens were loaded at a displacement rate of 3 mm/min until failure. Compression strength was calculated according to GB/T 15780-1995.

RESULTS AND DISCUSSION

Definition of Indentation Coefficient

The IC was defined as a factor to indicate the hardness of the cross section of bamboo. It is similar to the elastic modulus indicating the stiffness of a material. It was tested by V-shaped head indentation on the cross section of a 20-mm-high bamboo culm. The compression load and V-shaped head displacement in the process were recorded. Figure 3 shows a typical compression

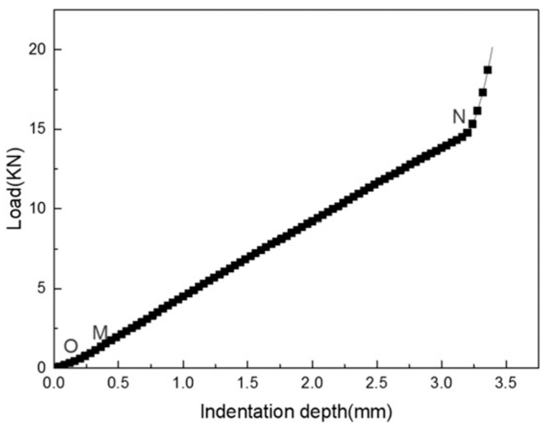


Figure 3. Load–displacement curve of the specimen under V-shaped compression head. Notes: $h = 3$ mm, $W = 12$ mm, $\alpha = 60°$.

load–displacement curve. The curve is divided into three stages. First, the OM section presents the initial touching stage. Second, the MN section presents the indentation stage. The curve is linear until the compression depth reaches 2.8 mm. When the compression depth at the point N nearly came to 3 mm, the V-shaped head was compressed into a bamboo culm totally and the platform was compressed into the whole cross section of the bamboo culm. Therefore, the load increased suddenly until the tests were completed. It is the third stage. There is an inflection point on the curve.

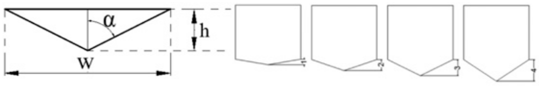
The compression load significantly affected the IC in the indentation test. According to the three segments of the load–displacement curve, a better regression line was obtained to fit the linear segment of load–displacement curve. The crossing point of two lines was defined as the compression load corresponding to the IC. A good linear correlation ($Y = 4.7161X + 0.2112$; $R^2 = 0.9997$) was obtained when fitting the MN section. Moreover, the slope of the regression line was defined as the IC of the bamboo culm under the V-shaped compression head.

According to the definition of indentation hardness, the hardness value of the test material can be expressed as the compression load on the unit indentation area (Liu et al 2005). Therefore, indentation hardness can be calculated as follows:

$$\sigma = \frac{P}{S}, \tag{1}$$

where σ is indentation hardness when it is pressed into a 3-mm depth, MPa (precision, 0.1 MPa); P is the compression load at the crossing point N; S is the indentation area at the depth of 3 mm displacement, mm^2.

The load increases after the indentation depth is greater than 3 mm (Fig 3). However, when the specimen contacts the pressure head plane (the indentation depth is 3 mm), the load is the maximum load. According to the geometric dimension of the customized pressure head (Fig 4), the maximum indentation width W is 12 mm



Notes: h=3 mm, W =12 mm, α = 60°

Figure 4. Dimensions of the U-shaped indentation head and V-shaped indentation head.

when the indentation depth h is 3 mm. The projected area S for the IC increases with h and can be calculated as follows:

$$s_v = W \times T = 4h \times T, \tag{2}$$

where T is bamboo wall thickness at indentation, mm; W is the length of indentation in the tangential direction of the bamboo culm, width of indentation, mm; H is indentation depth, mm.

Then, Eq 1 can be rewritten as follows:

$$\sigma_V = \frac{P}{H} \frac{1}{4(T_C + T_D)}, \tag{3}$$

where σ_V is the indentation hardness under the V-shaped indenter, MPa (precision: 0.1 MPa); P is the load at different indentation depths, N; H is the indentation depth of the bamboo ring, mm; TA, TB, TC, and TD are the wall thicknesses at the points A, B, C, and D, respectively, mm.

Eq 3) indicates that the wall thickness of bamboo is determined by the specimen itself. According to Eqs 1-3, the IC K_v is deduced as follows:

$$K_v = \sigma_v = \frac{P}{S} = \frac{P}{W \times T} = \frac{P}{4H \times T} = \frac{P}{4H \times (T_1 + T_2)}, \tag{4}$$

where K_v is the IC, Mpa; σ_v is the indentation hardness at the displacement of 3 mm, Mpa; P is the compression load, N; S is the projected area of indentation, mm^2; H is the indentation depth of the bamboo ring, mm; T is the sum of the specimen thickness at the two indentation points, mm; W is the indentation length in the tangential direction of the specimen, mm; T_1 and T_2 are the specimen thickness at the two indentation points, mm.

The bamboo culm has a thin culm wall and a hollow structure, and the fiber content in the bamboo culm gradually increases from the inner part to the outer part. Therefore, the IC can better reflect the compression properties of the whole cross section of the bamboo culm than the index proposed by D. Trujjio (Trujillo and Jangra 2016). Moreover, the V-shaped compression head was compressed into the axial direction of the bamboo rings to ensure the stability of the specimen during the loading process. In this way, the problem that Kim's wood hardness determination method is not applicable to bamboo will be solved. The IC was defined as the slope of the regression line and the correlation coefficient $R^2 > 0.9$. Therefore, the IC can reflect the compression properties. This method may be used to develop a rapid grading method for the bamboo culm.

Relationship between IC and Compression Strength

The IC presents a good correlation with compression strength. Figure 5 shows the positive correlation between the two factors. In a bamboo culm, the IC increases with the compression strength. A regression line is modeled as follows:

$$y = 1.1944x - 5.8797, \quad R^2 = 0.7948. \qquad (5)$$

Both factors reflect the compression property of the cross section of the bamboo culm. However, the IC reflects the local compression property, whereas compression strength reflects the longitudinal compression strength of the whole bamboo culm. Therefore, the IC is positively correlated with compression strength.

By analyzing the correlation between the compression strength of each specimen and V-shaped IC, the diagram was obtained (Fig 5). The correlation between the V-shaped IC and compression strength is relatively good ($R^2 = 0.7948$). The compression strength value is variable, and the V-shaped indentation test is convenient for rapid detection. Therefore, the V-shaped IC was used as the final evaluation index in this experiment.

Variations of IC with Bamboo Height

Bamboo IC increased from the bottom to top of the bamboo culm (Fig 6). The variation was consistent with the variation of mechanical properties and density of bamboo from the bottom to top with the increase in the fiber content (Li 2009).

As shown in Fig 6, the x-axis coordinate indicates the number of bamboo internodes, which is recoded from the bottom to top of the bamboo

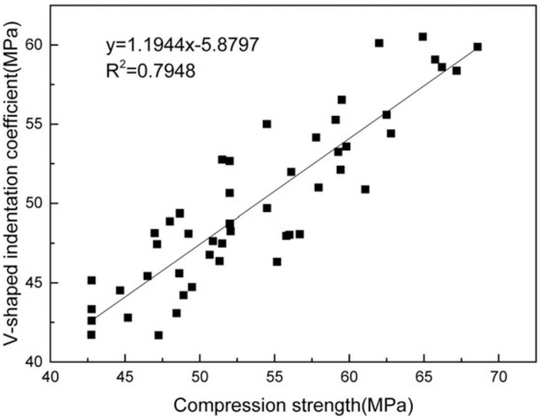


Figure 5. Diagram of the relationship between the compressive strength and indentation coefficient.

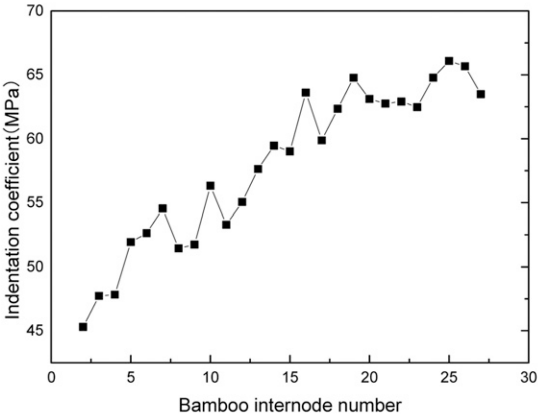


Figure 6. Variation of the indentation coefficient with bamboo height.

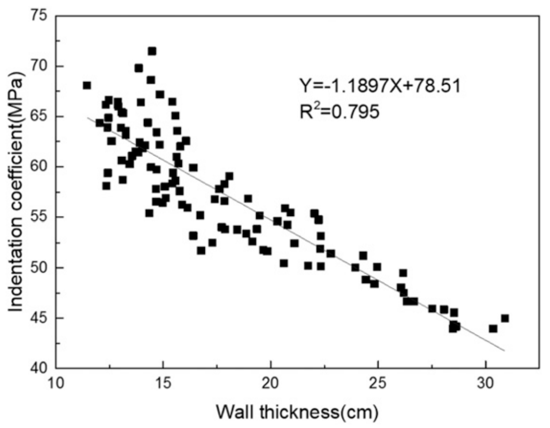


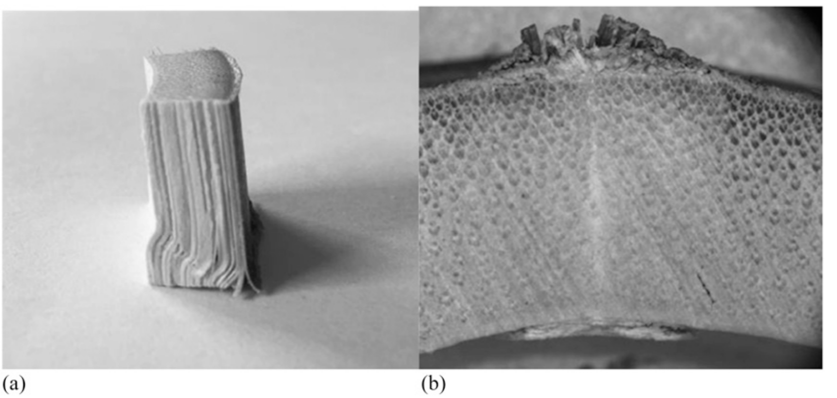
Figure 7. Relationship between the indentation coefficient and wall thickness.

culm. For example, the first internode above ground was marked as "No. 1," followed by No. 2, No. 3, etc.

First, the IC increased gradually in the bamboo culm until the No. 7 internode at the height of 1 m. Then, the curve increased wavily from No. 7 to No. 18 internode. At last, the curve became flat and then fluctuated. One bamboo culm has about 40 internodes (Liese and Tang 2015). The length of the internode increased rapidly from about 50 mm at the first internode to 280 mm at the No. 10 internode. Then, the length of the internode increased slowly or changed little until the first branch height. The internode above the first branch was short and shows a groove and the thinner culm wall. Therefore, the fluctuation and instability in the curve might be influenced by the dimensions of the specimen or the measurement error. By contrast, the thickness of the culm wall decreased gradually from bottom to top, so there was a negative correlation between the IC and thickness (Fig 7), as expressed in Eq 4. In addition, the variation of bamboo density directly affected its mechanical properties (Mohmod A 2011; Yu 2017). As is shown in Fig 8, with the increase in bamboo density, the IC also increased. This trend was consistent with the previous study (Li 2009).

Compression and Indentation Behaviors of Bamboo

The macroscopic morphology of compressed bamboo specimens is shown in Fig 8(a). The failure mode of bamboo under longitudinal compression is complex. The transverse tension is caused by the buckling and transverse shear of the vascular bundle, which leads to the interface separation and destruction between the thin-walled structure of the matrix material and the vascular bundle of the reinforcement material. The parenchyma as the matrix material and the vascular bundle as the reinforcing material work simultaneously. In Fig 8(b), the stiff fiber bundles bear the longitudinal compression load. The inner



(a) (b)

Figure 8. Damaged face of bamboo: (a) longitudinal compression of bamboo; (b) V-shaped indentation compression of bamboo.

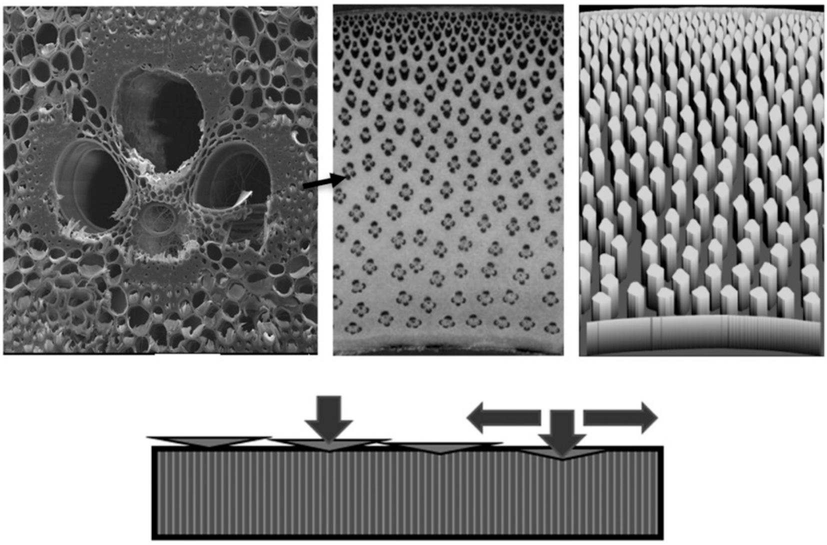


Figure 9. Diagram of indentation of bamboo vascular bundle.

part of the bamboo culm with the lower fiber volume fraction and the higher volume fraction of parenchyma tissues presented the weak structure. However, the inner layer with silicon also mainly bear the compression load, and the inner layer was slightly weaker than the outer layer. The lowest middle line of V indentation was deep. The outer layer was ruptured, and the inner layer was crushed (Ren et al 2007).

The indentation test solved the grading problem of round bamboo. The thickness of the two sides of round bamboo was measured, and the measured data were few and could be measured

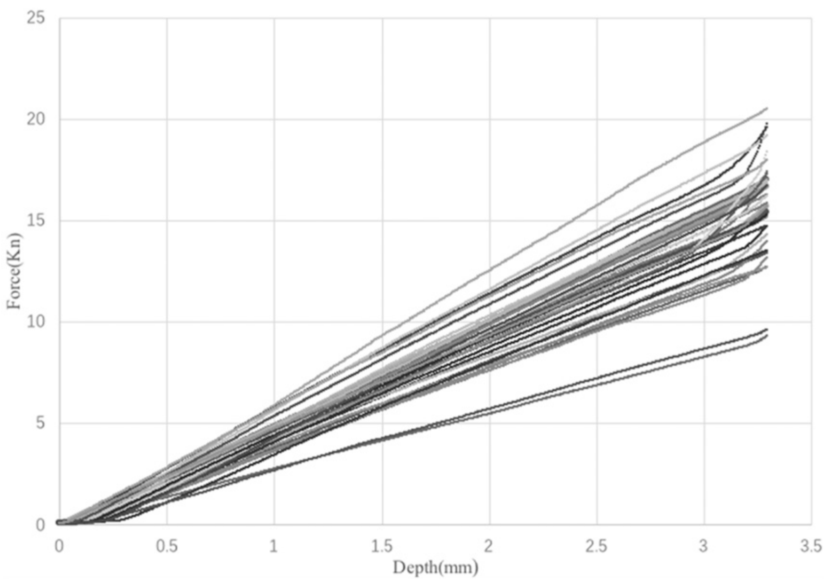


Figure 10. Repeatability of indentation coefficients of 200 specimens.

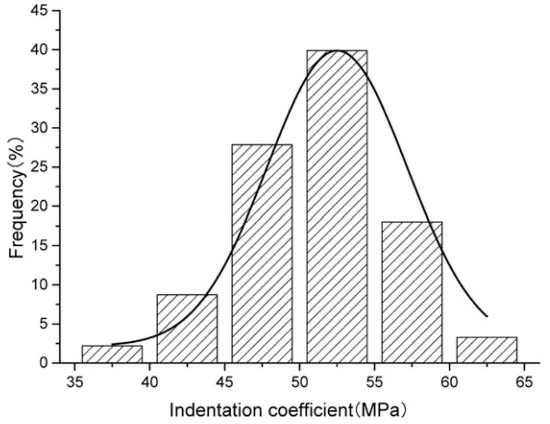


Figure 11. Distribution frequency of indentation coefficients of 200 specimens.

automatically. Moreover, the indentation test considered the average gradient variation at the end face of round bamboo. The measured area includes both sides of the bamboo end face and has a certain width, meanwhile, t he measured area shows the radial gradient variability and has a number of vascular bundles. The longitudinal end of the round bamboo has thin-walled cells and vascular bundles with the gradient variability. The vascular bundles are the dispersed phase of the island-type independent structure, but the thin-walled cells are the continuous phase (Fig 9).

The V-shaped compression head was compressed into the end face of round bamboo, and the vascular bundles bore the vertical load, thus resulting in the linear elastic displacement (Fig 9). The V-shaped head also generated a horizontal load, which was mainly caused by the horizontal displacement at the end of the vascular bundles, squeezing surrounding thin-walled cells. The linear elastic response was also observed in the early stage of the test, and there has the good linear relationship between the load and indentation area. The IC of linear slope showed the linear elastic response of thin wall cells of vascular bundles under vertical and horizontal loads.

IC Distribution of Moso Bamboo

The physical and mechanical properties of bamboo show significant variations (Qi et al 2014; Nath A et al 2007; Kaminski S et al 2016). In the test, 200 fresh bamboo specimens were loaded. The indentation load–displacement relationship curves of 200 specimens showed the same trend, except the different slopes (Fig 10). It was found that there is a good linear relationship between the load of each bamboo ring and the indentation depth (indentation area) In addition, the IC which reflecting the linear elastic behavior of bamboo can be obtained. The mechanical properties changes of bamboo can be characterized by the IC, thus, the classification method of the V-type IC can be used as the criterion and reference for the grading of round bamboo.

Using the grading method of the V-type IC of bamboo end face, the IC of 200 bamboo in Xinchang, Zhejiang Province, were obtained. Figure 11 showed the frequency distribution of the IC, which shows normal distribution trend. The range of the IC is 35.8-64.5 MPa. With 5 MPa as the grading interval, the properties of the bamboo could be roughly divided into 6 grades. The test and grades results were shown in Table 1. According to the results, IC45 and IC50 accounted for more than IC35, IC40, and IC60.

Table 1. Grading table of longitudinal face IC of round bamboo.

IC grades	IC level/MPa	Number of bamboo	Frequency, %	Average/MPa	Minimum/MPa
IC35	$35 \leq HM < 40$	4	2.19	38.06	37.71
IC40	$40 \leq HM < 45$	16	8.74	43.44	40.92
IC45	$45 \leq HM < 50$	51	27.87	47.86	45.05
IC50	$50 \leq HM < 55$	73	39.89	52.36	50.06
IC55	$55 \leq HM < 60$	33	18.03	57.11	55.02
IC60	$60 \leq HM < 65$	6	3.28	62.8	60.68

IC, indentation coefficient.

Table 2. Result statistics of the density of the bamboo based on IC grades.

IC grades	Average (g/cm^3)	Standard deviation	Coefficient of variation (%).	Minimum (g/cm^3)	Maximum (g/cm^3)
IC35	0.51	0.02	4.47	0.49	0.54
IC40	0.55	0.03	5.22	0.49	0.6
IC45	0.60	0.02	3.37	0.56	0.63
IC50	0.64	0.03	4.97	0.59	0.74
IC55	0.66	0.03	4.45	0.59	0.74
IC60	0.71	0.02	2.50	0.68	0.73

IC, indentation coefficient.

This classification method can eliminate the bamboo with small quantity but big performance difference. Also, it can divide the large quantity of moso bamboo into different grades to distinguish the difference between them. Because density is the main factor determining the mechanical strength and shrinkage of bamboo, the change of bamboo density directly affects the mechanical properties (Nordahlia et al 2011; Yu et al 2017). Therefore, the density of bamboo was tested, and test results with different IC grades can be seen in Table 2.

The basic density of this batch of bamboo ranged from 0.49 to 0.74 g/cm^3. As shown in Table 2 and Fig 12, as the increase of IC grade, the density increases gradually, and the density of IC60 grade is 0.71 g/cm^3. Through the comparison between different grades, it can be found that the variation of density within the same grade is kept within 6%,. The above result indicates that the density of bamboo can be controlled in a relatively small range by the grading method of the IC, and then the wood properties of round bamboo can be graded.

The correlation between the IC and density of bamboo was shown in Fig 13. It can be seen that the linear correlation between density and the IC is high ($R^2 = 0.7075$), indicating that both the IC and density represent the distribution law of bamboo vascular bundles.

Therefore, to ensure the stability of the subsequent products, the density and modulus range of bamboo can be obtained by the IC of bamboo, which is of great significance for bamboo rapid grading.

CONCLUSIONS

The indentation test of bamboo rings was carried out with the V-shaped prismatic head in the study. With the increase in the bamboo pole height, the V-shaped IC showed a good correlation with the

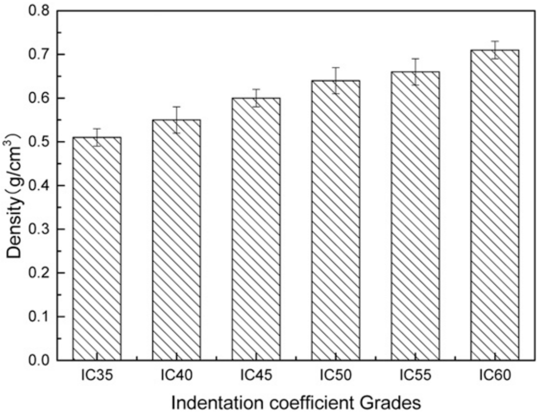


Figure 12. Distribution frequency of indentation coefficients of 200 specimens.

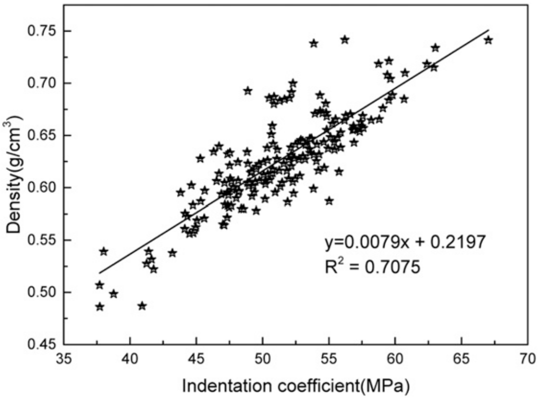


Figure 13. Correlation between density and indentation coefficient of 200 specimens.

wall thickness and density. The IC at the short axis is greater than that at the long axis for the same bamboo ring. Therefore, in the selection of the IC, the difference between different axial directions should be considered.

According to the statistics of the ICs of 200 bamboo, the ICs of bamboo ranged from 35.8 to 64.5 MPa. The ICs of bamboo specimens could be divided into 6 grades with a grading interval of 5 MPa. The V-shaped indentation testing method and the definition of the IC will be used in the classification of round bamboo for the design and comprehensive utilization of round bamboo. The mechanical strength of bamboo is closely related to density, bamboo age, and MC. The IC of bamboo under different conditions will be considered in the next work.

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