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Variation in tensile properties and relationship between tensile properties and air-dried density for moso bamboo

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Abstract This research investigated the variation in tensile properties and the relationship between the tensile properties and the air-dried density for the moso bamboo (*Phyllostachys pubescens*) by sampling at different heights and radial positions. Results showed that the variation of the longitudinal tensile properties in the radial direction was greater than that in the longitudinal direction. The longitudinal tensile modulus of elasticity (MOE) ranged from 8.49 to 32.49 GPa. MOE for the outermost layer was 3–4 times as high as that for the innermost layer. The longitudinal tensile strength (MOR) ranged from 115.94 to 328.15 MPa. MOR for the outermost layer is 2–3 times as high as that for the innermost layer. Linear and curvilinear regressions were done from tested data of MOE, MOR and air-dried density in this paper. The linear equation worked a little better than the curvilinear one to predict the longitudinal MOR and MOE from air-dried density.

Keywords moso bamboo (*Phyllostachys pubescens*), air-dried density, longitudinal tensile modulus of elasticity, longitudinal tensile strength

1 Introduction

Many researchers have investigated longitudinal tensile modulus of elasticity (MOE) and variation in longitudinal tensile strength (MOR) for *Phyllostachys pubescens*. Xi et al. (1995) have studied MOE and MOR for the inner, middle and outer wall, respectively, and

obtained the experience equation between material position and MOE. Ye (1995) has divided the wall of *P. pubescens* into three layers (inner, middle and outer), and tested MOR and vascular bundles in these three parts, the amount and area percentage of vascular bundles. According to these results, he deduced the experience equations between MOR and the area percentage of vascular bundles for these three parts, respectively. Yang et al. (1996) regarded *P. pubescens* as oriented composite material whose strength was enhanced by vascular bundles, and investigated the variation of vascular bundles and parenchyma cells in radial and longitudinal directions. Based on these, they predicted MOE and MOR of the vascular bundles and parenchyma cells in theory. Wang (2001) studied the variation of MOR for bamboo strips with cutin and pith, and analyzed the relationship between density and MOR. Most of these researches have a disadvantage, i. e., they regarded bamboo wall as one layer, or divided it into three layers. However, the anatomy and properties of the bamboo are variable in the radial direction of bamboo wall. So the law of variation of tensile properties in radial direction cannot be reflected fully by these researches.

The relationship between density and mechanical properties of wood is of importance to the study of wood science. Some previous researches have proven that there is a close relationship between density and mechanical properties of wood. Newlin et al. (1919) described this relationship with the equation: $S = \alpha \cdot G^\beta$, where S is some mechanical property, G density of wood, α and β constants. Armstrong et al. (1984) and Walton et al. (1986) verified this equation using a great deal of wood species. Researchers have always thought that the relation between mechanical characteristics and density of the wood species (Hska, 1965; Forest Products Laboratory, 1987; Zhang, 1996) is linear. And this linear equation has been applied widely over the years. Chinese research studied in system the relation between MOR and density of wood (Cheng, 1985). Few researches were carried out on the relation between mechanical properties

Translated from *Scientia Silvae Sinicae*, 2006, 42(3): 72–76 [译自: 林业科学]

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and density of bamboo. Moreover, there was few report on the relation for layered bamboo material.

Each Bamboo was divided into four segments in longitudinal direction, and divided into six layers in radial direction, then MOE, MOR and air-dried density were tested. The variation in tensile properties and the relationship between tensile properties and air-dried density for moso bamboo were studied in this paper. So the goal of this research was to discuss variation in tensile properties further and the relationship of MOE, MOR and air-dried density for different layers of moso bamboo.

2 Materials and methods

2.1 Materials

Moso bamboo was from shade slope of upland in Xiaojiang town, Xingchang county, Zhejiang Province in east of China (altitude of 750 m). Moso bamboo that are 4–6 years-old were selected. The diameter at breast height was 7–9 cm, and the culm height was 5–6.5 m. Every culm was cut into four 1.33 m-long segments (A, B, C, D) in longitudinal direction (Fig. 1). Two 15 mm-long bamboo strips from northern and southern directions were taken. The cutin and pith were scraped off and then split into six layers (1–6) in radial direction (Fig. 2). After air-drying, we measured thickness of segments A–D (middle position) by vernier caliper and calculated average values (Table 1). Sanding these layers to get 0.8 ± 0.1 mm-thick slices of bamboo. Samples for MOR were made and then the air-dried density from the middle (internode) of every bamboo layers were derived. Because the node in layer 1 is not sturdy, it is very easy to break when sanding. So the samples made from layer 1 were not enough. We cannot get MOE and MOR in different heights of layer 1.

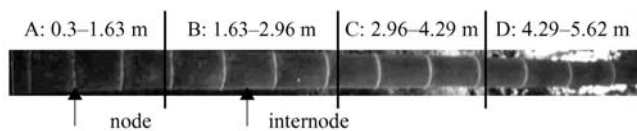


Fig. 1 Sampling from moso bamboo in longitudinal direction

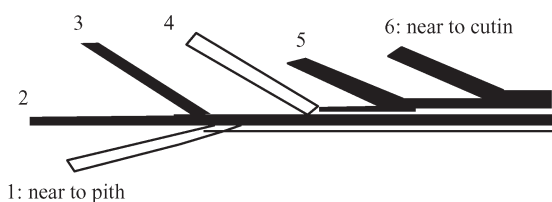


Fig. 2 Sampling from moso bamboo in radial direction

Table 1 Mean thickness of moso bamboo strips for samples at different positions (unit: mm)

segment	layer					
	1	2	3	4	5	6
A	2.34	2.3	1.78	1.55	1.73	0.94
B	1.90	2.00	1.49	1.34	1.33	0.95
C	1.77	1.74	1.40	1.32	1.22	0.94
D	1.53	1.48	1.30	1.31	1.22	0.95

2.2 Measurement for density, MOE and MOR

Rectangle samples were selected for MOE test (Fig. 3). Samples for MOR test were remade from the samples after MOE test. The shape of the samples are similar to a dumbbell (Fig. 4). After the samples stabilized under the condition of 20°C and 65% of relative humidity, we tested MOE of samples. We then scraped the strain gauges on these samples carefully, weighed their air-dried mass at once and measured the volume by water immersion method. According to the data, the air-dried density can be calculated. After these, we remade rectangle samples into dumbbell samples for MOR test and conditioned them under the environment of 20°C and 65% of relative humidity.

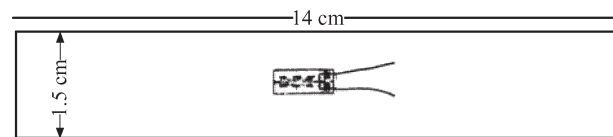


Fig. 3 Specimen from moso bamboo for TMOE

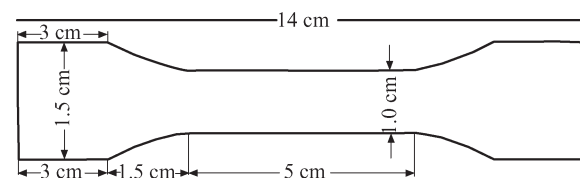


Fig. 4 Specimen from moso bamboo for TS

We tested the width, thickness and length of the middle part of the samples (precision: 0.02 mm). MOE was measured by mechanical tester and strain by resistance strain gauge. The loading velocity for MOE measurement was 0.5 mm/min. The formula for calculating MOE:

$$E = \frac{\Delta P \cdot \Delta \epsilon}{bt}$$

where E is MOE (GPa), ΔP loading increment in proportional limit (kN), $\Delta \epsilon$ strain increment corresponding with ΔP , t thickness (mm) and b width of samples (mm).

The loading velocity for MOR measurement was 3 mm/min. The samples were destroyed during the period

of 1 ± 0.5 min. We recorded the ultimate load and deleted invalid data. The formula for calculating MOR:

$$\sigma_t = \frac{P_{\max}}{t \cdot b}$$

where σ_t is MOR (MPa), P_{\max} maximal load (N), t thickness (mm) and b width of samples (mm).

2.3 Regression analysis

The regression analysis was completed by the curve fitting function of SPSS statistics software. Linear function $S = a + bG$ (where G is density, a and b are constants) was applied as well as curvilinear function $S = \alpha \cdot G^\beta$. The bamboo density was taken as an independent variable. The regression analysis of MOE and MOR were also performed. According to the regression coefficients R , we can determine the regression effect.

3 Results and discussion

3.1 Variation in tensile properties

3.1.1 MOE

The average moisture content of the samples was 10.2% when we tested for MOR at 20°C. The mean of MOE for the internode of the moso bamboo is shown in Fig. 5. MOE decreased gradually both in longitudinal direction and in radial direction. And variation in radial direction was far bigger than that in longitudinal direction. The values of MOE for the different positions ranged from 8.49 to 32.49 GPa. The value of MOE for the outermost layer was 3–4 times as much as that for the innermost layer. In segment B, the average value of MOE for the innermost layer was 8.49 GPa while the average value for the outermost layer was 31.28 GPa, it is 3.7 times the value for the innermost layer.

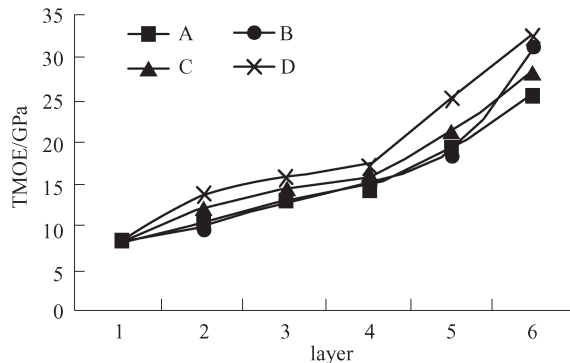


Fig. 5 Mean of the longitudinal tensile modulus of elasticity (TMOE) at different positions of moso bamboo culms

Xian et al. (1995) divided the radial plane of moso bamboo into 3–7 layers and measured MOE for these

layers. MOE for the outermost layer and the innermost layer were 18.1 and 4.6 GPa, respectively. However, both values of MOE measured by Xian et al. are lower than those obtained in our research. Several reasons can account for this difference. The area for sampling and the age of bamboo can affect material properties. However, these two points were not mentioned in the paper of Xian et al. (1995). Otherwise, different sampling methods can bring different results for MOE test due to anisotropic property of bamboo.

3.1.2 MOR

The average values of MOR for the internode of the moso bamboo are shown in Fig. 6. The values of MOR range from 115.94 to 328.15 MPa in different positions. MOR decreases from outer to inner positions, while increases from top to bottom positions. At the same height, MOR for the outmost layer is 2.3 times as much as that for the innermost layer. Variation in radial direction is far bigger than that in longitudinal direction.

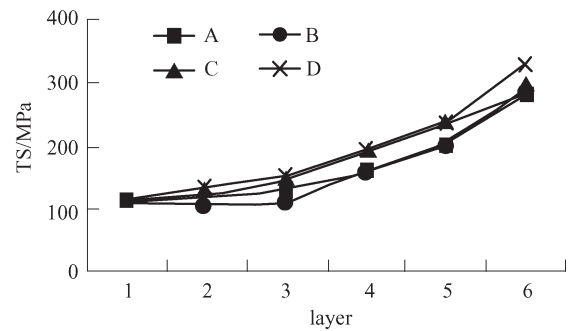


Fig. 6 Mean of the longitudinal tensile strength (TS) at different positions of moso bamboo culms

As for the variation of MOR in the moso bamboo, our research results are consistent with those of Xian et al. (1995), i.e., the radial direction MOR for the outmost layer is highest while for the innermost layer it is the lowest. However, our results for the values and amplitudes of the variation of MOE and MOR for the different positions of bamboo are different from those of Xian et al. (1995). According to the result of Xian et al., MOR for the outmost layer is 339 MPa, five times of that for the innermost layer (70.4 MPa). In our research, MOR for the outmost layer is 2.3 times as much as that for the innermost layer. In the same way, the differences can be attributed to the sampling area, the age of the bamboo and the sampling methods.

3.2 Relationship between tensile properties and air-dried density

By regression analysis, we obtained the regression equations between MOE/MOR and air-dried density

(Table 2). By analysis of variance and the regression coefficient test, all of the four regression equations have significant relativity. It is meaningful to express the relationships between MOE/MOR and air-dried density by a linear or curvilinear equation.

Table 2 Regression equation for the relationship between tensile properties and air-dried density and determination coefficient

dependent variables	equation type	determination coefficient $R^2/\%$	regression equation
MOE /GPa	Linear	79.8	$y = 41.956x - 18.431$
	Curvilinear	77.7	$y = 23.4309x^{2.1211}$
MOR /MPa	Linear	64.3	$y = 334.941x - 93.847$
	Curvilinear	60.5	$y = 233.929x^{1.5052}$

Moreover, determining the coefficient (R^2) can indicate the percentage of variation in the dependent variable that the regression model can explain. We did regression fitting by the linear and curvilinear models, respectively. R^2 for the linear model is slightly higher than that for the curvilinear model (Table 2). So, it is more suitable to use the linear equation to predict MOE and MOR by air-dried density. This conclusion agrees with those of previous researches (Liska, 1965; Forest Products Laboratory, 1987; Zhang, 1996). Figures 7 and 8 are scatter plots expressing these relationships.

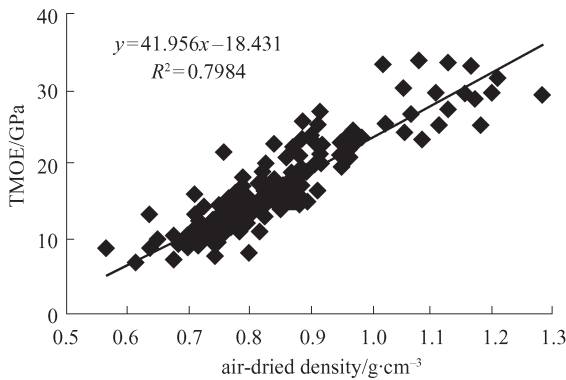


Fig. 7 The relationship of air-dried density with longitudinal tensile modulus of elasticity

4 Conclusions

1) Variations of MOE and MOR in radial direction are great. The values of MOE for different positions ranged from 8.49 to 32.49 GPa. The value of MOE for the outermost layer was 3–4 times as much as that for the innermost layer. Values of MOR range from 115.94 to

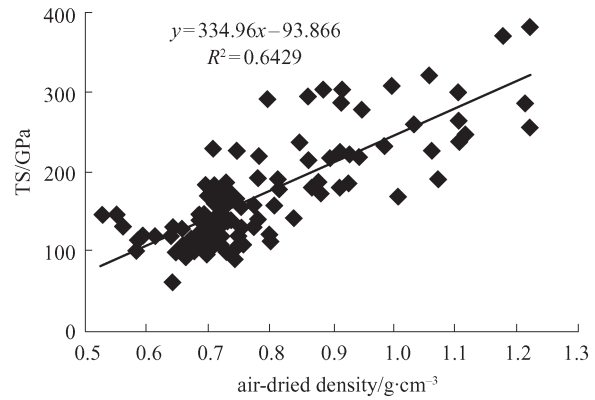


Fig. 8 The relationship of air-dried density with longitudinal tensile strength

328.15 MPa in different positions. MOR for the outermost layer is 2–3 times of that of the innermost layer.

2) To predict the effect of tensile properties for moso bamboo, the linear equation works a little better than the curvilinear equation. The two linear equations for MOE and MOR are $y = 41.956x - 18.431$ and $y = 334.941x - 93.847$.

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