Size effect on the compressive strength of laminated bamboo lumber

Han Zhang[1], Haitao Li[2], Chaokun Hong[3], Zhenhua Xiong[4], Rodolfo Lorenzo[5], Ileana Corbi[6], Ottavia Corbi[7]

[1]Graduate Student, College of Civil Engineering, Nanjing Forestry University, Nanjing 210037, China. Email: 962736499@qq.com

[2]Professor, College of Civil Engineering, Nanjing Forestry Univ., Nanjing 210037, China; Professor, Joint International Research Laboratory of Bio−composite Building Materials and Structures, Nanjing Forestry University, Nanjing 210037, China (corresponding author). Email: lhaitao1982@126.com

[3]Graduate Student, College of Civil Engineering, Nanjing Forestry University, Nanjing 210037, China. Email: hck@njfu.edu.cn

[4]Engineer, Ganzhou Sentai bamboo company LTD, Ganzhou 341001, China. 792232771@qq.com

[5]Lecturer, University College London, London WC1E 6BT, UK. r.lorenzo@ucl.ac.uk

[6]Professor, Dept. of Structures for Engineering and Architecture, Univ.of Naples Federico II, via Claudio 21, Napoli 80133, Italy. Email: Ileana.corbi@libero.it

[7]Professor, Dept. of Structures for Engineering and Architecture, Univ.of Naples Federico II, via Claudio 21, Napoli 80133, Italy. Email: ottavia.corbi@libero.it

*Corresponding author: Haitao Li, Professor, E-mail: lhaitao1982@126.com

ABSTRACT: The size effect on the axial compressive performance of laminated bamboo lumber is studied through compression tests on three groups of short columns with different heights and section sizes. The failure modes, bearing capacity, strain distribution, and deformation capacity were analyzed. Based on the test results, three groups of Ramberg-Osgood models of laminated bamboo lumber with different sizes are presented. The simulated results were in good agreement with the test results. The slope method and the parameter method were used to calculate the size effect coefficient and the results showed that the linear regression parameter analysis method is more efficient for analyzing the size effect. It is concluded that the size effect coefficients of compressive strength, ultimate load, elastic modulus, ductility, and compressibility are 0.043(1/23.26), 0.6676(1/1.52), 0.064(1/15.63), 0.0529(1/18.90), and 0.133(1/7.52) respectively.

Keywords: A. Laminated bamboo lumber; B: Compressive strength; C: Size effect; D: Stress-strain model

1 Introduction

Nowadays, because of the increasing carbon emissions in the construction industry, it is necessary to mobilise and develop new sustainable materials for construction use (Chen et al. 2020a, 2020b; Lv and Liu 2019; Sun et al. 2020; Yang et al. 2020). Bamboo, as a widely distributed natural resource especially in Asia and South America (Li et al. 2014) has the potential to fulfil this role (Sulaiman et al. 2006; Krzesinska et al. 2008; Chen et al. 2020; Wang et al. 2020). A relatively new engineered material — laminated bamboo lumber (LBL) (Li et al. 2016; Xu et al. 2019; Wu. 2014; Porras and Maranon 2012; Brito et al. 2018) has attracted increasing attention from researchers (Sharma et al. 2015; Mahdavi et al. 2011,2012). The mechanical properties of laminated bamboo lumber could be compared with that of wood, indicating this material has the potential to be an alternative and highly renewable building material (Verma and Chariar 2012, 2013; Lopez and Correal 2009; Flander and Rovers 2008; Nugroho and Ando 2001; Amada et al. 1997; Sharma 2017; Sinha et al. 2014; Correal et al. 2010,2014). As a new type of construction material, laminated bamboo lumber not only maintains the advantage of high strength, good stiffness, and low shrinkage, but can also be designed and manufactured into units of different shapes and sizes which are easy to standardize and modularize (Li et al. 2015).

A specific code is essential for the application of laminated bamboo, and the size effect is an important factor to determine design values. There has been multiple related researche studies on the compressive properties of laminated bamboo lumber (Li et al. 2013, 2015), however, theoretical research on the size effect on the compressive strength of laminated bamboo lumber is still lacking (Sharma 2017; Sinha et al. 2014; Correal et al. 2010, 2014; Verma 2013; Hong et al. 2019; Verma and Chariar 2012,2013). Therefore, it is necessary to find out the size effect on structural laminated bamboo lumber for the further development and promotion of standards based on exsiting studies.

The effect of size on the strength of brittle materials, such as wood, is based mostly on the Weibull brittle-fracture theory. (Weibull 1939). Madsen and Buchanan (1986) studied the relationship between flexural strength and the size of wood beams. Based on Weibull brittle-fracture theory, Zhou et al. (2010, 2011) calculated the parameters of size effect by both the slope method and parameter method. Barrett and Griffin (1989) conducted tests on the flexural properties of Canadian SPF lumber from and concluded that the size effect coefficient of bending strength is 0.22. Also, research showss that this theory is feasible in analyzing the size effect of some bamboo-based composites. Madsen (1992, 2011) used the Weibull brittle-fracture theory to explain the size effect of bamboo lumber and calculated the size effect coefficient. Wang and Shao (2014) analyzed the fracture strength distribution of bamboo fibers and determined the influence of size variations on their length and diameter according to Weibull brittle-fracture theory. Monteiro et al. (2017) used the Weibull method to analyze the relationship between tensile strength and the diameter of fibers extracted from a giant bamboo stem. Zhang et al. (2002) selected four groups of specimens with different sizes to study the effect of size on the elastic modulus and tensile strength of KENAF fiber. Zhao and Zhang (2019) designed specimens with five cross-section types to verify the feasibility of using the Weibull brittle-fracture theory to explain the size effect of structural bamboo scrimber. The studies above showed the feasibility of applying Weibull brittle-fracture theory on the analysis of size effect of wood and bamboo composites. However, it is still not clear whether Weibull theory is efficient to study the size effect on laminated bamboo lumber.

In this paper, specimens with three different cross-section sizes were designed and conducted axial compression test to verify the feasibility of Weibull theory. The brittle-fracture theory of material strength obeying Weibull distribution was established to study the size effect on the compressive strength of laminated bamboo lumber. On this basis, the analysis model of size effect and the size effect coefficient s_τ of laminated bamboo lumber were determined.

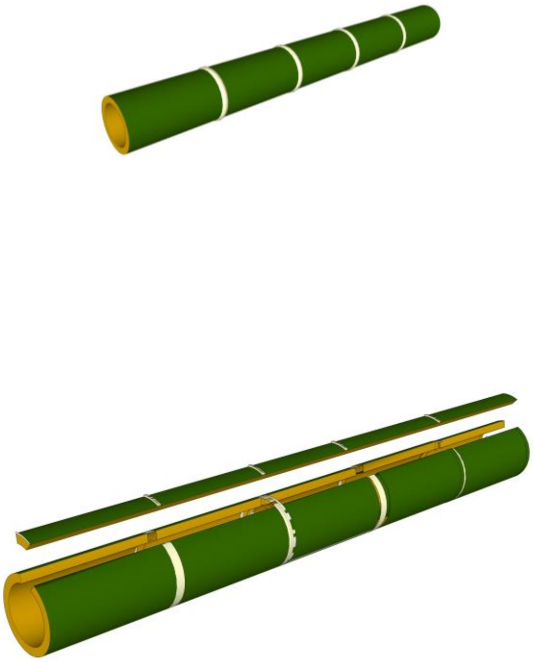
2 Test methods

2.1 Design and fabrication of specimens

The source Moso bamboo (*Phyllostachys pubescens*, from Feng-xin, Jiang-xi province, China) was harvested at the age of 3-4 years and manufactured into bamboo strips with the size of 2005mm×21 mm ×7 mm. Then the specimens were made by hot pressing for 15 minutes under the conditions of main pressure of 9 MPa, side pressure of 6.5 MPa, and temperature of 157 °C with resorcin as adhesive. The production process is shown in Fig. 1.

Fig. 1 Schematic diagram of the side-pressing laminated bamboo lumber production process

In this experiment, three groups of compression sp



ecimens of different sizes were used based on ASTM D143. The ratio of height to thickness of all specimens was 2. The design sizes were 25mm×25mm×50mm, 50mm×50mm×100mm, and 100mm ×100mm×200mm, respectively. ASTM D143 sepecifies the use of specimens with an aspect ratio of 1:1:4 however, Li et al. (2019) investigated the influence of length upon the behavior of parallel bamboo strand lumber (PBSL) specimensconcluding that the size of the specimen with instability failure was 50mm×50 mm×200mm (slenderness ratio is 1:1:4). Therefore, 50mm×50 mm×200mm is not a good specimen size to include in a standard for measuring compression strength. This study also found that a 100 mm-long specimen with the same section size (50 mm×50 mm×100 mm) was subjected to a state of stress close to ideal axial compression. Therefore, 50 mm×50 mm×100 mm (slenderness ratio 1:1:2) would be the preferred size to include in a code of standard to measure compression strength. According to the above analysis, LBL and PBSL both belong to engineered bamboo, thus, specimens with an aspect ratio of 1:1:2 were designed. The dimensions (b, h, l), moisture content (w), and density (ρ) of each set of specimens are listed in Table 1. As an example, 36 specimens in group C25 were numbered C25-1 to C25-36, with the remaining specimens following the same nomenclature.

2.2 Test method

The test was carried out in the civil engineering and structural laboratory of Nanjing Forestry University. Three different tonnage microcomputer-controlled electro-hydraulic servo universal testing machines were used due to the differences in the maximum bearing capacity of the specimens with different sizes, the broad side of the bamboo is marked as ‘A’ side, and then the clockwise direction is marked as A, B, C, and D side in turn. The strain gauges are arranged in a ‘T’ shape and are attached to the four surfaces of A, B, C, and D respectively.

The data were collected by a TDS-530 data acquisition instrument, and the axial displacement is measured by a displacement meter. Load control was applied first with the speed of 700N/s until 150kN was reached, then the displacement contol was adopted by 5mm/min The test duration of all specimens was controlled in about 8 minutes, and the test was stopped when the load dropped to 70% of the ultimate load. The diagram of the test set up is shown in Fig. 2.

Fig. 2 Experimental setup for determining the compressive strength

3 Analysis of failure modes

The typical failure modes of each group of laminated bamboo lumber are divided into three types, namely, end compression and buckling failure (mode 1), middle compression and buckling failure (mode 2), adhesive layer failure (mode 3), the number of failure in each mode for each group of specimens is shown in Table 1.

Table 1 Number of failure modes for each group of specimens

3.1 Failure mode 1

Fig. 3 shows the failure mode of six faces of the specimen C25-12 under failure mode 1. It can be seen that the failure mode 1 is an end-buckling failure. The crack appeared at the end of the specimen where this failure occured, and the crack extended from the end to the middle and upper part of the specimen. As shown in Table 1, 25 specimens were damaged in this way, accounting for 32.05% of the 78 specimens.

Fig. 3 Mode 1 failure state (C25-12)

3.2 Failure mode 2

Fig. 4 shows the failure mode of the six surfaces of the specimen C50-14. It can be seen cracks occurred first at the middle part of the specimens and extended to both ends of the specimens. Obvious cracks can be seen at the lower part of the A and D faces, and the cracks at the middle part of the B and D sides extended toward the end, accompanied by parallel cracks, which were not obvious around the bottom. With the appearance of the joint, specimens were divided into two or more units, the whole rigidity of the specimens were reduced and the bearing capacity were decreased. With the increase of deformation, the bamboo strips broke and the specimens were destroyed.

Fig. 4 Mode 2 failure state (C50-14)

There were 36 middle compression-buckling failure specimens, accounting for 46.15% of the 78 specimens. Combined with the first failure mode, 61 specimens were damaged by ultimate buckling, accounting for 78.21% of the total specimens. It can be seen that the compression specimens along the grain were destroyed mainly because of buckling.

3.3 Failure mode 3

The failure mode of the C50-23 specimen is presented in Fig. 5. It can be seen that the failure mode 3 was caused by a crack in the glue line. At first, many parallel cracks occurred in the top part of the B face. With the increase of load, the cracks extended downward and penetrated to the bottom of the specimen, the laminated bamboo lumber was damaged by the bending of bamboo strips due to the cracking of the glue joint between the laminates.

Fig. 5 Mode 3 failure state (C50-23)

It can be seen that when a certain load was reached, tiny cracks occurred first at the weak part of the glue joint. With the continuous increase of the load, the crack began to spread to the whole glue joint surface, and the weak side (the side close to the glue joint partition) began to bend. The number of such failure was 17, accounting for 21.79% of the total number of specimens. The main cause of the damage was the adhesive failure, leading to the rapid decline of the load-carrying capacity.

3.4 Displacement-load analysis

The load-displacement curves are shown in Fig. 6, from group C25 to group C100.

Fig. 6 Displacement-load diagrams

As can be seen from Fig.6, specimens with compression load along to grain of LBL showed obvious elastic-plastic behavior. Taking the specimen C50-5 as an example, the deformation stages of compression along to grain were analyzed briefly. The failure process of specimen C50-5 can be divided into three stages: ealstic stage, yield stage, and failure stage.

Elastic stage: At this stage, the specimen was completely in the linear elastic state, the load and displacement show a positive linear correlation, and there were no cracks.

Yield stage: The specimen showed an obvious plastic deformation after the elastic stage. In the second half of this stage, bamboo strips showed an obvious increase in bending deformation while the load increase was very small with accompanying micro-cracks which occurred locally and gradually extended to the whole bonding surface.

Failure stage: With the appearance and extension of the crack, the specimen was divided into two or more units with the whole rigidity of the specimen reduced and its bearing capacity decreased leading to an uneven bearing force due to the inclination of the spherical seating of the loading platen. Due to the friction between the two ends and the support surface, the transverse deformation was restrained leading to the bulging of the bamboo specimen.

4 Results and discussion

4.1 Ramberg-Osgood model

In this paper, the Ramberg-Osgood model (Ramberg and Osgood 1943) was used for fitting the stress-strain curve. The Ramberg-Osgood model (ROR) is suitable for stress-strain curves without an obvious yield point. As shown in Eq. 1, the original formula for the Ramberg-Osgood model (Ramberg and Osgood 1943) is:

$$\varepsilon = \frac{\sigma}{E} + k(\frac{\sigma}{E})^n \tag{1}$$

Where ε is the strain; n is the strain index; k and n are set according to the properties of the material. σ/E and $k(\sigma/E)^n$ are the elastic and plastic strains respectively. A parameter α, which is related to k, is defined by introducing σ_e as the reference strength in any state of the material at the elastic stage:

$$\alpha = k(\frac{\sigma_e}{E})^{n-1} = k\varepsilon_e^{\ n-1} \tag{2}$$

The improved equation of the Ramberg-Osgood model is obtained by substituting Eq. 2 into Eq. 3：

$$\varepsilon = \frac{\sigma_{\mathrm{e}}}{E} + \alpha\left(\frac{\sigma_{\mathrm{e}}}{E}\right)^{n} \tag{3}$$

Substituting ε and ε_e in Eq. 8, and introducing the corresponding ratios to eliminate the elastic modulus E, the stress-strain equation of Ramberg-Osgood model is obtained as follows:

$$\frac{\varepsilon}{\varepsilon_{\mathrm{e}}} = \frac{\sigma}{\sigma_{\mathrm{e}}} + \alpha\left(\frac{\sigma}{\sigma_{\mathrm{e}}}\right)^{n} \tag{4}$$

As long as the coefficients α and n are confirmed, a Ramberg-Osgood stress-strain constitutive model can be determined as shown for specimens C25 to C100 in Fig. 7 below.

Fig. 7 Ramberg-Osgood model

As shown in the diagram above, the Ramberg-Osgood stress-strain models of different sizes of laminated bamboo lumber are fitted according to the group type. The Ramberg-Osgood equation for each group is shown below:

Group C25：

$$\begin{cases} \dfrac{\varepsilon}{0.003} = \dfrac{\sigma}{38} + 0.133\left(\dfrac{\sigma}{38}\right)^{4.85} & (0 \le \varepsilon < 0.019) \\ \dfrac{\sigma}{65.90} = 1 & (0.019 \le \varepsilon < 0.064) \end{cases} \tag{5}$$

Group C50：

$$\begin{cases} \dfrac{\varepsilon}{0.003} = \dfrac{\sigma}{28} + 0.112\left(\dfrac{\sigma}{28}\right)^{4.48} & (0 \le \varepsilon < 0.016) \\ \dfrac{\sigma}{62.32} = 1 & (0.016 \le \varepsilon < 0.088) \end{cases} \tag{6}$$

Group C100：

$$\begin{cases} \dfrac{\varepsilon}{0.004} = \dfrac{\sigma}{30} + 0.133\left(\dfrac{\sigma}{30}\right)^{5.49} & (0 \le \varepsilon < 0.023) \\ \dfrac{\sigma}{57.03} = 1 & (0.023 \le \varepsilon < 0.054) \end{cases} \tag{7}$$

4.2 Theory

Weibull brittle-fracture theory (Weibull 1939) lays the foundation for the study of the failure of brittle materials such as wood or fiber-reinforced composites. The theory assumes that the material is composed of many randomly selected units, and that failure of any unit leads to the failure of the specimen with the strength of the unit following a Weibull distribution. According to Weibull theory, for the same loading mode, the relation of average strength f to f_0 of specimens with volumes of V and V_0 can be given by the following equation:

$$\frac{f_0}{f}=(\frac{V}{V_0})^{S}=(\frac{V_0}{V})^{-S}=(\frac{b}{b_0})^{S_b}(\frac{h}{h_0})^{S_h}(\frac{l}{l_0})^{S_l} \tag{8}$$

$$\frac{f_0}{f}=(\frac{V_0}{V})^{-S}=(\frac{b_0}{b}\times\frac{h_0}{h}\times\frac{l_0}{l})^{-S}=(\frac{b_0}{b}\times\frac{h_0}{h}\times\frac{\tau b_0}{\tau b})^{-S}=(\frac{h_0}{h}\times\frac{{b_0}^2}{b^2})^{-S_\tau} \tag{9}$$

Where f and f_0 are the specimen strength; V and V_0 are specimen volumes; s is the size effect coefficient; s_τ is the cross-section effect parameter; h and h_0 are specimen width; b and b_0 are the thickness of the specimen; l and l_0 are specimen length; τ is the height-thickness ratio of the specimen; s_b, s_h and s_l are size effect coefficients of specimen width, thickness and length respectively. In this test, the value of τ is 2.

The coefficient s_τ can be evaluated by Weibull's brittle fracture theory. The slope method was used in this paper. For two specimens with the same section width to thickness ratio and different widths, Eq. 8 can be simplified to Eq. 9 when the section ($b\times h$) and the strength f of the basic unit have been determined, the compressive strength f_0 of any specimen with the section ($b_0\times h_0$) can be obtained.

Assuming that the laminated bamboo lumber specimen consists of an infinite number of randomly selected brittle units, the total specimen strength distribution function for all brittle units can be expressed by a three-parameter Weibull distribution function:

$$F(f)=1-\exp\left[-\left(\frac{f-\kappa_0}{m}\right)^z\right] \tag{10}$$

In Eq. 10, z, m, κ_0 are the shape, scale, and position parameters of the Weibull's brittle fracture theory, respectively. If the position parameter κ_0 is assumed to be 0. Then the Eq. 10 becomes a two-parameter Weibull distribution function, as shown in Eq. 11.

$$F(f)=1-\exp\left[-(f/m)^z\right] \tag{11}$$

If a specimen contains n units, the cumulative distribution function of the specimen should be derived from a unit function. When a unit function is a two-parameter Weibull distribution function, then n unit functions are:

$$1-F_n(f)=\left[1-F_1(f)\right]^n=\exp\left[-n\left(f/m\right)^z\right] \tag{12}$$

As shown in Eq. 12, $F_n(x), F_1(x)$ are two-parameter Weibull's brittle fracture theory functions of n

units and one unit, respectively. Eq. 12 can be transformed to give the compressive strength under different fractile of probabilistic distribution：

$$f_q = m \cdot n^{-1/z} \left[-\ln(1-q) \right]^{1/z} \qquad (13)$$

For two specimens of different sizes containing n_1 and n_2 units, the compressive strength ratio at any fractile is：

$$\frac{f_q(n_1)}{f_q(n_2)} = \frac{m n_1^{-1/z} \left[-\ln(1-q) \right]^{1/z}}{m n_2^{-1/z} \left[-\ln(1-q) \right]^{1/z}} = \left(\frac{n_1}{n_2}\right)^{-1/z} \qquad (14)$$

The parameter method is used to estimate the size effect coefficient based on the Weibull's brittle fracture function. When the distribution of the compressive strength follows a two-parameter Weibull's brittle fracture theory function, the distribution of the compressive strength under any fractiles $s_\tau = 1/z$. Therefore, for specimens with the same height to thickness ratio and different section widths, the s_τ is equal to the reciprocal of the shape parameter z in the Weibull's brittle fracture. Currently, there are three distribution function fitting methods: probability weighted moments, maximum likelihood, and linear regression. In this paper, the linear regression method and maximum likelihood were used.

The linear regression method for calculating the size effect coefficient is as follows: firstly, the compressive strength is arranged in ascending order $x_1, x_2, \cdots, x_n$: each value is assigned a position $p_i = i/(n+1)$; by calculating $t_i = \ln\left[-\ln(1-p_i)\right]$ and $y_i = \ln x$, then the coordinate point (t_i, y_i) is determined. All coordinate points are linearly regressed according to $y = bt + c$. The shape parameter, the scale parameter, and the fitting line slope b of the two-parameter Weibull's brittle fracture theory function are obtained, and the relation of intercept c is $z = 1/b, m = \exp(c)$.

For maximum likelihood, the likelihood function of the two parameter Weibull's brittle fracture theory function can be written as Eq. 15:

$$\ln L = \sum_{i=1}^{n} \ln f(x_i) = n \ln z - nz \ln m + (z-1) \sum_{i=1}^{n} \ln x_i - \sum_{i=1}^{n} \left(\frac{x_i}{m} \right)^z \qquad (15)$$

The partial derivatives of Eq. 15 are solved by an asymptotic method and iterative method.

4.3 Size effect of compressive strength

Table 2 presents the statistics of the ultimate load P_0, the ultimate displacement u_0, the compressive strength σ_0, the average longitudinal strain of the four faces ε_{y0}, the average transverse strain of the four faces under ultimate load ε_{x0}. In addition, $\upsilon_{A,C}$ is the average Poisson's ratio of face A to face C, $\upsilon_{B,D}$ is the average Poisson's ratio of face B to face D, μ is ductility factor, α is compression coefficient, ρ is the density of each group, and the mean value, standard deviation, coefficient of variation, and 95% confidence value of the elastic modulus E. In this table, COV is the coefficient of variation; SDV the standard deviation and CHV the characteristic value, calculated on the basis that 95% of specimens exceeding the characteristic value (mean value-1.645×SDV).

Table 2 Statistics of test results

As can be seen from Table 2, the compressive strength of C25, C50, and C100 specimens decreases with the increase of the cross-sectional area, which shows that there is an obvious size effect. The density of the C25 group with a 95% confidence was 0.755g/mm^3 (COV=2.31%), the C50 group was 0.667g/mm^3 (COV=5.85%) and the C100 group was 0.720 g/mm^3 (COV=0.935%). It can be seen that the density of group C50 is lower than that of group C100, but its strength is higher than group C100, which shows that the effect of density on the strength of bamboo laminated lumber is uncertain. Besides, the difference of density with a 95% confidence between C50 and C100 groups is large, but the difference of MOE is small, which shows that the effect of density on elastic modulus is uncertain.

The results show that when the ratio of height to thickness is constant, the compressive strength decreases with the increase of the cross-sectional dimension, which indicates that the compressive strength is obviously affected by the size values of laminated bamboo.

4.3.1 Determination of size effect coefficient by slope method

According to Weibull brittle-fracture theory (Weibull 1939) and ASTM D2915-1047 (2010), the compressive strength along the grain direction of laminated bamboo lumber was determined knowing that the length and thickness of the specimen have no size effect on the compressive strength along the grain (ASTM D1990-2007). The application of the "Weibull brittle-fracture theory" to analyze the mechanical properties of bamboo materials has been studied and the results showed that it is feasible to use the Weibull brittle-fracture theory to study the size effect of laminated bamboo lumber.

In this paper, by applying the slope method and parametric method, specimens of group C25 were taken as standard specimens. The fitted curve of the ultimate load of all groups is shown in Fig. 8(a). The ultimate load size effect coefficient is 0.6254. The fitted curve of the compressive strength is shown in Fig. 8(b). The size effect coefficient of the compressive strength is 0.035(1/28.57).

In addtion, the fitted curves of the mean Poisson's ratios of face A to face C and face B to face D are given in Fig. 8(c) and Fig. 8(d) respectively. The size effect coefficients of the average Poisson's ratio of face A and C, face B and D were 0.035 (1/28.57) and 0.027 (1/37.04), respectively. Fig. 8(e) shows the fitted curves of the elastic moduli of all the test groups. In Fig. 8(g), it can be seen that the size effect coefficient of the compression modulus of the laminated bamboo lumber is 0.09(1/11.11).

Fig. 8 Scatter plot of material parameters

P_0 is the ultimate load, V is the volume, σ_0 is the compressive strength, $\upsilon_{A,C}$ is the average poisson's ratio of face A and face C, $\upsilon_{B,D}$ is the average poisson's ratio of face D and face E, μ is the ductility coefficient of each specimen; a is the compression coefficient, E is the elastic modulus of each specimen.

In this paper, the size effect coefficient was calculated based on the test group C25. Fig. 9 shows the fitted curves of different mechanical properties with a 95% guarantee rate for each group of specimens and gives the fitted equations. As shown in Fig. 9(a), the fitted curve of the ultimate load with a 95% confidence for each group of specimens varies with the volume of the specimens. The size effect coefficient for the ultimate load is 0.668(1/1.50).

The compressive strength values of the three groups of specimens with a 95% confidence are respectively marked in Fig. 9(b). The size effect coefficient of the average compressive strength of laminated bamboo lumber specimens with a 95% confidence is 0.034(1/29.41).

The ductility coefficient of three groups of specimens with a 95% confidence is shown in Fig. 9(c). From the fitted curve it can be seen that the size effect coefficient of the laminated bamboo lumber compression specimen is 0.0529(1/18.90).

The compression coefficient of three groups of specimens with a 95% confidence is shown in Fig. 9(d). It can be seen that the size effect coefficient of the compression coefficient is 0.135(1/7.41). As shown in Fig. 9(e), the size effect coefficient of the elastic modulus is 0.064(1/15.63) at the test with a 95% confidence.

Fig. 9 Fitted curves of mechanical properties with 95% guarantee rate

In the figures, $P_{0,95\%}$ is the values of the ultimate load, $\sigma_{0,95\%}$ the compressive strength, $\mu_{0,95\%}$ the ductility coefficient value of the sample group and $a_{0,95\%}$ the compression coefficient of each test group all with a 95% confidence level.

With the increase volume of specimens, the average compressive strength alongzxx grain decreased. It can be concluded that the size effect coefficient is 0.034(1/29.41), which indicates that there is an obvious size effect on the compressive strength of laminated bamboo lumber.

4.3.2 Determination of size effect coefficient by the parametric method

The size parameters of Weibull distribution estimated by the parametric method are almost consistent with the results of non-parametric calculation when the two-parameter Weibull distribution functions are fitted to the strength data (Zhou et al. 2011). This section uses the two-parameter method to calculate the size effect coefficient. Currently, there are three commonly used methods, including the probability-weighted moment method, maximum likelihood method, linear regression method. The linear regression method and maximum likelihood calculation were used in this paper. As shown in Fig. 10, for the linear regression fitted curves of three groups of specimens, the shape parameters z and the size parameters m of each group can be obtained, as well as the values of z are averaged and compared with the reciprocal of the size effect coefficient s_τ obtained by the slope method. The results are shown in Table 3.

Fig. 10 Two parameter Weibull distribution linear regression curves

Table3 Estimated parameters of 2P-Weibull

As can be seen from Table 3, when the compressive strength follows a two-parameter Weibull distribution function, the mean value of the shape parameter z obtained by both linear regression and maximum likelihood estimation is lower than the reciprocal of the shape parameter s_τ obtained by the slope method and so the slope method underestimates the effect of specimen size on compressive strength. The size effect coefficient z is obtained by the slope method, and the size effect coefficient s_τ is obtained by the linear regression method and the maximum likelihood method. The final size effect coefficients are 0.043(1/23.08) and 0.036(1/27.16) respectively, that is to say, when the ratio of height to thickness is the same, the compressive strength decreases to 0.971 and 0.975 times when the width is doubled.

Therefore, the Weibull brittle-fracture theory can be used to analyze the compressive strength of the laminated bamboo lumber and other engineered bamboo.

The size effect of the 5%-fractile of the laminated bamboo lumber compressive strength is 0.034, that is to say, the compressive strength of bamboo laminated lumber decreases to 0.977 when the width of the laminated bamboo lumber is doubled under a certain ratio of height to thickness. The size effect coefficient obtained by the slope method is smaller than that obtained by the parameter method, so it is suggested to use the shape parameter method to obtain the size effect coefficient s_τ.

The results of Zhou et al. (2010) show that the size effect coefficient of the compressive strength of Chinese fir for wood structures is 0.11, with the linear regression method dopted to determine the final value, the size effect coefficient of compressive strength along laminated bamboo lumber was 0.043(1/23.26). The results showed that the effect of dimension on wood compressive strength was more obvious than that of laminated bamboo lumber. Zhao et al. (2019) studied the effect of the size of the bamboo reconstituted material on the compressive strength. The results showed that the size effect coefficient of the parallel bamboo strand lumber was 0.053, that is, the compressive strength of the parallel bamboo strand lumber decreased by a factor of 0.964 for every doubling of the sample volume. It can be seen that the compressive strength of engineered bamboo such as laminated bamboo lumber and parallel bamboo strand lumber is lower than engineered timber, and the reason for this result is that there are more internal defects (such as nodes and knots and other local wood characteristics) in wood than laminated bamboo lumber, and engineered bamboo timber is made by hot pressing and has a higher density and fewer pores than wood, so the size effect of laminated bamboo lumber is smaller than wood. Besides, the results of this study apply to axially compressed laminated bamboo lumber columns with strength failure, but not to those with unstable failure.

Through the above analysis, it can be seen that the compression test for laminated bamboo lumber conforms to the general rule of size effect, and the size effect formula of compressive strength of bamboo aggregate can be obtained as Eq. 16:

$$\frac{f_0}{f} = \left(\frac{V}{V_0}\right)^{0.043} \qquad (16)$$

f_0 and V_0 are the control specimens with known volume and axial compressive strength. If the volume V of laminated bamboo lumber aggregate is known, the compressive strength f can be obtained. The units of f and f_0 are megapascal (MPa), and the units of V and V_0 are cubic meters (m^3). In this paper, the C25 specimens are used as A reference, and its average resistance to pressure f_0 degree is 69.4 MPa and its volume V_0 is $3.125\times10^{-5}m^3$. Therefore, this formula can be further simplified into Eq. 17. In this test, the compressive strength of three groups of specimens can be expressed in Eq. 18:

$$\frac{69.4}{f} = \left(\frac{V}{3.125\times10^{-5}}\right)^{0.043} \qquad (17)$$

$$f_{25} = 1.030 f_{50} = 1.061 f_{100} \qquad (18)$$

In the formula, f_{25} is the average compressive strength of the group C25, f_{50} is the average compressive strength of the C50 group, f_{100} is the average compressive strength of the C100 group.

5 Conclusions

In this paper, the effects of different sizes on the compressive strength of laminated bamboo lumber were studied, and the failure mechanism and size effects of different sizes were analyzed. An increase in the specimens volume led to a decrease in the compressive strength along the grain. Based on the Ramberg-Osgood model, a new stress-strain curve model was proposed.

The slope method and the parameter method were used to calculate the size effect coefficient. The results showed that the linear regression parameter analysis method is more suitable to analyze the size effect. It is concluded that the size effect coefficients are: 0.043(1/23.26) for compressive strength, 0.064(1/15.63) for elastic modulus, 0.0529(1/18.90) for ductility coefficient, and 0.133(1/7.52) for compression coefficient. Compared with wood, the size effect has less effect on the compressive strength of laminated bamboo lumber.

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Figure Caption List

Fig. 1 Schematic diagram of the side-pressing laminated bamboo lumber production process: (a) Original bamboo (b) Splitting (c) Original bamboo strip (d) Peeling (e) Bamboo strip (f) Laminated bamboo lumber

Fig. 2 Experimental setup for determining the compressive strength

Fig. 3 Mode 1 failure state (C25-12): (a) A side (b) B side (c) C side (d) D side (e) Top side (f) Bottom side

Fig. 4 Mode 2 failure state (C50-14): (a) A side (b) B side (c) C side (d) D side (e) Top side (f) Bottom side

Fig. 5 Mode 3 failure state (C50-23): (a) A side (b) B side (c) C side (d) D side (e) Top side (f) Bottom side

Fig. 6 Displacement-load diagrams: (a)Displacement-load diagram of group C25 specimens (b) Displacement-load diagram of group C50 specimens (c) Displacement-load diagram of group C100 specimens

Fig. 7 Ramberg-Osgood model: (a)Ramberg-Osgood model of a C25 group specimen (b) Ramberg-Osgood model of a C50 group specimen (c) Ramberg-Osgood model of a C100 group specimen

Fig. 8 Scatter plot of material parameters: (a)Relationship between ultimate load and volume (b) Relationship between compressive strength and volume (c) Mean Poisson's of A and C surfaces (d) Mean Poisson's of B and D surfaces (e) Elastic modulus (f) Ductility coefficient.tif (g) Coefficient of compressibility

Fig.9 Fitted curves of mechanical properties with 95% guarantee rate: (a) 95% guaranteed ultimate load (b) 95% guaranteed compressive strength (c) 95% guaranteed ductility coefficient (d) 95% guaranteed compression coefficient (e) 95% guaranteed elastic modulus

Fig10 Two parameter Weibull distribution linear regression curves

Table 1 Number of failure modes in compression test for each group of Specimens

Specimen set	Mode 1	Mode 2	Mode 3	Total
C25	9	16	10	35
C50	13	16	6	35
C100	3	4	1	8
Total	25	36	17	78

Table 2 Statistics of test results

Group		P_{max} (kN)	u_0 (mm)	σ_0 (MPa)	ε_{y0}	ε_{x0}	$\upsilon_{A,C}$	$\upsilon_{B,D}$	E (MPa)	μ	a	ρ (g/cm³)
C25	AVG	44.47	8.3	69.4	55267	30814	0.38	0.311	10619	2.07	0.172	0.787
	SDV (%)	2.468	2.2	3.76	22824	17974	0.119	0.073	1419	0.442	0.032	0.018
	COV	5.55	26	5.41	41.3	58.33	31.43	23.54	13.37	21.31	18.88	2.31
	CHV	40.41	4.8	63.2	17722	1247	0.183	0.191	8284	1.35	0.119	0.787
C50	AVG	170.2	13	66.8	39271	20606	0.361	0.296	8355	1.80	0.130	0.738
	SDV (%)	11.4	2	4.38	12971	10950	0.091	0.063	1235	0.426	0.019	0.043
	COV	6.70	15	6.55	33.03	53.14	25.19	21.23	14.78	0.236	0.147	5.85
	CHV	151.5	9.9	59.6	17933	2593	0.211	0.192	6323	1.10	0.099	0.667
C100	AVG	571	20	57.8	36390	10751	0.355	0.273	7781	2.20	0.098	0.731
	SDV (%)	16.27	3.71	1.82	10243	4781	0.035	0.039	877	0.319	0.019	0.007
	COV	2.85	19	3.14	28.15	44.47	9.76	14.18	11.28	0.145	0.190	0.935
	CHV	544.2	14	54.8	19541	2887	0.298	0.209	6338	1.68	0.068	0.720

Table3 Estimated parameters of 2P-Weibull

Specimen	Regression		Likelihood		Slope method
	z	m	z	m	z
C25	21.10	71.10	21.52	71.15	
C50	17.57	68.77	17.56	68.95	—
C100	30.58	58.69	42.40	58.58	
Mean value	23.08	66.19	27.16	66.23	29.41