Experimental Study on Tensile and Compressive Strength of Bamboo Scrimber

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The objective of this study was to provide fundamental parameters for the utilization of bamboo scrimber in the building structure field as a green building material. Both static tensile and compressive tests were conducted on bamboo scrimber, with 180 specimens for compressive tests and 173 specimens for tensile tests. The normal and lognormal distributions were selected to fit the experimental data. The design values were calculated according to the Chinese allowable stress design method and ASTM D2915 (2003). The results showed that both tensile strength (UTS) and compressive strength (CS) parallel to the fiber of bamboo scrimber were significantly higher than those of wood and other bamboo-based composite materials. Kolmogorov-Smirnov and chi-squared test results indicated that a lognormal distribution was a good fit for the UTS and CS except for the fitting result of UTS by the chi-squared test. The calculated design values of UTS and CS using ASTM D2915 (2003) were higher compared with those found using the Chinese allowable stress design method.

Keywords: Allowable stress design; Bamboo scrimber; Compressive strength; Tensile strength; Design value

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INTRODUCTION

With the rapid development of wood structure in China, increasingly more engineered wood products are being invented, such as laminated veneer lumber, oriented strand board, and laminated timber. However, because of the prohibition on harvesting of natural forests that has been in effect since 2015 in China, wood resources used to produce wood engineering products have been in serious shortage. Therefore, the raw materials for wood engineering products should be substituted with other, new, materials, such as bamboo. There are 39 genera and 509 species of bamboo plants naturally distributed in areas from north latitude 18 to 38 degrees and east longitude 92 to 122 degrees in China, accounting for 36% and 39% of the world, respectively (Dou *et al*. 2011; Wang *et al*. 2012). Bamboo is a fast-growing, renewable, high-strength/weight ratio, and environmental friendly resource. It has great potential to improve poverty alleviation and economic development (Lee and Liu 2003; Yu *et al*. 2013).

However, because of the small size of bamboo, its promotion in various applications is restricted. To overcome these shortcomings of bamboo, as well as expand upon its applied fields, bamboo has been widely used to fabricate bamboo-engineering products, such as bamboo plywood and laminated bamboo lumber, which have been applied to indoor decoration, especially in China and India (Zhang *et al*. 2012; Zhong *et* *al*. 2014). The manufacturing process, mechanical behavior, and performance of laminated bamboo lumber have been previously studied (Obataya *et al.* 2007; Shao *et al*. 2010; Zhu *et al*. 2011). Aimed at higher efficiency and mechanical performance of bamboo-based composite material, a new product of bamboo scrimber has been explored, of which the hot-press technology, glue immersion, and process parameters were studied (Zhang *et al.* 2008; Wang *et al.* 2013; Yu *et al*. 2014). In a previous study, the tensile strength and compressive strength parallel to grain of bamboo scrimber manufactured with *Sinocalamus affinis* were about 1.0 times higher than those of wood (Gao *et al*. 2008; Zhang *et al*. 2012).

Because of the high strength and good dimensional stability of bamboo scrimber, it has been widely applied in furniture, construction formwork, wind-power blades, and container flooring. However, its promotion in the field of civil engineering is restricted because the characteristic values and design values of the bamboo scrimber are almost unknown. Hence, it is unsafe to use the new type of bamboo-engineering products in building structures without a design value. Therefore, the objective of this study was to select normal and lognormal distributions to fit the experimental data obtained using static tensile and compressive tests, and to determine the design values of UTS and CS for bamboo scrimber based on the Chinese allowable stress design method and ASTM D2915 (2003). Research on strength properties and design values will provide basic data for the application of bamboo scrimber in the building structures filed.

EXPERIMENTAL

Materials

Neosinocalamus affinis, aged 3 to 4 years, harvested from the Hongya Forest Reserve, Sichuan province, in southwestern of China, was used as a raw material to produce bamboo scrimber. The bamboo scrimber plates were produced by Sichuan Hongya Bamboo Co., Ltd. Bamboo scrimber included plurality bamboo strips impregnated with an adhesive and modified through heat-treatment (Shangguan *et al*. 2014). The untreated bamboo was sawn into bamboo tubes, and then the tubes were fluffed along the direction of the longitudinal fiber to interlace bamboo fiber bundles.

After that, oriented bamboo fiber bundles were immersed in a PF162510 phenol-formaldehyde resin (Beijing Dynea Chemical Industry Co., Ltd., 45.59% of solids content, 36 CP.s viscosity, 10 to 11 pH). The amount of adhesive was controlled at approximately 15% of the dry weight of the bamboo scrimber during the dipping glue process. A pressure of 5.0 MPa and a temperature of 140 °C were applied during manufacturing. The dimension of the plates was 2500 (length) × 1250 (width) × 20 mm (thickness). The average density and moisture content of the samples were 1.12 ± 0.09 g/cm^3 and 7.42 ± 0.96 %, respectively.

To ensure randomness and representativeness of the sampling process, 10 plates were selected for static testing, and each plate was cut into two halves in the longitudinal direction and divided into 18 subzones (Fig. 1). Two specimens from each subzone were used for tensile and compressive testing, a total of 180 specimens for static tensile and static compressive testing, respectively. The dimensions of the specimens used for tensile testing and compressive testing were 370 (length) × 20 (width) × 15 mm (thickness), and 30 (length) × 20 (width) × 20 mm (thickness), respectively.

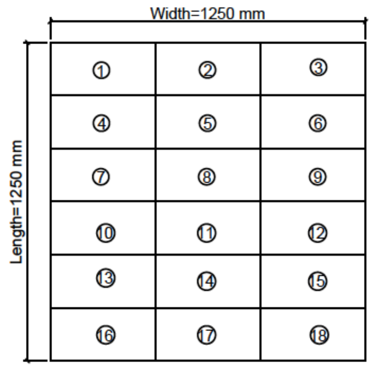

Fig. 1. Divided subzones of the bamboo scrimber

Static Test Methods

The tensile and compressive tests were conducted according to Chinese national standards GB 1938 (2009) and GB 1935 (2009; Fig. 2). The tests required failure between 3 and 10 min after initial loading. To accommodate the time to failure requirement, loading speeds were adjusted to 1 mm/min for tensile testing, and 2 mm/min for compressive testing. The specimens were tested using an Instron 5582 machine (100 KN of load limit; Instron Corporation, USA) and the maximum load was taken as the failure load. All specimens were conditioned at 20 °C and 65% relative humidity (RH). The weight, dimensions, and moisture content of each specimen were recorded after the equilibrium moisture content was reached. The UTS and CS of bamboo scrimber were calculated using Eq. (1).

$$s = \frac{F_{max}}{bt} \tag{1}$$

where σ represents the tensile strength or compressive strength, F_{max} is the maximum force applied to the specimens during the test (N), b is the width of the specimens (mm), and t is the thickness of the specimens (mm).

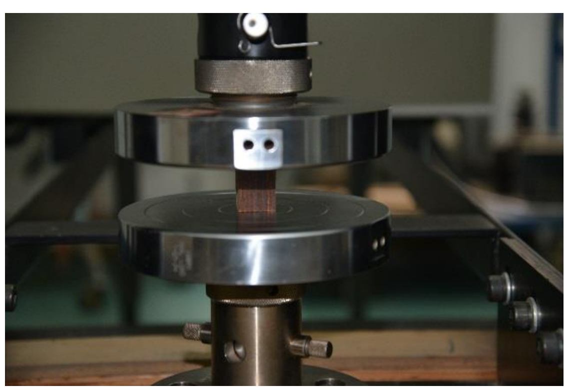

Fig. 2. Test set-up for determination of compressive strength

Probability Distribution

Usually, the normal and lognormal are adopted as parametric statistical models in the analysis of mechanical properties. The distribution function f (x) and cumulative distribution function ϕ (x) can be expressed as follows:

(1) Normal distribution

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left\{ -\frac{(x-\mu)^2}{2\sigma^2} \right\} \quad (2)$$

$$\phi\left(\frac{x-\mu}{\sigma}\right) = p \quad (3)$$

where x is the random variable, μ is the mean, and σ is the standard deviation. p is the percentile value of the cumulative distribution function.

(2) Lognormal distribution

$$f(x) = \frac{1}{xs\sqrt{2\pi}} \exp\left\{ -\frac{(Inx - M^2)}{2s^2} \right\} \quad (4)$$

$$\phi\left(\frac{x-M}{s}\right) = p \quad (5)$$

where M is the mean value of logarithm x and S is the standard deviation of Inx.

Kolmogorov-Smirnov test

The Kolmogorov-Smirnov test (K-S test) can be used to estimate goodness of fit for specified model distributions (Kolmogorov 1932). K-S test was performed using SPSS Statistics 20 software. The formula can be expressed as follows:

$$D = \max(|\phi(x) - s(x)|) \quad (6)$$

where $\phi(x)$ and $s(x)$ represent the cumulative probability value and theoretical distribution, respectively. D is the maximum absolute difference between $\phi(x)$ and $s(x)$.

At the 0.05 level of significance, the $D_{0.05}$ should be equal to $1.36/\sqrt{n}$, n is the number of samples. If $D < D_{0.05}$, than the theoretical distribution, $s(x)$, can provide a good fit for the cumulative probability value, $\phi(x)$, obtained via static testing. If $D > D_{0.05}$, than the theoretical distribution fits unsuccessfully.

Chi Squared test (χ^2)

The deviation between the actual value and the theoretical value can be verified using the Chi Squared test (Mao *et al.* 2006). The formula can be expressed as follows,

$$\chi^2 = \sum_{i=1}^{k} \frac{(n_i - np_i)^2}{np_i} \quad (7)$$

where k is the sum of interval numbers, n_i is the observed numbers located in the i^{th} interval, and np_i is the predicted number of random variables on interval. For example, the k, n_i, and np_i of the UTS are shown in Table 1.

Table 1. Observed Numbers and Predicted Numbers of Tensile Strength

Interval (x_i)	Observed numbers (n_i)	Probability (p)		Predicted numbers (np_i)	
		Normal	Lognormal	Normal	Lognormal
[100-110]	2	0.0074	0.0030	1.2783	0.5134
[110-120]	3	0.0172	0.0123	2.9942	2.1257
[120-130]	4	0.0349	0.0343	6.0656	5.9360
[130-140]	11	0.0614	0.0699	10.6886	12.0920
[140-150]	23	0.0942	0.1101	16.3846	19.0568
[150-160]	24	0.1256	0.1406	21.8486	24.3258
[160-170]	28	0.1456	0.1507	25.3444	26.0784
[170-180]	18	0.1470	0.1397	25.5750	24.1693
[180-190]	14	0.1290	0.1146	22.4505	19.8228
[190-200]	17	0.0985	0.08478	17.1438	14.6641
[200-210]	15	0.0654	0.0575	11.3884	9.9389
[210-220]	11	0.0378	0.0361	6.5808	6.2522
[220-230]	2	0.0190	0.0213	3.3080	3.6903
[230-240]	1	0.0083	0.0119	1.4464	2.0623

RESULTS AND DISCUSSION

Tensile and Compressive Strength

The UTS and CS of the bamboo scrimber are shown in Table 2. The average values of UTS and CS for bamboo scrimber were 170.65 and 104.82 MPa, respectively. Compared with common wood materials in China such as scrimber, larch (*Larix*), Chinese fir (*Cunninghamia lanceolata*), and Masson pine (*Pinus massoniana*, Lamb.), the tensile strength of bamboo scrimber was found to be 0.39, 0.98, and 0.62 times higher than that of larch, Chinese fir, and Masson pine, respectively. Meanwhile, the compressive strengths of larch, Chinese fir, and Masson pine were 52.2, 35.6, and 46.5 MPa, respectively. These are obviously lower than the compressive strength of bamboo scrimber. This is due to fewer natural defects in bamboo scrimber, such as knots, crackle, and warping, ensuring better mechanical properties than wood. The coefficient of variation for UTS and CS for bamboo scrimber was lower than that for other materials.

Table 2. Summary of Tensile and Compressive Strength for Bamboo Scrimber and Wood

Material	Density		UTS		CS	
	Avg (g/cm^3)	COV (%)	Avg (MPa)	COV(%)	Avg (MPa)	COV(%)
Bamboo scrimber	1.24	7.64	170.65	15.61	104.82	10.75
Larch [a]	0.53	10.12	122.60	26.00	52.20	14.60
Chinese fir [a]	0.31	9.87	86.10	21.20	35.60	17.30
Masson pine [a]	0.52	9.10	104.90	28.10	46.50	17.50

[a] The physical and mechanical properties of larch, Chinese fir, and Masson pine were described in detail in Yin *et al.* (2014). The UTS and CS of all materials were obtained using a static test parallel to the direction of the grain.

Compared with bamboo-based composite materials, bamboo scrimber had stronger competition in building structures. The UTS and CS of raw bamboo and bamboo-based composites, such as bamboo and glued laminated bamboo (GLB) are shown in Table 3. The average value of CS for bamboo scrimber was 0.75 and 0.14 times higher than that of bamboo and GLB, respectively. Meanwhile, the UTS of bamboo scrimber was obviously higher than that of raw bamboo and other bamboo-based composites. The strength of bamboo-based composites is mainly dependent on the interface bonding between bamboo fiber and resin. The resin was distributed more uniformly in the manufacturing process of bamboo scrimber; thus it has better mechanical properties than raw bamboo and other bamboo-based composites.

Table 3. Summary of Tensile and Compressive Strength for Raw Bamboo and Bamboo-based Composites

Material	Density		UTS		CS	
	Avg (g/cm^3)	COV (%)	Avg (MPa)	COV (%)	Avg (MPa)	COV (%)
Bamboo scrimber	1.24	7.64	170.65	15.61	104.82	10.75
Bamboo [b]	0.68	11.93	114.08	17.10	59.81	9.45
GLB [c]	0.84	9.28	144.29	10.95	92.28	2.62

[b,c]The physical and mechanical properties of bamboo and glued laminated bamboo were described in detail by Huang (2007) and Li (2013), respectively. The UTS and CS of all materials were obtained using a static test parallel to the direction of the grain.

Probability Distribution

It is important to determine the probability distribution of mechanical strength of bamboo scrimber for its utilization in building structures. The normal and lognormal distributions curve of UTS and CS are shown using a histogram in Fig. 2. Greater differences between the normal and lognormal distributions were observed in UTS and CS, where the lognormal distribution fit the UTS and CS better than the former. The maximum frequency of UTS and CS was around 170 and 105 MPa, respectively. The basic fitted parameters were important for determining the characteristic values, and the values of the parameters of two models are shown in Table 4.

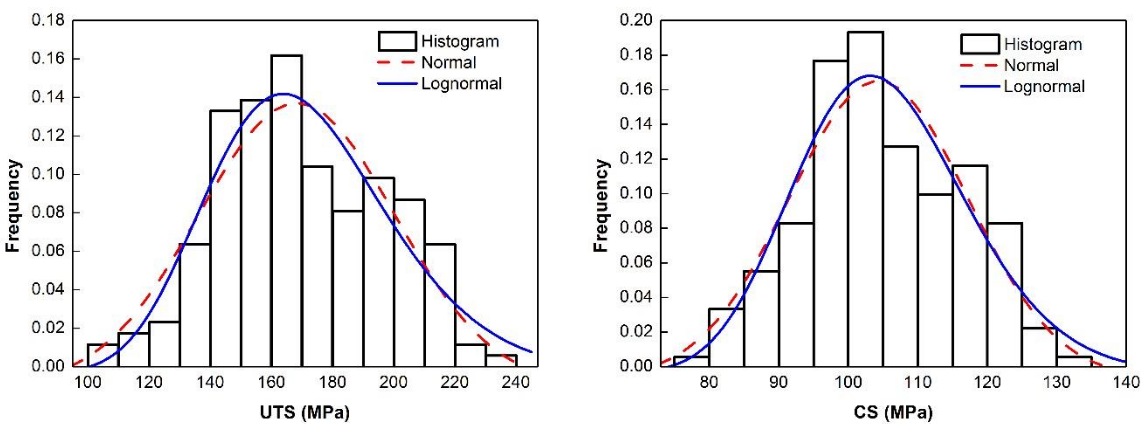

Fig. 2. Lognormal and normal fit of UTS and CS for bamboo scrimber

Table 4. Basic Fitted Parameter of Two Kinds of Distribution

Distribution	Parameter Type	UTS	CS
Normal	Mean value (MPa)	170.65	104.82
	Standard deviation (MPa) COV (%)	26.63 15.61	11.27 10.75
Lognormal	Mean value (MPa)	5.13	4.65
	Standard deviation (MPa) COV (%)	0.16 3.11	0.11 2.37

The results of K-S tests are listed in Table 5. The D values of lognormal distributions for UTS and CS were 0.054 and 0.051, respectively, and both of which were less than the critical value. The lognormal distribution was judged to be a good model for the actual distribution of UTS and CS for bamboo scrimber.

Table 5. Results of Tensile and Compressive Strength using the K-S Test Method

	Distribution	(D value)	Critical value
UTS	Normal	0.058	0.1013
	Lognormal	0.054	
CS	Normal	0.061	0.1033
	Lognormal	0.051	

Chi-squared tests can also assess the proposed models to fit the experimental data. Different critical χ^2-values correspond to different probability levels. For example, at a probability level of 0.05 and 14 data points, the critical χ^2-value is 19.675. If χ^2 <19.675, it is evident that the predicted models provide a good fit for the experimental values. Table 6 indicates that the χ^2-values of normal and lognormal distributions for UTS and CS were less than the critical values. It was evident that both normal and lognormal distribution did provide good fitting results for UTS and CS at a probability level of 0.05. The lognormal distribution also fit the CS experiment data much better than normal distribution. However, results for the UTS were the opposite. In order to assess the more secure strength index, both the normal and lognormal distributions for UTS and CS were selected to calculate the characteristic values in this study.

Table 6. Results of Tensile and Compressive Strength using the Chi-Squared Test

Statistical Values	UTS		CS	
	N	L	N	L
χ^2	14.474	17.505	11.305	10.969
$\chi^2_{0.05}$	19.675		16.919	

Characteristic Values

According to Chinese national standards (GB 50068 (2001)) and ASTM D2915 (2003), the characteristic values of UTS and CS for bamboo scrimber could be estimated at the 5% percentile with 75% confidence. As a lognormal distribution, the calculated characteristic values can be expressed using the following equation:

$$f = e^{\mu_f(1-k\delta_f)} \tag{8}$$

where μ_f is the average value of logarithmic UTS and CS, δ_f is the coefficient of variance (COV) of logarithmic UTS and CS (Table 4), and k is a confidence level factor. Different standards have different k values (k = 1.645 for Chinese national standards and k = 1.727 for ASTM D2915 for the 5% percentile with 75% confidence）.

As a normal distribution, the calculated characteristic values can be expressed as follows,

$$f = \mu_f - ks \tag{9}$$

where μ_f is the average value of UTS and CS, s is the standard deviation of UTS and CS (Table 4), and k is a confidence level factor. The characteristic values of UTS and CS are shown in Table 7.

According to Chinese national standards, the characteristic values of UTS and CS were 126.83 and 86.28 MPa, respectively, corresponding to the normal distribution, which were less than those of lognormal distribution. Meanwhile, there were no significant differences between the calculated characteristic values of UTS and CS using GB 50068 (2001) and ASTM D2915 (2003). This is due to the fact that the confidence level factor k value is not significantly different between GB 50068 (2001) and ASTM D2915 (2003). To consider the security of structures, the f_3 and f_4 values for UTS and CS were selected for calculating the design values.

Table 7. Characteristic Values of UTS and CS according to Different Standards and Distributions

Characteristic Values	UTS (MPa)	CS (MPa)
f_1	129.99	87.24
f_2	128.31	86.46
f_3	126.83	86.28
f_4	124.66	85.35

f_1 and f_2 represent the calculated characteristic values using the Chinese national standards and ASTM D2915 (2003), respectively, corresponding to lognormal distributions. f_3 and f_4 represent the calculated characteristic values using the Chinese national standards and ASTM D2915 (2003), respectively, corresponding to normal distributions.

Design Values

Bamboo scrimber can be used as a biomass composite material in a manner similar to that of glued wood boards. Thus, the design values (f_{3d}) of bamboo scrimber using the Chinese allowable stress design method, and (f_{4d}) using ASTM D2915 (2003) can be calculated according to Eqs. 10 and 11 (Xiao *et al.* 2012),

$$f_{3d} = f_3 \times k_1 \times k_2 \times k_3 \times k_4 / (k_5 \times k_6) \tag{10}$$

$$f_{4d} = f_4 \times k_2 \times k_3 / K \tag{11}$$

where k_1, k_2, k_3, k_4, k_5, and k_6 are adjusting factors representing the long-term load factor, wood defects factor, drying defects factor, concentration stress factor, overload factor, and structural deviation factor, respectively. K represents reduction factors (K = 2.1 for tensile strength and K = 1.9 for compressive strength). The adjusting factors are shown in Table 8.

Table 8. Statistical Parameters of Adjusting Factors (Xiao *et al.* 2012)

Component Type	k_1	k_2	k_3	k_4	k_5	k_6
Tensile parallel to the fiber	0.67	0.46	0.94	0.90	1.20	1.10
Compressive parallel to the fiber	0.67	0.80	1.00	-	1.20	1.10

According to the ASTM D2915 (2003), test specimens are the full sized members, including their wood defects and drying defects, whereas the small clear specimens were used in our study. This had a significant difference on the mechanical properties when compared with the full sized test specimens. Thus, Eq. 12 should to be multiplied by the adjustment factor of k_2 and k_3. The design values of UTS and CS are listed in Table 9. The calculated design values for UTS and CS using ASTM D2915 (2003) were more than those found using the Chinese allowable stress design method. The design values of UTS and CS for bamboo scrimber calculated using the Chinese allowable stress design method were significantly higher than those of wood and other bamboo-based materials. In order to consider the security of structures, it is suggested that the design values of UTS and CS for bamboo scrimber calculated using the Chinese allowable stress design method be 25.05 and 35.04 MPa, respectively. In the future, bamboo scrimber can be applied as a construction material in the structural field.

Table 9. Design Values of UTS and CS according the Different Standards

Materials	Design Values	UTS (MPa)	CS (MPa)
Bamboo scrimber	f_{3d}	25.05	35.04
	f_{4d}	25.67	35.94
Larch	f_{3d}	13.86	16.10
	f_{4d}	13.91	16.44
Masson pine	f_{3d}	11.14	13.45
	f_{4d}	11.12	13.66
Bamboo	f_{3d}	16.19	20.51
	f_{4d}	16.55	21.07
Glubam	f_{3d}	11.00	19.00
	f_{4d}	11.19	19.62

f_{3d} and f_{4d} represent the calculated design values using the Chinese national standards and ASTM D2915 (2003), respectively, corresponding to normal distributions.

CONCLUSIONS

1. The average values of UTS and CS for bamboo scrimber were 170.65 and 104.82 MPa, respectively. The UTS and CS of bamboo scrimber were significantly higher than those of wood, raw bamboo, and other bamboo-based composite materials.
2. Kolmogorov-Smirnov and chi-squared test results indicated that lognormal distribution was a good fit for the UTS and CS, except for the fitting result of UTS by chi-square test.
3. The characteristic values were affected by distribution type. The characteristic values

of UTS and CS calculated using normal distribution were 126.83 and 86.28 MPa, respectively, which were less than the characteristic values of lognormal distribution.

4. The design values were affected by calculation standards. The calculated design values for UTS and CS using the ASTM D2915 (2003) were greater than using the Chinese allowable stress design method. The design values of UTS and CS for bamboo scrimber were significantly higher than those for wood and other bamboo-based materials. In order to consider the security of structures, it is suggested that the design values of UTS and CS for bamboo scrimber calculated using the Chinese allowable stress design method be 25.05 and 35.04 MPa, respectively.

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