Experimental Study on the Shear Strength Parallel to the Fibers of Original Bamboo

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Abstract. Bamboo is a natural material with excellent mechanical properties and environmental benefits. It is susceptible to longitudinal splitting, which can be attributed primarily to its shear behavior parallel to the fibers. However, there is a lack of statistical assessment of the shear stre3ngth. In this study, 124 bamboo tubes were subjected to bowtie tests to determine the shear strength parallel to the fibers of original bamboo. In addition, the distribution, standard value, and design value of shear strength were investigated through statistical analysis. The results indicate that there is no statistically significant difference in shear strength between internode specimens and node specimens, with an average of 17.17 MPa and 17.48 MPa, respectively. The Normal distribution and Log-normal distribution are found to be more suitable for fitting the actual shear strength distribution, while the Weibull distribution exhibits a poor fitting effect. Moreover, the non-parametric method and reliability analysis yield standard and design values of shear strength of 14.91 and 9.47 MPa, respectively.

Keywords: original bamboo; shear strength; experimental study; statistical analysis

1 Introduction

Bamboo is a feasible substitute for steel because of its exceptional mechanical and processing properties [1]. In regions where bamboo is abundant, it is frequently utilized as a readily available building material for constructing single-story houses, simple bridges, and construction platforms [2]. However, bamboo's mechanical properties are anisotropic [3], which may cause longitudinal splitting [4]. This failure mode is common in bolted joint holes, bamboo beams, and even compressed bamboo columns, which limits the application of bamboo as a building material [5]. According to fracture mechanics theory, longitudinal splitting of bamboo is mainly caused by shear parallel to the fibers (type II fracture). To determine the shear strength parallel to the fibers, Janssen [6] proposed the bowtie test, which is now standardized and included in ISO 22157-2019 [7]. Bautista [8] improved the loading device by adding two steel rods to fix the plates, which was widely adopted by subsequent researchers. However, the shear properties parallel to the fibers of original bamboo have received little attention, with most studies focusing on factors affecting shear strength. Deng [9] found that

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bamboo node limit crack development, resulting in slightly higher shear strength of node specimens compared to internode specimens. Previous studies by Meng [10] and Gauss [11] have also examined the shear strength internode specimens of and node specimens, but many of these studies lacked statistical evaluation. In general, existing studies on bamboo rarely provide statistical parameters on the shear properties parallel to the fibers. This hinders the promotion and application of bamboo, particularly in design and standardization. To clarify the shear properties parallel to the fibers of original bamboo, 124 bamboo tubes were subjected to bowtie tests. This study concluded the shear properties parallel to the fibers, statistically quantified the effect of specimen type on shear strength, and explored the distribution, standard and design values of shear strength.

2 Material and Method

In this study, four-year-old moso bamboo was utilized to process test specimens for the bowtie test. According to ISO 22157-2019 [7], two specimen types were employed: internode specimen and node specimen, as illustrated in Figure 1(a)-(b). The test was conducted using an electro-hydraulic servo tester with a loading rate of 0.15 to 0.30 mm/min. The specimen was subjected to compression through two plates, resulting in the bamboo tube being sheared on four planes, as shown in Figure 1(c). At the conclusion of the test, the specimen was visually evaluated to determine whether it had failed due to shearing parallel to the fibers. In the event that this was not the case, the specimen should be discarded.

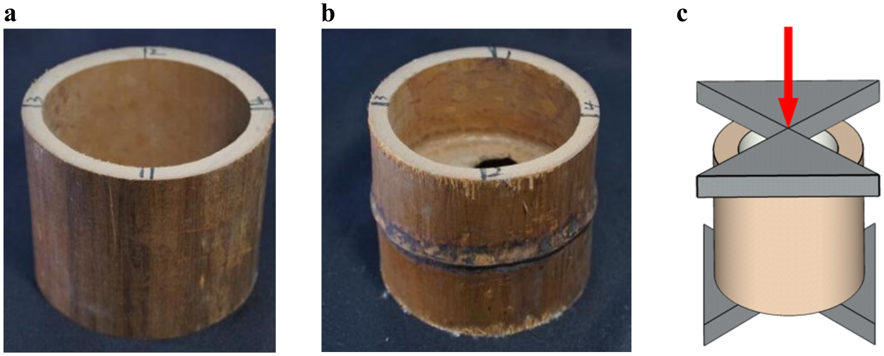

Fig. 1. Test material and method

3 Test Results and Discussion

The study subjecting 124 bamboo tubes to the bowtie test. Six specimens were considered as invalid due to irrelevant damages, leaving a total of 118 valid specimens.

3.1 Phenomena and Failure Modes

The test phenomena observed in the internode and node specimens were essentially identical, with a crack forming at the edge of the shear plane and extending axially. However, the crack in the internode specimens developed more continuously and led to failure more rapidly, whereas the crack in the node specimens was impeded by the bamboo node and remained at the node for a period of time before penetrating.

It was observed that valid specimens were failed by splitting along one or more of the shear planes, as shown in Figure 2. Due to differences in initial defects, processing quality, and geometry, the four shear planes did not reach their limit states at the same time. Consequently, the most common failure mode in this study was single shear plane failure, which occurred in 79.7% of cases.

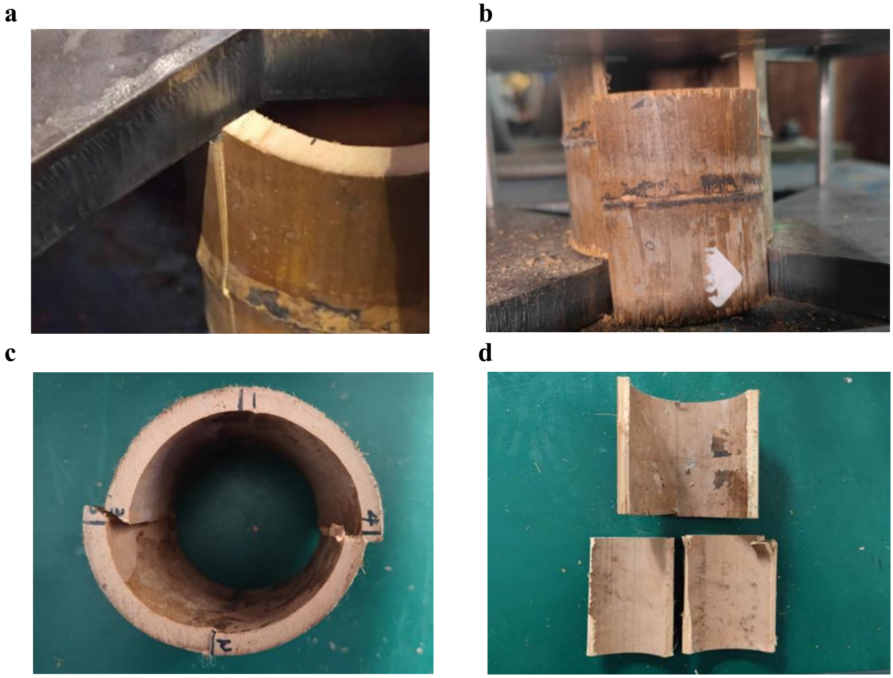

Fig. 2. Failure modes

3.2 Shear Strength Parallel to the Fibers

The shear strength parallel to the fibers (f_v) was calculated according to equation (1) and processed using the interquartile range (IQR) method, which eliminates one outlier data point. Table 1 presents the statistical result for shear strength parallel to the fibers. The mean shear strength parallel to the fibers of internode specimens and node specimens was 17.17 MPa (CV = 7.84%) and 17.48 MPa (CV = 7.32%), respectively. The mean shear strength of node specimens was found to be slightly higher than that of internode specimens, with a more concentrated distribution. This was attributed to the presence of the bamboo diaphragm [10].

$$f_v = \frac{F_{ult}}{\sum Lt} \tag{1}$$

Where, f_{v} is the shear strength parallel to the fibers (MPa); F_{ult} is the destructive load (N); $\sum Lt$ is the sum of the four measured areas at the shear planes (mm).

To quantitatively assess the effect of specimen type on shear strength, the analysis of variance (ANOVA) was employed in this study, as demonstrated in Table 1. The *p*-value of 0.205, which is greater than the significance level of 0.05, indicates that there is no statistically significant difference between the shear strength of internode and node specimens.

Table 1. Statistical result for shear strength parallel to the fiber.

Type	MEAN /MPa	SD /MPa	CV	ANOVA *P*-value	n
Internode specimens	17.17	1.3469	7.84%	0.205	59
Node specimens	17.48	1.2805	7.32%		58

4 Distribution and Design Value of Shear Strength

4.1 Distribution

The shear strength parallel to the fibers was fitted using Normal, Log-normal, and Weibull distributions, as shown in Figure 3. The Normal and Log-normal distribution curves are basically consistent and have similar trends to the frequency distribution histogram. The Weibull distribution curve is positively skewed and its peak does not match the frequency distribution histogram. The K-S and A-D tests were used to evaluate the goodness-of-fit of the three distributions. Table 2 shows the test results, which indicate that the p-values of the Normal and Log-normal distributions are greater than 0.05. However, the p-value of the Weibull distribution is less than 0.05 in the A-D test. The Normal and Log-normal distributions are better at representing the actual distribution of shear strength parallel to the fibers, while the Weibull distribution is less effective.

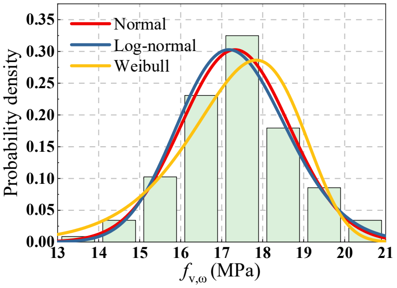

Fig. 3. Distribution of shear strength.

Table 2. Fitting and testing of distributional models

Distribution model	Test method	Evaluation value	*p*-value
Normal	K-S	0.0478	1
	A-D	0.2165	0.8411
Log-normal	K-S	0.0547	0.9802
	A-D	0.2124	0.8516
Weibull	A-D	1.2496	<0.01

Note: The Weibull distribution does not support the K-S test, so it is not listed in the table.

4.2 Design Value

GB 50005-2017 [12] assumes that the actual distribution of strength follows the Normal distribution and determines the standard value of strength by a coefficient of 1.645, without considering the effects of confidence level and sample size. Zhong [13] proposed a method for calculating the standard value based on the 5% quantile value at the 75% confidence level, including parametric and non-parametric methods. Considering the limited sample size of this study, the non-parametric method was employed. The actual strengths of the specimens were arranged in order from smallest to largest, with the strength value corresponding to the serial number (S) considered the standard value. Li [14] provided a formula for calculating the serial number S, as shown in equation (2).

$$S = \frac{0.053n}{1+e^{4r-4.64}} - 2.755r^{5.5} + 0.224 \tag{2}$$

Where, S is the serial number, rounded down when non-integer; r is the confidence level, taken as 0.75; n is the sample size. The serial number (S) was calculated as 4 according to equation (2), while the standard value of shear strength parallel to the fibers (f_k) was established at 14.91 MPa.

The reliability analysis was employed to ascertain the design value of strength:

$$\beta = \frac{K_R\gamma_R(\gamma_G+\gamma_Q\rho)-(K_G+K_Q\rho)}{\sqrt{\left[K_R\gamma_R(\gamma_G+\gamma_Q\rho)\delta_R\right]^2+(K_G\delta_G)^2+(K_Q\rho\delta_Q)^2}} \tag{3}$$

$$f_d = \frac{f_k K_D}{\gamma_R} \tag{4}$$

Where, β is the reliability index; γ_R is the resistance component coefficient; γ_G is the permanent load component coefficient, taken as 1.2; γ_Q is the variable load component coefficient, taken as 1.4; K_G is the permanent load uncertainty coefficient; K_Q is the variable load uncertainty coefficients; δ_G is the permanent load variation coefficient; δ_Q

is the variable load variation coefficients; f_d is the design value of shear strength parallel to the fibers; KD is the long-term load effect coefficient, taken as 0.72.

In accordance with the recommendations set forth by Zhu [15], the strength design values were calculated using the load combinations of constant loads, office floor live loads, and a load impact ratio (ρ) of 1. The structural resistance and load were quantified in accordance with GB 50005-2017 [12], as shown in Table 3.

Table 3. Statistical parameters for the reliability analysis.

K_R	δ_R	K_G	δ_G	K_Q	δ_Q
1.080	0.096	1.060	0.070	0.524	0.288

According to GB 50068-2018 [16], the reliability index (β) was determined to be 3.7 due to the brittle failure caused by shear parallel to the fibers of the original bamboo. The design value of shear strength parallel to the fibers (f_d) was calculated to be 9.47 MPa using equation (4).

5 Conclusion

In this study, 124 bamboo tubes were subjected to bowtie tests to determine the shear strength parallel to the fibers of original bamboo and statistically analyze. The main conclusions are as follows:

(1) The analysis of variance (ANOVA) reveals that there is no statistically significant difference in the shear strength of internode and node specimens. However, further study is required to elucidate the effect of the bamboo diaphragm and node.

(2) The K-S and A-D tests indicate that the actual shear strength distribution follows the Normal and Log-normal distribution, but not the Weibull distribution.

(3) According to the non-parametric method and reliability analysis, the standard and design values of shear strength are obtained as 14.91 and 9.47 MPa, respectively.

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