Design Value of Tensile Strength of Raw Bamboo

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Bamboo has the advantages of a short growth cycle, good mechanical properties, energy savings, and environmental protection. It is regarded as a new building material with great development potential and application prospects. However, current research on the design values of raw bamboo materials is lacking. In this study, the design value of tensile strength of raw bamboo material was determined by a tensile test of the raw bamboo material, and the statistical values of the tensile strength and elastic modulus of the raw bamboo material were obtained. The standard value and resistance uncertainty statistical parameters of the tensile strength of the raw bamboo material were determined. Considering different load combinations and load effect ratios, the relationship between the reliability index and the resistance component coefficient and the optimal resistance partial coefficient under different load combinations were obtained, and the design value of the tensile strength of the raw bamboo material was obtained.

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Keywords: Raw bamboo material; Longitudinal tensile strength; Resistance component coefficient; Design strength

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INTRODUCTION

The construction industry has made great contributions to the economic growth of every country, especially developing countries, where the demand for housing and other activities is increasing day by day (Anaman and Osei-Amponsah 2007). Traditional building materials can no longer meet the requirements of sustainable development (Guan *et al.* 2022; Bala and Gupta 2023). Bamboo is a natural composite material with a fast growth rate, which can be formed in about 3 years (Kuang *et al.* 2022). In addition, bamboo is cheap and widely distributed around the world. Due to industrialization and urbanization, natural aggregates used in construction are gradually becoming depleted. Therefore, the development of sustainable building materials (such as bamboo) and recyclable building resources is necessary.

There have been recent achievements in the study of bamboo. Zhou *et al.* (2022) studied the stress-strain relationship of raw bamboo, grouped bamboo based on density, and proposed a stress-strain constitutive model of raw bamboo. Liu *et al.* (2022) analyzed the relationship between the mechanical properties of bamboo and its height and proposed a prediction model for the mechanical properties of bamboo. Zhou *et al.* (2023) developed a new type of raw bamboo-phosphogypsum composite floor, carried out experimental research and theoretical analysis on the composite floor, explored the failure mechanism of the composite floor, and put forward the design calculation method of the composite floor. Tian *et al.* (2019) carried out experimental research on sprayed lightweight composite mortar-original bamboo composite beams, analyzed the failure mechanism of composite beams, studied the influence of parameters on the mechanical properties of composite beams, and put forward a theoretical calculation method. In addition, in the past few decades, bamboo has been more and more applied in developing countries by virtue of its flexibility and earthquake resistance (Lv *et al.* 2019). Research and applications of bamboo in the world have been continuously enriched (Huang *et al.* 2017; Huang and Sun 2021; Donini *et al.* 2022; Manandhar *et al.* 2023). The research cited above shows that bamboo has good mechanical properties and can be used in low-cost assembly construction of buildings, but the research needs to be further systematic and in-depth, and research on the design value of raw bamboo's material strength has been rarely conducted.

In this paper, the longitudinal tensile test of raw bamboo material was carried out, and its standard strength value and uncertainty statistical parameters were obtained through statistical analysis of the test data. Considering different load combinations and load effect ratio, the resistance component coefficient of bamboo to meet the reliability requirements under different load combinations was obtained, and the design value of strength was further derived by solving the optimal resistance component coefficient. This research has the potential to provide reference for further improving the design method of bamboo structures.

EXPERIMENTAL

According to JG/T199-2007 (2007), "Test Method for Physical and Mechanical Properties of Bamboo for Construction," the longitudinal tensile test of raw bamboo materials was carried out. The raw bamboo used in the experiment was moso bamboo, which was collected from Hunan Province, China, in winter. The material diameter class was 95 to 115 mm. After sawing, drying, grinding, and other processes, it was processed into longitudinal tensile specimens with dimensions of 330 mm × 15 mm × t mm and effective segment size of 60 mm × 4 mm × *t* mm (Fig. 1), where *t* refers to the thickness (mm). The number of specimens was 320. After removing the unqualified specimens, a universal testing machine was used to load the specimens with a loading rate of 0.01 mm/s, referring to the standard JG/T199-2007 (2007). After the end of the test, the sample for the determination of moisture content was taken from the damaged part immediately, and the moisture content of bamboo was tested by referring to JG/T199-2007 (2007).

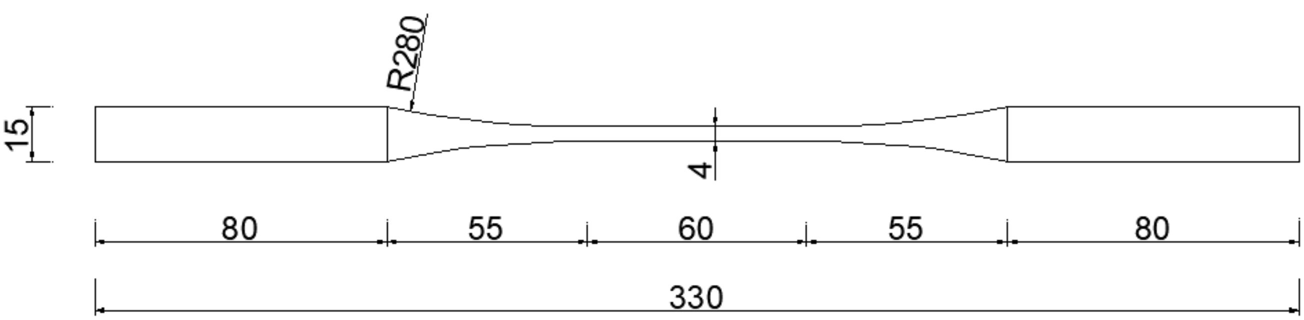


Fig. 1. Standard size of longitudinal tensile specimen of raw bamboo material

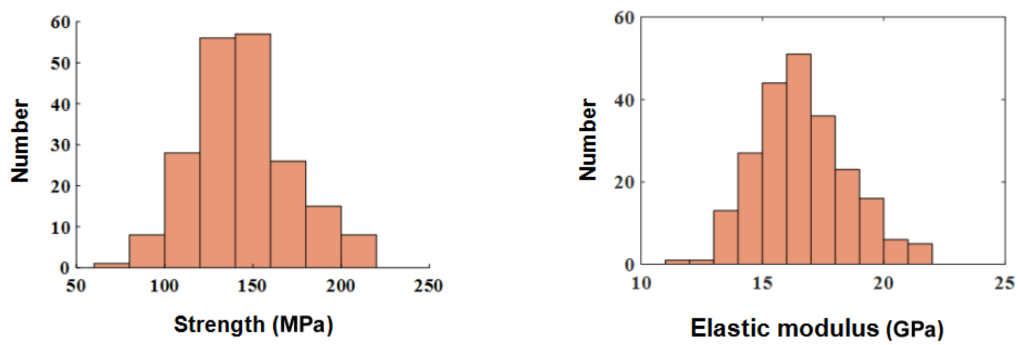
RESULTS AND DISCUSSION

Experimental Results

The average moisture content of bamboo measured in this paper was 15%. Due to the significant influence of moisture content on the strength test results of raw bamboo material, the reference point of moisture content should be determined first when calculating the strength design value of raw bamboo material from the test value. The standard JG/T199-2007 (2007) specifies 12% as the reference point for moisture content of raw bamboo materials. Therefore, in the drying process of raw bamboo materials, the moisture content was 12% as the standard point. After adjustment, the longitudinal tensile strength and elastic modulus of the raw bamboo material are shown in Table 1, and the statistical distribution is shown in Fig. 2.

Table 1. Statistical Results of Longitudinal Tensile Test of Raw Bamboo Materials

	Number	Mean Value	Standard Deviation	Coefficient of Variation
Strength	320	144.810 MPa	35.502 MPa	0.245
Elastic modulus	320	16.592 GPa	2.550 GPa	0.154
Moisture content	320	15%	0.23%	0.101
Thickness (*t*)	320	10.56 mm	1.96 mm	0.186



(a) Strength **(b)** Elastic modulus

Fig. 2. Histogram of tensile strength and elastic modulus distribution of raw bamboo

Resistance Component Coefficient

Strength standard value

The standard value of tensile strength of bamboo material is a strength index that reflects the characteristics of bamboo material itself. Generally, the strength value corresponding to the 5% quantile value under 75% confidence is defined as the standard value of the material, and the methods adopted mainly include parametric method and non-parametric method (Zhong *et al.* 2018). The accumulated basic data of raw bamboo materials is small, and the use of parameter method to predict the standard value of its strength will lead to distortion in the probability distribution model, especially the low quantile value (Zhong *et al.* 2018). Therefore, the standard value of longitudinal tensile strength of the raw bamboo material was obtained by using the non-parametric method, and the obtained standard value was 86.4 MPa.

The uncertainty of material properties

The uncertainty of material properties of structural components mainly refers to the variability of material properties in the structure caused by material factors, processing technology, loading method, and environmental conditions. The material properties of structural members mainly include physical and mechanical properties such as strength, elastic modulus, and Poisson ratio. For the material properties of structural members, it is necessary to further consider the difference between the actual performance of the material and the performance of the standard specimen and the difference between the actual working conditions and the standard test conditions. The mean value $\mu_{\Omega f}$ and coefficient of variation $\delta_{\Omega f}$ of the material property uncertainty Ω_f are,

$$\mu_{\Omega_f} = \frac{\mu_{\Omega_0}\mu_{\Omega_1}}{\omega_0} = \frac{\mu_{\Omega_0}\mu_{f_t}}{\omega_0 f_k} \tag{1}$$

$$\delta_{\Omega_f} = \sqrt{\delta_{\Omega_0}^2 + \delta_{f_t}^2} \tag{2}$$

where μ_{f_t}, μ_{Ω_0} and μ_{Ω_1} are the average values of the material properties of the specimen (f_t) and the average values of the random variables Ω_0 and Ω_1 respectively; δ_{f_t} and δ_{Ω_0} are the coefficient of variation of sample material properties and the coefficient of variation of random variable Ω_0, respectively. ω_0 is the coefficient that reflects the difference between the material properties of structural members and the material properties of specimens stipulated in the code; f_k is the standard value of material properties.

At present, there is a lack of relevant literature on the difference between the mechanical properties of bamboo structural materials and the actual structure. For the samples taken from the same batch of bamboo, this study considers their mechanical properties to be the same as the actual structure, so $\omega_0 = 1$, $\mu_{\Omega_0} = 1$, $\delta_{\Omega_0} = 0$. Based on the average longitudinal tensile strength μ_{f_t}=144.81 MPa, standard value f_k=86.413 MPa and coefficient of variation δ_{f_t}=0.245, the mean value of material uncertainty $\mu_{\Omega f}$=1.676 and coefficient of variation $\delta_{\Omega f}$=0.245 were obtained by substituting the data into Eqs. 1 and 2.

The uncertainty of geometric parameters

The uncertainty of geometrical parameters of structural members mainly refers to the variability of geometrical parameters of structural members caused by fabrication size deviation and installation error. According to the degree of influence on the resistance of structural members, general members can only consider the variation of section geometric parameters. The relationship between the mean value μ_{Ω_a} and the coefficient of variation δ_{Ω_a} of the uncertainty of the geometric parameters of structural members are Ω_a as follows,

$$\mu_{\Omega_a} = \frac{\mu_a}{a_k} \tag{3}$$

$$\delta_{\Omega_a} = \delta_a \tag{4}$$

where a_k, μ_a and δ_a are the standard value, average value, and coefficient of variation of the geometric parameters of the structural members respectively.

According to the statistical analysis of the stress area of the longitudinal tensile specimen of the original bamboo material, the standard width of the stress surface of the specimen is a_k=4 mm, the measured value is μ_a=3.53 mm, and the coefficient of variation is δ_a=0.089. The mean value was obtained as μ_{Ω_a} =0.882 and that coefficient of variation was δ_{Ω_a} =0.089. Thus, uncertainty Ω_a of the geometric parameters of the longitudinal tensile specimen of the original bamboo material were obtained.

The uncertainty of the calculation model

The uncertainty of structural member calculation mode mainly refers to the variability caused by the basic assumption and the inaccuracy of calculation formula. With reference to the statistical parameters of wood structure members (Zhu *et al.* 2017), the uncertainty of calculation model is given by μ_{Ω_A} =1.0, δ_{Ω_A} =0.05.

The statistical parameters of resistance uncertainty

Considering material property uncertainty, geometric parameter uncertainty, and calculation mode uncertainty, the resistance expression of structural members is as follows:

$$R = \Omega_A \Omega_f \Omega_a \tag{5}$$

The standard value of resistance of the structural members is:

$$R_{\mathrm{k}} = \omega_0 f_k a_k \tag{6}$$

According to the operation method of statistical parameters of random variable function, the mean value μ_{R} and coefficient of variation δ_{R} of structural member resistance are respectively:

$$\mu_R = \mu_{\Omega_A} \mu_{\Omega_f} \mu_{\Omega_a} R_k \tag{7}$$

$$\delta_R = \sqrt{\delta_{\Omega_A}^2 + \delta_{\Omega_f}^2 + \delta_{\Omega_a}^2} \tag{8}$$

The resistance uncertainty is:

$$K_R = \frac{\mu_R}{R_{\mathrm{k}}} = \mu_{\Omega_A} \mu_{\Omega_f} \mu_{\Omega_a} \tag{9}$$

Based on the above analysis, the structural resistance uncertainty parameters of bamboo longitudinal tensile resistance can be obtained, as shown in Table 2.

Table 2. Statistical Parameters of Raw Bamboo Material Resistance

	Uncertainty of Material Properties		Uncertainty of Geometric Parameters		Uncertainty of the Calculation Model		Resistance Uncertainty	
	μ_{Ω_f}	δ_{Ω_f}	μ_{Ω_a}	δ_{Ω_a}	μ_{Ω_A}	δ_{Ω_A}	K_R	δ_R
Value	1.676	0.245	0.882	0.089	1.0	0.05	1.478	0.265

According to GB 50009-2012 (2012) "Load Code for Building Structures" and GBJ 68-84 (1984) "Uniform Standard for Design of Building Structures," seven load combinations were considered. These included constant load + continuous office floor live load ($D + R_{a1}$), constant load + continuous residential floor live load ($D + R_{b1}$), constant load + temporary office floor live load ($D + R_{a1}$), constant load + temporary residential floor live load ($D + R_{b1}$), constant load + wind load that is not based on the direction of wind ($D + Q_{w1}$), constant load + wind load based on the direction of the wind ($D + Q_{w2}$), and constant load + snow load ($D + Q_s$). The maximum load in the base period is used for the calculation. The load uncertainty coefficient K and variation coefficient δ of bamboo under different load combinations are shown in Table 3, where the load uncertainty coefficient K is the average load/standard value.

Table 3. Load Statistical Parameters

Para-meters	Constant Load	Sustained Office Floor Live Load	Continuous Residential Floor Live Load	Temp. Office Floor Live Load	Temp. Residential Floor Live Load	Wind Load not based on Direction of Wind	Wind load Based on the Direction of Wind	Snow Load
K	1.060	0.406	0.471	0.441	0.523	1.109	0.999	1.139
δ	0.070	0.292	0.229	0.369	0.322	0.193	0.193	0.225

Determination of the resistance component coefficient

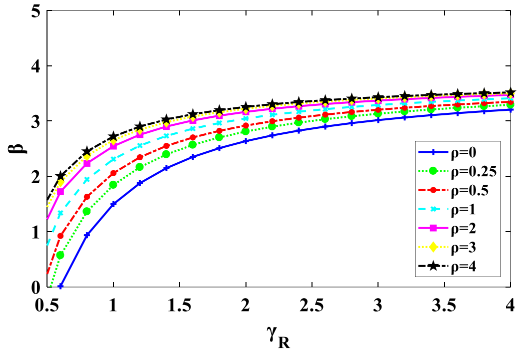
When determining the resistance component coefficient of bamboo γ_R, it is necessary to consider the ratio of load effect to ρ and the ratio of variable load effect to permanent load effect S_Q/S_G. The load effect ratio ρ of 0, 0.25, 0.5, 1.0, 2.0, 3.0, 4.0, and other seven cases were considered respectively, where ρ=0 represents the single action of constant load. When calculating the subcoefficient of resistance, the structural safety grade was considered according to the second level, the design base life was considered according to 50 years, and the structural importance coefficient corresponding to the design service life of the specific bamboo structure was reduced accordingly when in use, and the structural importance coefficient was determined according to the safety grade and design service life of the structure.

According to the failure limit state equation of bearing capacity Z=R-S=0, the relationship between the target reliability index and the resistance component coefficient was derived by the central point method, as shown in Eq. 10, in which the default load effect and resistance component coefficient are independent normal random variables,

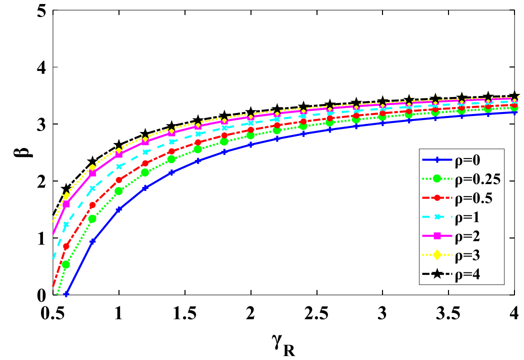
$$\beta = \frac{K_R\gamma_R(\gamma_G + \gamma_Q\rho) - (K_G + K_Q\rho)}{\sqrt{[K_R\gamma_R(\gamma_G + \gamma_Q\rho)\delta_R]^2 + (K_G\delta_G)^2 + (K_Q\rho\delta_Q)^2}} \tag{10}$$

where γ_R is the partial coefficient of resistance and γ_G and γ_Q are the partial coefficients of permanent load and variable load. The parameters K_G and δ_G are uncertainty coefficient and variation coefficient of permanent load. K_Q and δ_Q are variable load uncertainty coefficients and variation coefficients. ρ is the ratio of the variable load to the standard value of the permanent load effect. The partial coefficients of permanent load γ_G and variable load γ_Q are respectively 1.2 and 1.4.

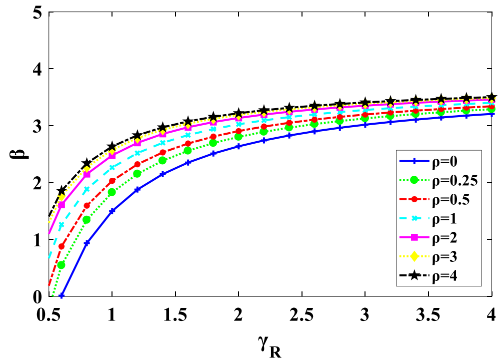
Considering the influence of load combination and load effect ratio ρ comprehensively, the relationship curves between reliability index β and resistance component coefficient γ_R are obtained, as shown in Fig. 3.



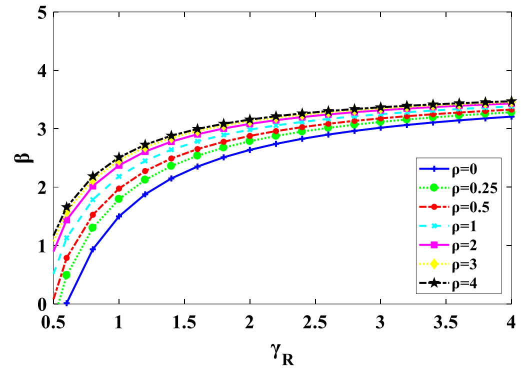
(a) D+R_{a1}



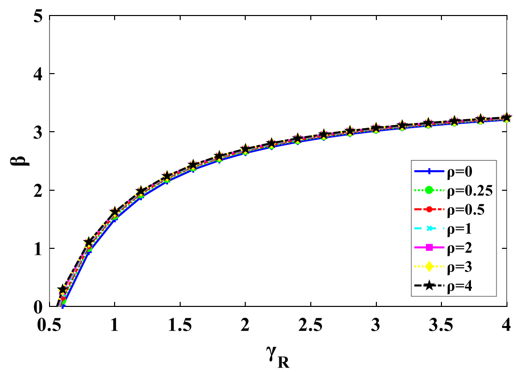
(b) D+R_{b1}



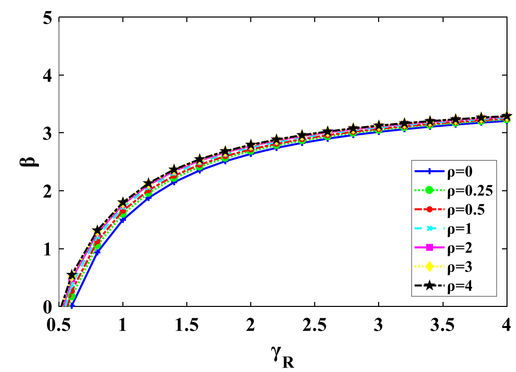
(c) D+R_{a2}



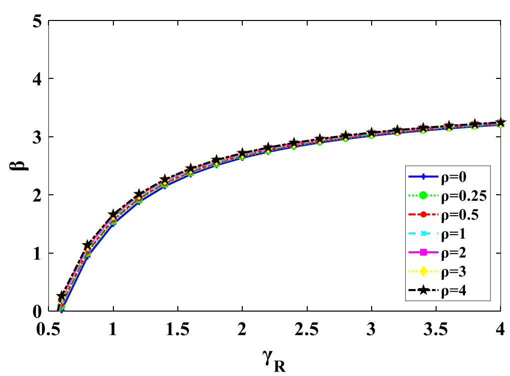
(d) D+R_{b2}



(e) D+Q_{w1}



(f) D+Q_{w2}



(g) D+Q_s

Fig. 3. Relationship between β and γ_R under different load combination types and different load ratios

China's national standard GB50068 (2001) "Unified Design Standard for the Reliability of Building Structures" stipulates that the reliability index β under the bearing capacity limit state of structural members during the design service life is determined by the safety grade of building structures and the damage nature of the members, and the reliability index β should not be lower than the provisions in Table 4.

Table 4. Reliable Indicators of the Limit State of the Bearing Capacity of Structural Members

Failure Type	Reliability Index β		
	Safety Level Ⅰ	Safety Level II	Safety Level Ⅲ
Ductile failure	3.7	3.2	2.7
Brittle failure	4.2	3.7	3.2

The longitudinal tensile failure of raw bamboo material belongs to ductile failure, and its target reliability β_0 is 3.2. The resistance component coefficient γ_{Ri} under different load effect combinations and ratios are shown in Table 5. As can be seen from the table, the sub-coefficient of resistance gradually decreased with the increase of load effect ratio under target reliability. When the load effect ratio was 0 (that is, there was only dead load action), the subcoefficient of resistance of all load combinations was equal. Under the same load effect coefficient, $D+Q_S$ load combination had the largest component coefficient of corresponding resistance.

Table 5. Resistance Component Coefficient Under Various Load Effect Combinations and Ratios of Raw Bamboo Materials

ρ	γ_{Ri}						
	$D+R_{a1}$	$D+R_{b1}$	$D+R_{a2}$	$D+R_{b2}$	$D+Q_{w1}$	$D+Q_{w2}$	$D+Q_s$
0	3.953	3.953	3.953	3.953	3.953	3.953	3.953
0.25	3.352	3.398	3.379	3.438	3.859	3.779	3.883
0.5	2.976	3.051	3.022	3.118	3.807	3.676	3.848
1	2.532	2.640	2.604	2.745	3.752	3.559	3.816
2	2.117	2.255	2.219	2.401	3.706	3.455	3.796
3	1.921	2.072	2.039	2.240	3.687	3.407	3.789
4	1.807	1.966	1.936	2.148	3.677	3.380	3.786

A set of optimal resistance component coefficients was determined to minimize the error between the reliability index of the member and the specified reliability index in various load effect ratios. The expression is as follows,

$$H = \sum_{i=1}^{n} [\gamma_{R_i}(\gamma_G E_{GK_i} + \gamma_Q E_{QK_i}) - \gamma_R(\gamma_G E_{GK_i} + \gamma_Q E_{QK_i})]^2 \quad (11)$$

where H is the sum of error squares; E_{G_k} and E_{Q_k} are the standard values of permanent load and variable load; and γ_{R_i} is the resistance component coefficient under the ratio of the i load effect. The optimal resistance component coefficient of the bamboo should satisfy the condition that the sum of squares of error of Eq. 11, where H is the minimum, and the optimal resistance component coefficient of the bamboo is determined accordingly, as shown in Table 6.

Table 6. The Optimal Resistance Component Coefficient Under Various Load Effect Combinations of Raw Bamboo Materials

Load Combination	D+R_{a1}	D+R_{b1}	D+R_{a2}	D+R_{b2}	D+Q_{w1}	D+Q_{w2}	D+Q_s
γ_R	2.27	2.39	2.37	2.54	3.73	3.50	3.81

Determination of Design Value of Tensile Strength

Based on the limit state design method of reliability, the formula for calculating the strength design value f_d of structural bamboo is as follows,

$$f_d = \frac{f_k K_D}{\gamma_R} \tag{12}$$

where f_k is the standard value of bamboo tensile strength; K_D is the long-term load effect coefficient, 0.72 according to GB50005-2003 (2003) "Code for Design of Wood Structures"; and γ_R is the resistance component coefficient of bamboo, as shown in Table 6.

When the standard value of tensile strength of bamboo and the optimal resistance component coefficient are known, the design value of the longitudinal tensile strength of raw bamboo material under various load combinations is obtained by using Eq. 12, as shown in Table 7.

Table 7. Strength Design Values of Raw Bamboo Material

Load Combination	D+R_{a1}	D+R_{b1}	D+R_{a2}	D+R_{b2}	D+Q_{w1}	D+Q_{w2}	D+Q_s
f_d (MPa)	27.372	25.989	26.263	24.543	16.684	17.787	16.321

CONCLUSIONS

1. The longitudinal tensile test of the raw bamboo material was carried out, and the data were statistically analyzed. The standard tensile strength and elastic modulus of the raw bamboo material were 86.4 MPa and 16.6 GPa.
2. The properties uncertainty, geometric parameter uncertainty, and calculation model uncertainty of raw bamboo were obtained by statistical analysis, and the resistance uncertainty was derived. Considering different load combinations and load effect ratio, the relationship between reliability index and sub-coefficient of resistance was obtained, and the optimal sub-coefficient of resistance under different load combinations was further obtained.
3. The design values of longitudinal tensile strength of raw bamboo materials under seven load combinations of constant load + continuous office floor live load, constant load + continuous residential floor live load, constant load + temporary office floor live load, constant load + temporary residential floor live load, constant load + wind direction wind load, constant load + not wind direction wind load and constant load + snow load were determined, respectively, as: 27.4, 26.0, 26.3, 24.5, 16.7, 17.8, and 16.3 MPa.

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