Improved Method to Determine Standard Values of Mechanical Properties of Original Bamboo

Jianwei Li, Pengcheng Liu,* Haodi Chen, and Fangjie Cheng

The standard values of mechanical properties are important performance indexes of original bamboo as a sustainable building material. Such values should be determined by combining the requirement of confidence level and the number of samples. In this paper, systematic tests of longitudinal compression, bending, longitudinal tensile, longitudinal shear, transverse compression, and transverse tensile of bamboo were performed. Based on parametric and non-parametric methods, the influencing factors of the standard values of mechanical properties of bamboo were analyzed. A calculation method and prediction formulas were proposed and the standard values of mechanical properties of bamboo were determined. The results show that the choice of parametric method to calculate the standard value of bamboo strength in the case of a small number of samples may lead to distortion of the results, and the use of non-parametric analysis can effectively reduce the error.

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*Contact information: School of Civil Engineering, Central South University, Changsha 410075, China; *Corresponding author: pengchengliuwork@163.com*

INTRODUCTION

Bamboo is a natural, green, renewable material that can be an ideal building component. Bamboo has a wide distribution range, many varieties, and is rich in resources. China is the most developed country in the bamboo industry and its bamboo planting area and bamboo product production rank first in the world. Bamboo has a close connection with Chinese culture and people's life. Bamboo is found everywhere, in clothing, food, housing, transportation, history, and culture. With its excellent mechanical properties, bamboo is known as "plant reinforcement" and "ultimate green material" and is an ideal green building material (Sun *et al.* 2019; Tian *et al.* 2019a; Dauletbek *et al.* 2023; Zhou *et al.* 2023). At present, industrial bamboo building products have been developed, including cladding materials (Von Seidlein *et al.* 2017), bamboo plywood (Li *et al.* 2019), bamboo laminate (Guan *et al.* 2022b), bamboo fiberboard (Shi *et al.* 2023), bamboo scrap board (Guan *et al.* 2022a), bamboo decorative materials (Chen *et al.* 2019), *etc*.

In 1984, a bamboo building (Fig. 1a) combining traditional Chinese construction techniques with modern science and technology was exhibited in Zurich, Switzerland. The building area was about 1200 m^2, meeting the requirement load of 300 kN/m^2 (Yang 2014). In 2008, the "Green School" (Fig. 1b) was built in Bali, Indonesia. The campus not only has the largest bamboo building complex in the world, but also adopts the green energy system for supporting facilities (Landwehr and Bambú 2016).

The German-Chinese Pavilion at the 2010 Shanghai World Expo (Fig. 1c) is a two-story building with original bamboo and bamboo laminated timber (Markus and Liu 2013), which has become a typical project symbolizing German-Chinese friendship. In 2011, the pure original bamboo bird wing structure (Fig. 1d) in Vinh Phuk Province, Vietnam was awarded the International Architecture Award by the Science Museum of Chicago as a typical example of eco-green architecture (Tian *et al.* 2019b).

In 2019, the bamboo and rattan pavilion of Beijing International Horticultural Exposition (Fig. 1e) adopted the original bamboo arch architecture system, with the span of bamboo arch reaching 32 m, which is the largest non-fulcrum arch of original bamboo architecture in northern China (Su *et al.* 2020). In 2021, the original bamboo building (Fig. 1f) of Baizhi Mountain Tourist Reception Center in Zunyi, Guizhou, developed by China Metallurgical Construction Engineering Group, was completed. The scale of the project is 1000 m^2, the span is 28 m, and the height is 15 m. Under the background of the strategic goal of “carbon peak and carbon neutrality” stated by the Chinese government, ten departments of China have presented opinions on accelerating the innovation and development of the bamboo industry. Under the condition of satisfying the quality and safety, bamboo structure building and bamboo building materials should be gradually promoted.

For wood used in construction, the strength standard value is usually selected to determine its strength grade. Therefore, the reasonable determination of the standard value of structural wood strength is one of the keys to its reliable application in building structures.

The Chinese standard “Specification for Wood Structure Design” (GB 50005 2017) does not mention any method of obtaining values and formulas used to predict standard values of bamboo mechanical properties. It is assumed that the index values of mechanical properties obey a normal distribution, and that the calculation coefficient of standard values is uniformly stipulated as 1.645. This method has major disadvantages. Not only does it not consider the confidence level, but also ignores the influence of the number of samples on the results, which may lead to a large error in the results.

At present, other national specifications (ASTM D2915-17; EN 1058-2009) all take 5% quantile value under 75% confidence level as their standard strength value, and the methods to determine it include parametric and non-parametric methods. The key of parameter method analysis is to determine the calculation coefficient of standard value according to the number of samples. The key to non-parametric analysis is to determine the sampling sequence number of the standard value according to the number of samples. Based on three probability distribution models, this study derived the calculation formula of the standard value of bamboo, respectively, based on the parametric method and non-parametric method. Additionally, it provided the value requirements of the value coefficient of the standard value (parametric method) and the sampling sequence number of the standard value (non-parametric method) under different strength variation coefficient, sample number, and confidence level. The calculation method of strength standard value proposed in this paper can provide reference for material analysis and structural design.

Fig. 1. Application of original bamboo structures: (a) The Zulli Bamboo Tower in Switzerland; (b) Green School, Bali, Indonesia; (c) German-Chinese pavilions at the Shanghai World Expo; (d) Vietnamese bird-winged bamboo structure; (e) Bamboo and rattan Pavilion of Beijing World Horticultural Exhibition; (f) Baizhi Mountain Tourist Reception Center

EXPERIMENTAL

Materials and Test Methods

The bamboo species considered in this paper is *P. edulis* bamboo, which was collected from Hunan Province, China. The bamboo was 3 to 4 years old, and the average moisture content was approximately 11%. Multiple mechanical properties tests were performed on the bamboo with reference to JG/T199-2007 (2007) and ISO 22157-1-2019 (2019), and the following mechanical properties were obtained: longitudinal compressive strength (UCS), longitudinal compressive elastic modulus (UCE), bending strength (MOR), bending elastic modulus (MOE), longitudinal tensile strength (UTS), longitudinal tensile elastic modulus (UTE), longitudinal shear strength (USS), transverse compressive strength (CCS), and transverse tensile strength (CTS).

The design of the specimens is shown in Table 1 and Fig. 2. The size ratio H/D (height/diameter) of the longitudinal compression and longitudinal shear specimens was 1, and the loading rate was 0.01 mm/s.

The bending specimen size was 220 mm × 15 mm × t mm (t refers to the wall thickness), and the loading rate was 150 N/mm^2 per minute. The size of the longitudinal tensile specimen was 330 mm × 15 mm × t mm, and the tensile rate was 0.01 mm/s. The size of the transverse compressive specimen was 15 mm × 15 mm × t mm, and the compressive rate was 20 N/mm^2/min. The length of the transverse tensile specimen was 100 mm, and the tensile rate was 0.005 mm/s. And the mechanical properties were calculated using Eqs. 1 through 4,

$$f_{\mathrm{W}} = \frac{P_{\max}}{A} \tag{1}$$

$$E_{\mathrm{W}} = \frac{20\Delta P}{A\Delta l} \tag{2}$$

$$MOR_{W} = \frac{150P_{\max}}{tb^2} \tag{3}$$

$$MOE_{W} = \frac{1920000\Delta P}{8\delta_m tb^3} \tag{4}$$

where f_{W} is the strength of the specimen under the moisture content W with UCS, USS, UTS, CCS, and CTS (MPa). E_{W} is the elastic modulus along the grain direction under the moisture content W (MPa); MOR_{W} is the flexural strength under the moisture content W (MPa); MOE_{W} is the flexural elastic modulus under the moisture content W (MPa); $P_{\max}$ is failure load (N); A is the force area (mm^2); t is the thickness of the specimen (mm); b is the height of the specimen (mm); ΔP is the difference between upper and lower loads (N); Δl is the difference between the deformation value of the specimen under the upper and lower loads (mm); and δ_{m} is the pure deflection of the specimen under the action of ΔP (mm).

Table 1. Test Specimen Design

	Number of specimens	Specimen size	Rate of loading
UCS	321	height/diameter=1	0.01 mm/s
UCE	314	height/diameter=1	0.01 mm/s
MOR	171	220 mm × 15 mm × t mm	150 N/mm^2/min
MOE	167	220 mm × 15 mm × t mm	150 N/mm^2/min
UTS	307	330 mm × 15 mm × t mm	0.01 mm/s
UTE	325	330 mm × 15 mm × t mm	0.01 mm/s
USS	216	height/diameter=1	0.01 mm/s
CCS	292	15 mm × 15 mm × t mm	20 N/mm^2/min
CTS	120	length is 100 mm	0.005 mm/s

Note: In the table, t refers to the wall thickness.

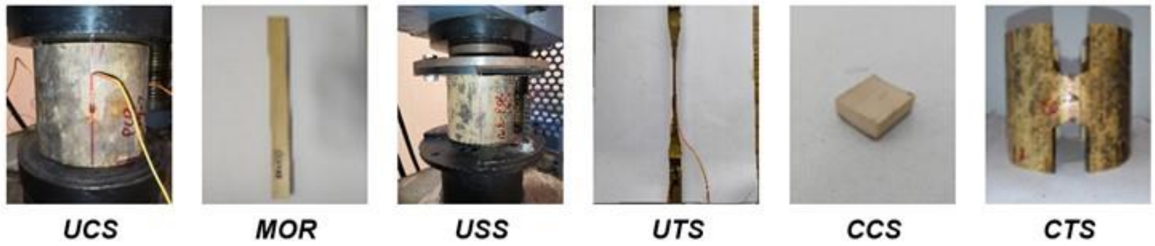


Fig. 2. Specimen preparation

After the failure of the specimen, the small specimen was immediately cut off at the failure site for the determination of moisture content. Equation 5 is the calculation method of moisture content. The mechanical properties of bamboo were adjusted to the values under the standard moisture content (12%), and the calculation formula is Eq. 6,

$$W = \frac{m_1 - m_0}{m_0} \times 100 \tag{5}$$

$$M_{12} = K_{\mathrm{W}} M_{\mathrm{W}} \tag{6}$$

where W is the air-dried moisture content (%); m_1 and m_0 are the mass of air dry and full dry, respectively (g); M_{12} is the strength or elastic modulus of the specimen under the standard moisture content (12%); M_{W} is the strength or elastic modulus of the specimen when the moisture content is W; and K_{W} is the moisture content correction factor.

The Calculation of Confidence of Standard Value under Parameter Method

Under the parameter method, the calculation coefficient K of the standard value of the mechanical properties of bamboo has nothing to do with the true mean value of the material (Zhong *et al*. 2018). Using MATLAB (MathWorks, R2022a, U.S.) programming, suppose the mean value of mechanical properties μ = 200 MPa, the range of coefficient of variation Cv is [0.05, 0.5], and the range of standard deviation δ is [10 MPa, 100 MPa]. The 5% quantile value P of the original bamboo strength sample data can be calculated according to the mean μ, standard deviation δ, and probability distribution model. First, it is assumed that the mechanical properties of bamboo obey the Normal distribution, Lognormal distribution, or 2-P-Weibull distribution, and a random sequence of columns I and rows J is generated according to the assumed μ and δ, where I = 10000. Assume that the mean value of each column of the resulting matrix is μ_i and the standard deviation is δ_i. If the calculation coefficient of the standard value is K, the standard value X_i of the mechanical properties of original bamboo can be calculated according to the following Eq. 7,

$$X_{\mathrm{i}} = \mu_{\mathrm{i}} - K\delta_{\mathrm{i}} \tag{7}$$

Compare the X_i of each column with the 5% percentile value P, and if the value of column Z is not greater than P, the confidence level r for the calculation coefficient K is calculated as follows:

$$r = Z / I \tag{8}$$

The calculation flow chart of the confidence level r of the standard value of mechanical properties of the original bamboo based on the parameter method is shown in Fig. 3a.

Calculation of Confidence of Standard Value under Non-parameter Method

Under the non-parametric method, the calculation coefficient K of the standard value of the mechanical properties of bamboo has nothing to do with the true mean value of the material (Zhong *et al*. 2018). When analyzing the standard value of bamboo strength through the nonparametric method, using MATLAB (MathWorks, R2022a, U.S.) programming, each sample is sorted according to the value size from small to large, and then the data in the row of each sample is compared with the 5% quantile value P. If the value of W samples is less than or equal to P, the corresponding confidence level r can be calculated as follows for S = i:

$$r = W / I \tag{9}$$

The calculation flow chart of the confidence level r of the standard value of the mechanical properties of the original bamboo based on the non-parametric method is shown in Fig. 3b.

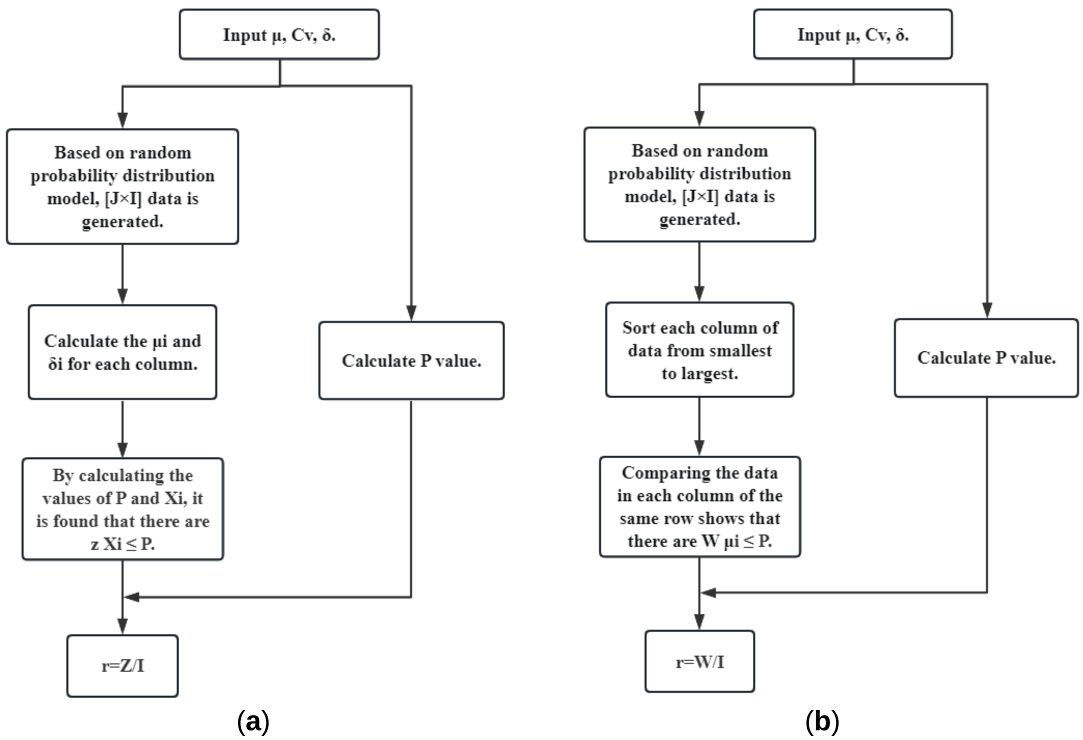


Fig. 3. Calculation flow chart: (a) Parameter method; (b) Non-parametric method

RESULTS AND DISCUSSION

Analysis of Test Results

The failure modes of mechanical properties of bamboo can be divided into ductile failure and brittle failure. The longitudinal compressive specimens have a long yield platform in the loading process, which provides obvious warning before failure. The bending deformation of the flexural specimen is visible to the naked eye in the loading process, and finally the specimen suddenly fails. The transverse tensile, transverse shear, and transverse tensile specimens all fail without warning during the test. The transverse compressive specimens are similar to the transverse compressive specimens in that the deformation varies greatly with loading. To summarize, the tests for ductile failure include longitudinal compression and transverse compression, while the tests for brittle failure include flexural, longitudinal tensile, longitudinal shear, and transverse tensile. Figure 4 shows the photos of the specimens when they are damaged.

The mechanical properties of bamboo were statistically analyzed, and the results as shown in Table 2 and Fig. 5 were obtained. The average UCS, UCE, MOR, MOE, UTS, UTE, USS, CCS, and CTS of bamboo were 57.48 MPa, 13.92 GPa, 132.36 MPa, 17.84 GPa, 145.08 MPa, 16.44 GPa, 15.92 MPa, 27.29 MPa, and 4.70 MPa, respectively. Bamboo has good longitudinal tensile, compressive, and flexural properties, but relatively poor longitudinal shear and transverse mechanical properties.

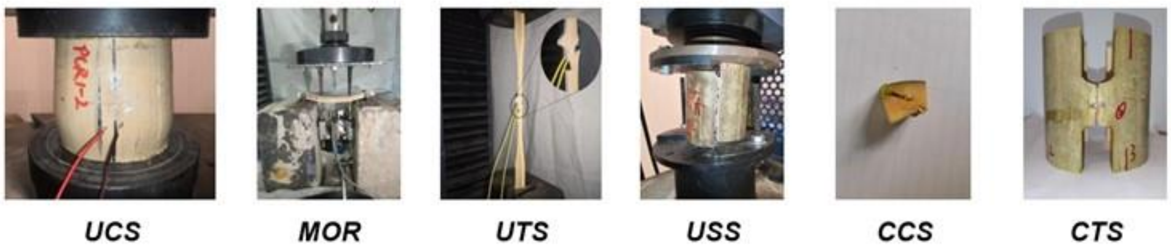


Fig. 4. Damage forms of bamboo

Table 2. Mechanical Properties Statistics

	μ	δ	Cv
UCS	57.48 MPa	7.30 MPa	0.127
UCE	13.92 GPa	1.41 GPa	0.101
MOR	132.36 MPa	7.02 MPa	0.053
MOE	17.84 GPa	1.29 GPa	0.074
UTS	145.08 MPa	35.54 MPa	0.245
UTE	16.44 GPa	1.17 GPa	0.071
USS	15.92 MPa	1.26 MPa	0.079
CCS	27.29 MPa	5.35 MPa	0.196
CTS	4.70 MPa	1.80 MPa	0.383

Note: μ is the average value, δ is the standard deviation, and Cv is the coefficient of variation.

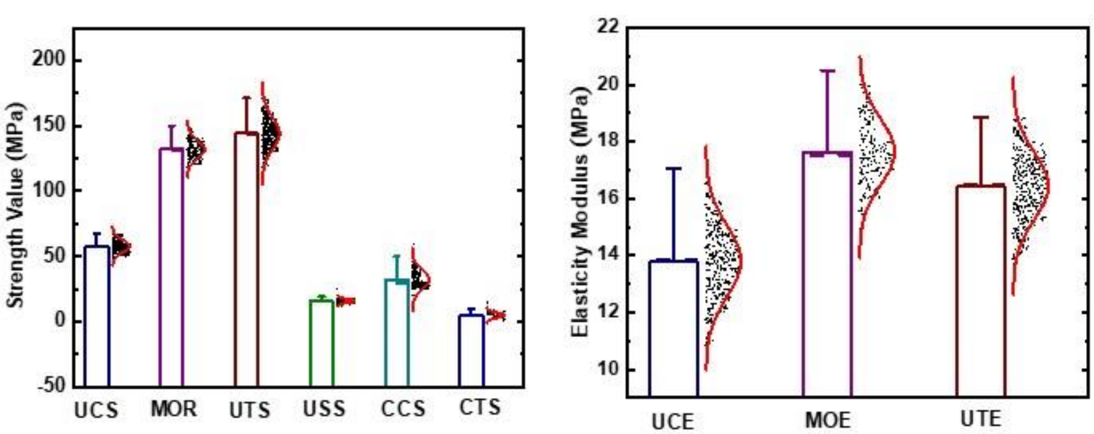


Fig. 5. Statistics of mechanical properties of bamboo: (a) Strength; (b) Elastic modulus

Analysis of Influencing Factors of Standard Values under Parametric Method

The influencing factors of confidence

The calculation coefficient K of the characteristic values of the mechanical properties has nothing to do with the material mechanics performance of the real average. Therefore, the assumption is the average size of various mechanical properties of original bamboo (UCS, UCE, UTS, UTE, MOR, MOE, USS, CCS, and CTS) is 200 MPa. The range of variation coefficient Cv of various mechanical properties of bamboo is [0.05, 0.50]; that is, the range of standard deviation δ is [10 MPa, 100 MPa]. Normal model, Lognormal model, and 2-P-Weibull model are generally used as the probability distribution models of original bamboo. Different probability distribution models have certain influence on the value of mechanical properties characteristic values of original bamboo. The results under Normal model, Lognormal model, and 2-P-Weibull model are obtained through MATLAB programming and calculation. Figures 6 through 8 show the results of calculation and analysis under Normal model, Lognormal model, and 2-P-Weibull model, respectively, in which the coefficient of variation is 0.2 and 0.4, the number of samples *n* is 50, and the calculation coefficient K of parameter method is 1.5, 2.0, and 2.5, respectively. It can be seen from Fig. 6 that under Normal probability distribution model, when the coefficient of variation is constant, confidence *r* increases with the increase of calculation coefficient K. When Cv = 0.2, the confidence *r* corresponding to K 1.5, 2.0, and 2.5 are 0.2331, 0.9232, and 0.9985, respectively, that is, 2331, 9232, and 9985 mechanical properties characteristic values of original bamboo in 10,000 samples are less than 5% of their true values *P*. When Cv = 0.4, there are 2323, 9231, and 9989 mechanical properties of bamboo with K are 1.5, 2.0, and 2.5, respectively, which are less than 5% of their true values P. Through comparing the results of different coefficient of variation, it can be seen that Cv increases from 0.2 to 0.4, and the change of confidence r is extremely small and negligible.

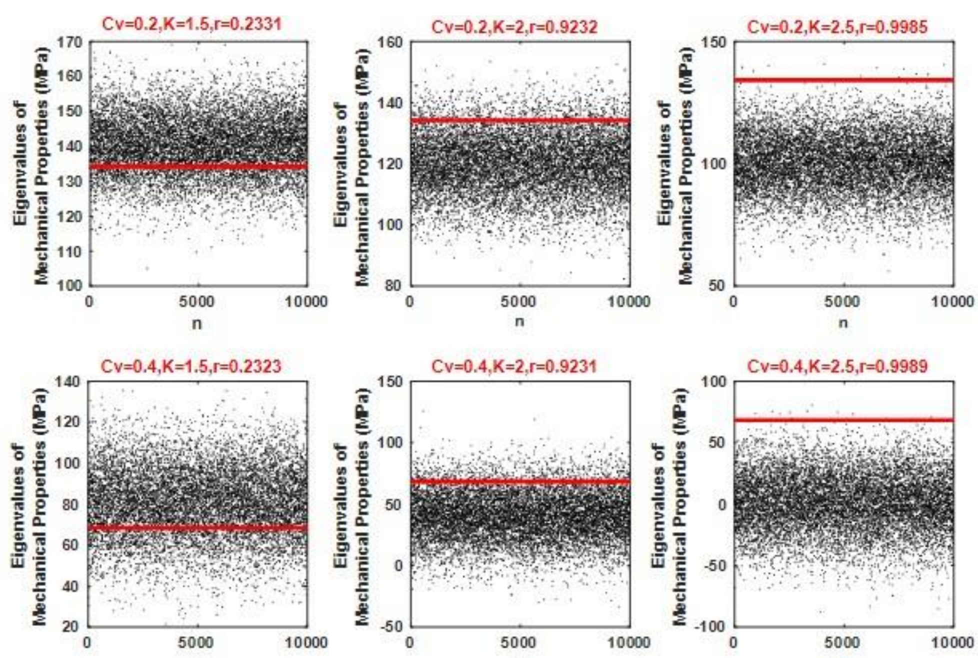


Fig. 6. Influence of K and Cv on r under Normal distribution model

According to Fig. 7, under the Lognormal probability distribution model, confidence r gradually increases with the increase of K under the same Cv. For the same K, the confidence r increases with the increase of Cv. Through comparing Figs. 6 and 7, it can be seen that under the same conditions, the confidence r of Lognormal probability distribution model is higher than that of Normal probability distribution model.

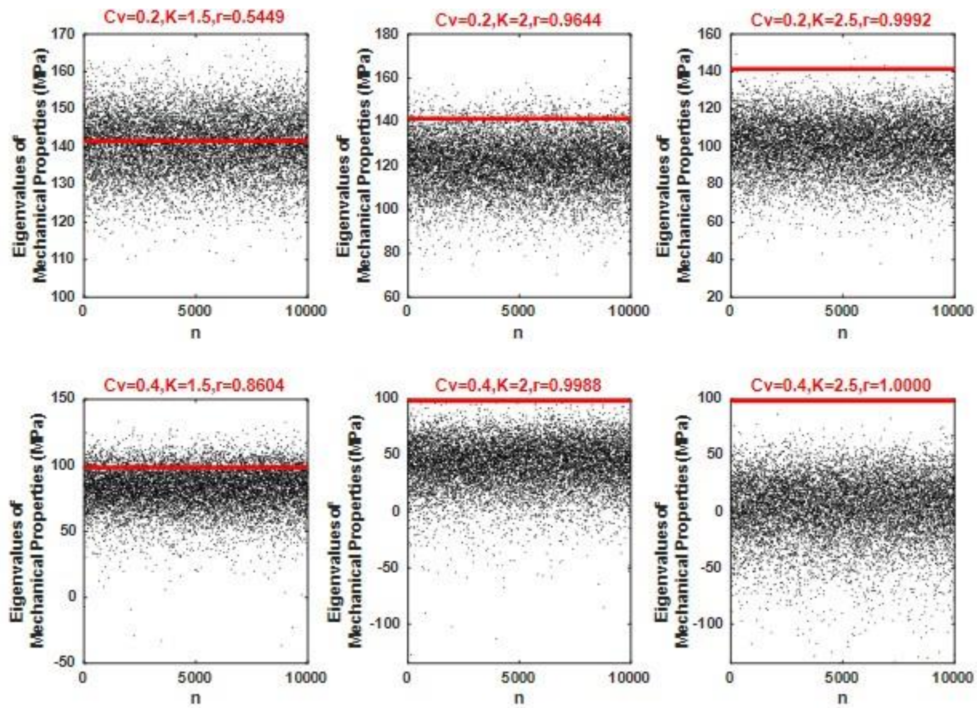


Fig. 7. Influence of K and Cv on r under Lognormal distribution model

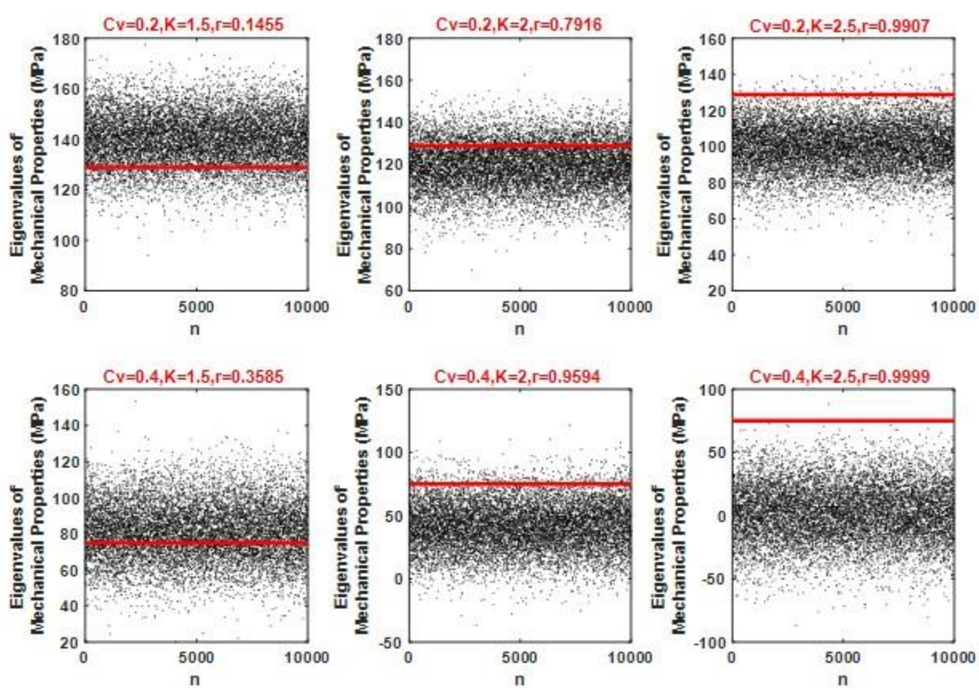
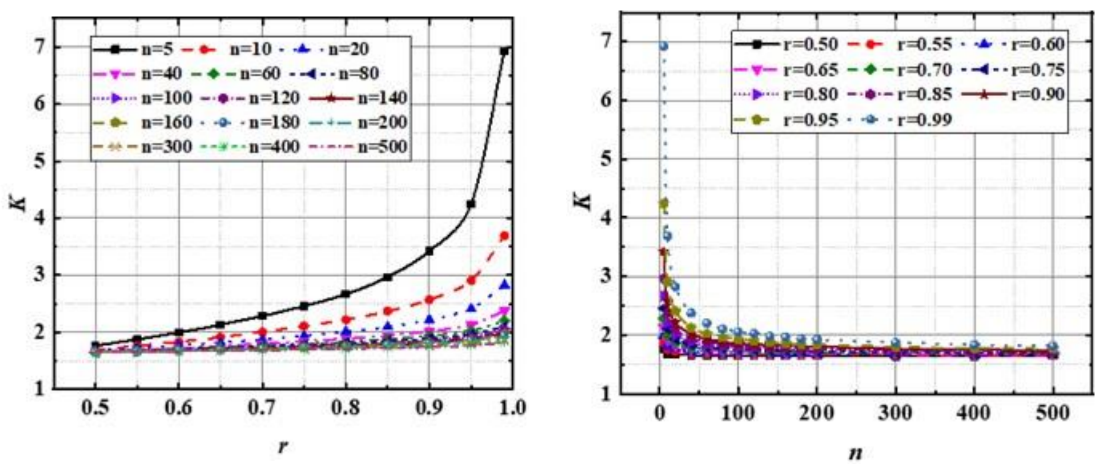


Fig. 8. Influence of K and Cv on r under 2-P-Weibull distribution model

As shown in Fig. 8, the confidence r of 2-P-Weibull model is smaller than that of Normal model and Lognormal model. When the calculation coefficient K and coefficient of variation Cv are constant, the confidence r of the three probability distribution models is sorted as Lognormal model > Normal Model > 2-P-Weibull model.

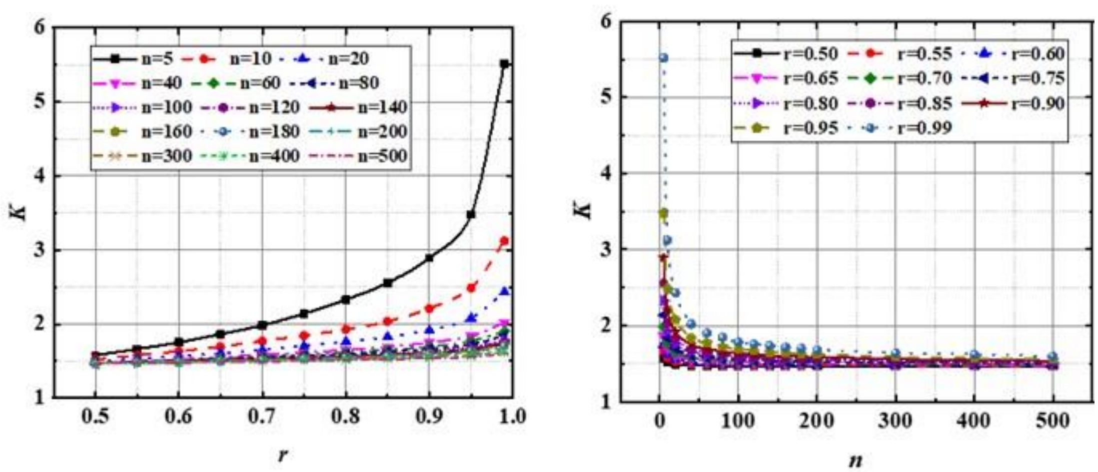
Analysis of K values

The relationship between r, K, and n was obtained through MATLAB (MathWorks, R2022a, Natick, MA, USA) programming. The results are shown in Figs. 9 through 11 and Tables 3 through 5. As shown in Figs. 9 through 11 and Tables 3 through 5, the calculation coefficient K presents a nonlinear increase trend with the increase of confidence *r*, and the slope of the curve gradually increases. The calculation coefficient K decreases with the increase of the number of samples *n,* and the slope of the curve gradually decreases. When the number of samples exceeds a certain value, K tends to coincide. The rules under Normal model, Lognormal model, and 2-P-Weibull model are consistent.



(a) (b)

Fig. 9. Relationship between K, r, and n under Normal distribution model: (a) relationship between K and r; and (b) relationship between K and n



(a) (b)

Fig. 10. Relationship between K, r, and n under Lognormal distribution model: (a) relationship between K and r; and (b) relationship between K and n

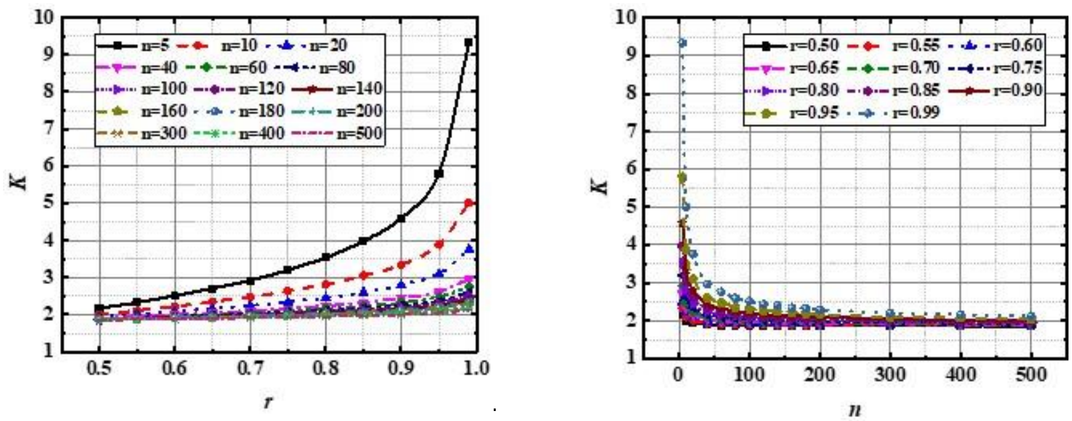


Fig. 11. Relationship between K, r, and n under 2-P-Weibull distribution model: (a) relationship between K and r and (b) relationship between K and n

Table 3. Calculation Coefficient K (Normal Model, Cv = 0.2)

n \ *r*	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	0.99
5	1.761	1.870	1.994	2.128	2.284	2.455	2.667	2.965	3.420	4.244	6.922
10	1.688	1.759	1.832	1.913	2.006	2.107	2.217	2.368	2.568	2.904	3.690
20	1.678	1.722	1.770	1.817	1.873	1.936	2.007	2.092	2.215	2.409	2.825
40	1.658	1.687	1.720	1.757	1.795	1.837	1.882	1.938	2.015	2.128	2.374
60	1.656	1.680	1.708	1.737	1.766	1.796	1.831	1.878	1.934	2.025	2.202
80	1.655	1.677	1.699	1.724	1.748	1.777	1.807	1.842	1.887	1.960	2.100
100	1.650	1.667	1.687	1.708	1.731	1.755	1.783	1.818	1.862	1.929	2.054
120	1.649	1.667	1.686	1.707	1.726	1.749	1.776	1.805	1.844	1.903	2.027
140	1.648	1.664	1.681	1.699	1.717	1.738	1.760	1.787	1.820	1.875	1.977
160	1.647	1.662	1.678	1.696	1.715	1.734	1.754	1.780	1.812	1.862	1.969
180	1.650	1.664	1.679	1.694	1.709	1.727	1.748	1.773	1.804	1.849	1.937
200	1.646	1.660	1.674	1.688	1.704	1.721	1.739	1.763	1.794	1.840	1.925
300	1.645	1.657	1.668	1.681	1.694	1.709	1.724	1.743	1.765	1.801	1.870
400	1.645	1.655	1.666	1.676	1.688	1.700	1.715	1.730	1.750	1.778	1.834
500	1.646	1.655	1.664	1.674	1.684	1.696	1.707	1.722	1.739	1.766	1.816

Table 4. Calculation Coefficient K (Lognormal Model, Cv = 0.2)

n \ *r*	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	0.99
5	1.575	1.658	1.751	1.861	1.980	2.138	2.326	2.553	2.889	3.478	5.517
10	1.521	1.575	1.632	1.692	1.766	1.840	1.925	2.032	2.209	2.486	3.123
20	1.489	1.526	1.562	1.602	1.647	1.702	1.757	1.826	1.915	2.074	2.428
40	1.472	1.498	1.523	1.550	1.579	1.611	1.647	1.689	1.746	1.835	2.019
60	1.471	1.491	1.512	1.535	1.558	1.583	1.613	1.649	1.691	1.769	1.900
80	1.467	1.484	1.501	1.522	1.544	1.565	1.590	1.623	1.659	1.719	1.843
100	1.466	1.482	1.497	1.514	1.532	1.552	1.572	1.597	1.630	1.684	1.782
120	1.464	1.478	1.493	1.509	1.526	1.545	1.565	1.589	1.621	1.667	1.755
140	1.465	1.479	1.492	1.507	1.523	1.539	1.557	1.578	1.603	1.648	1.735
160	1.463	1.475	1.488	1.502	1.517	1.532	1.550	1.570	1.596	1.637	1.714
180	1.462	1.475	1.486	1.499	1.512	1.527	1.543	1.563	1.589	1.628	1.700
200	1.463	1.474	1.485	1.498	1.510	1.525	1.540	1.556	1.580	1.619	1.677
300	1.462	1.471	1.480	1.490	1.499	1.510	1.523	1.538	1.558	1.586	1.637
400	1.464	1.471	1.479	1.487	1.496	1.506	1.516	1.530	1.546	1.569	1.619
500	1.462	1.469	1.476	1.483	1.491	1.499	1.509	1.520	1.534	1.555	1.593

Table 5. Calculation Coefficient K (2-P-Weibull Model, Cv = 0.2)

r / n	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	0.99
5	2.167	2.325	2.502	2.700	2.915	3.195	3.530	3.972	4.585	5.799	9.334
10	1.992	2.105	2.213	2.343	2.477	2.629	2.813	3.045	3.338	3.882	5.008
20	1.939	2.010	2.081	2.159	2.244	2.338	2.454	2.596	2.795	3.098	3.756
40	1.889	1.939	1.992	2.040	2.101	2.163	2.233	2.322	2.435	2.612	2.958
60	1.870	1.909	1.951	1.995	2.042	2.095	2.156	2.225	2.320	2.470	2.752
80	1.875	1.908	1.943	1.980	2.018	2.061	2.110	2.167	2.243	2.356	2.596
100	1.869	1.900	1.930	1.964	2.000	2.039	2.081	2.132	2.199	2.303	2.509
120	1.866	1.895	1.922	1.951	1.983	2.019	2.057	2.101	2.159	2.257	2.430
140	1.863	1.888	1.916	1.942	1.972	2.005	2.042	2.087	2.141	2.232	2.403
160	1.865	1.888	1.912	1.938	1.964	1.997	2.029	2.070	2.125	2.207	2.339
180	1.865	1.888	1.911	1.935	1.961	1.988	2.020	2.060	2.108	2.182	2.319
200	1.859	1.882	1.905	1.926	1.950	1.978	2.008	2.046	2.089	2.156	2.284
300	1.860	1.877	1.895	1.914	1.934	1.956	1.980	2.008	2.042	2.099	2.198
400	1.857	1.872	1.887	1.903	1.921	1.938	1.959	1.984	2.015	2.066	2.155
500	1.857	1.870	1.885	1.898	1.913	1.929	1.947	1.970	1.996	2.037	2.121

Analysis of Influencing Factors of Standard Values under Nonparametric Method

The influencing factors of confidence

Figures 12 through 14 show the relationship between S and Cv and r under the Normal distribution model, Lognormal distribution model, and 2-P-Weibull distribution model when nonparametric method is adopted through MATLAB analysis.

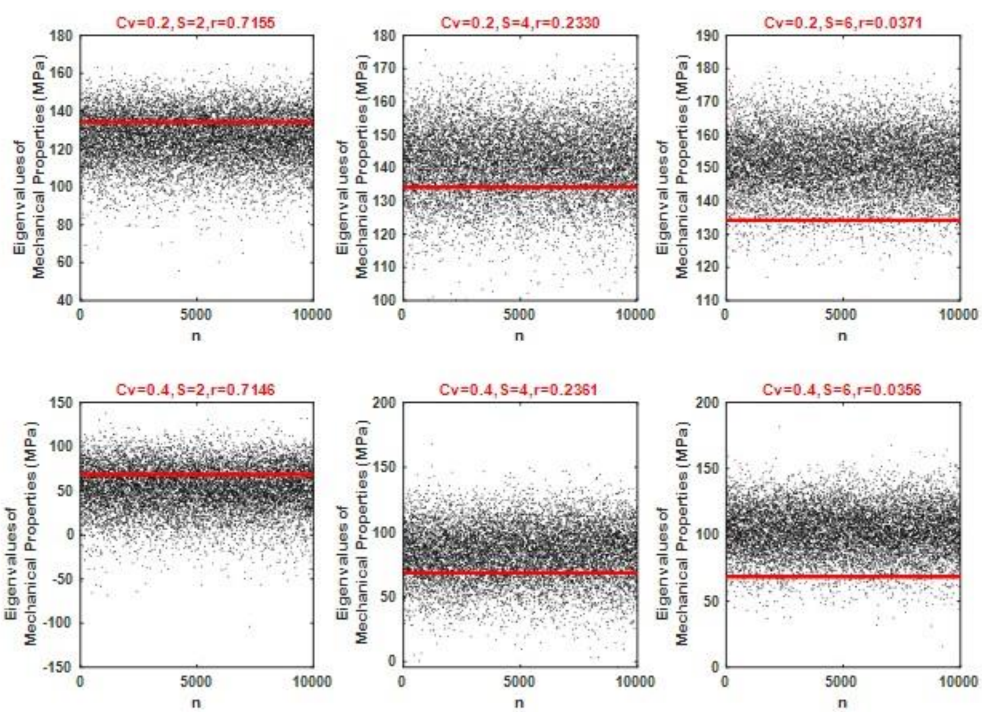


Fig. 12. Influence of S and Cv on r under Normal distribution model

According to Figs. 12 through 14, taking Cv = 0.2 and S = 4 as an example, the confidence r of Normal distribution model, Lognormal distribution model, and 2-P-

Weibull distribution model are 0.2330, 0.2355, and 0.2488, respectively; that is, in 10,000 samples, there are 2330, 2355, and 2488 mechanical properties values of original bamboo, respectively, which are less than 5% of their true value P. When Cv is constant, r increases with S. When S is constant, r increases with the increase of Cv. When Cv and S are the same, r under the three distribution models is roughly equal and the error is small.

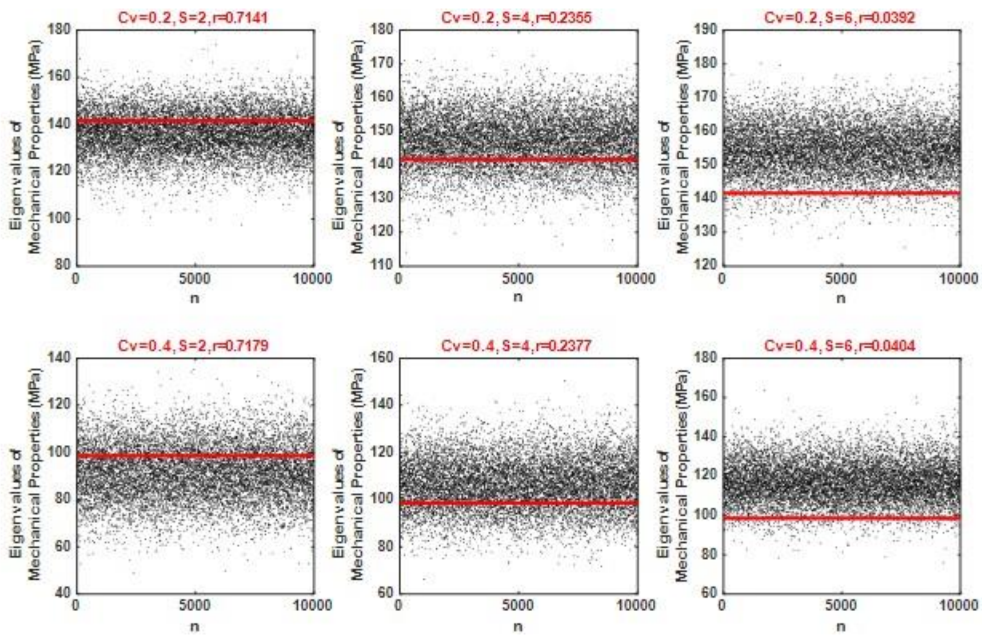


Fig. 13. Influence of S and Cv on r under Lognormal distribution model

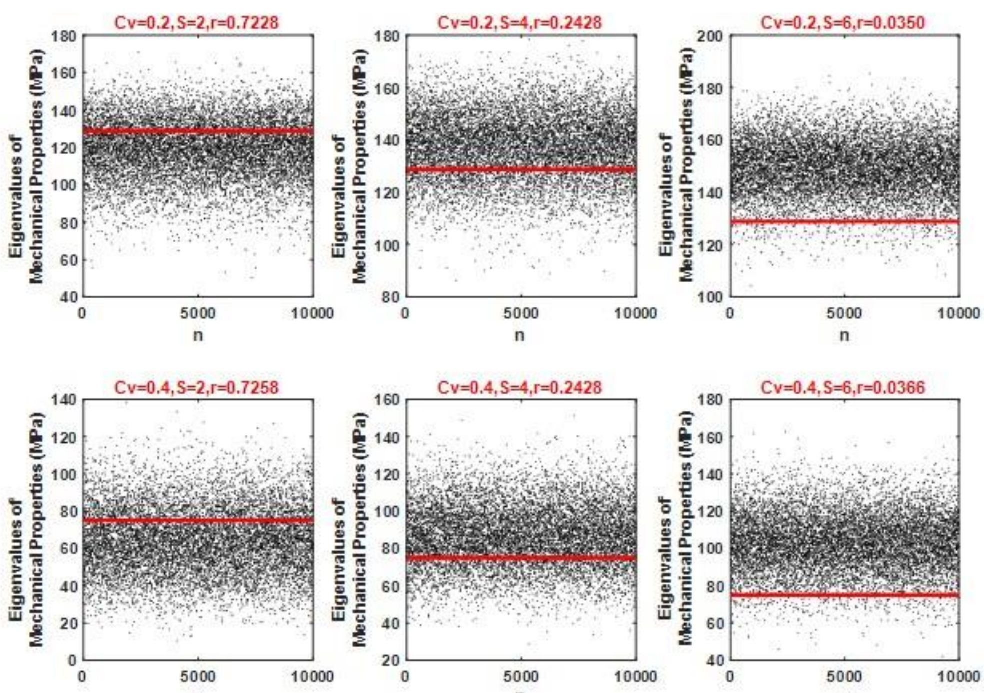
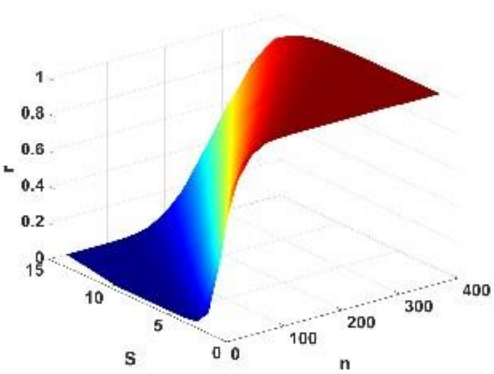


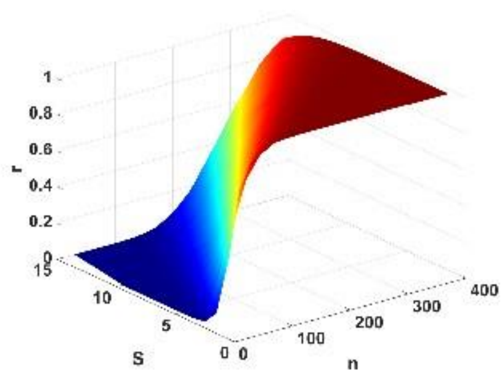
Fig. 14. Influence of S and Cv on r under 2-P-Weibull distribution model

Analysis of the values of S

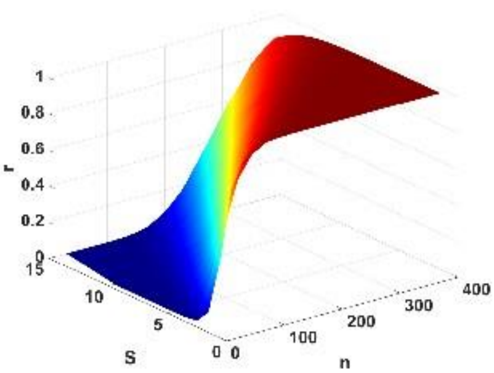
Figure 15 shows the relation surfaces of S, r, and n under each distribution model. It can be seen from the surface that the confidence degree r presents a nonlinear decreasing trend with the increase of the sampling sequence number S, and the slope of the surface decreases first and then increases. The r increases nonlinearly with the increase of the number of samples n, and the surface slope increases first and then decreases. The surfaces of different Cv almost coincide, which is consistent with the results in the literature. It can be seen that the influence of the coefficient of variation on the relationship between the confidence degree r and the sampling sequence number S is negligible. The minimum sample number n under different confidence and sampling sequence number requirements is shown in Tables 6 to 8. The minimum sample number n in the table is the value rounded up. Referring to Tables 6 to 8, the minimum number of samples under different probability distribution models, confidence, and sampling sequence numbers can be conveniently obtained.



(a)



(b)



(c)

Fig. 15. Relation between *S* and *r* and *n*: (a) Normal distribution model; (b) Lognormal distribution model; (c) 2-P-Weibull distribution model

Table 6. Relationship between Minimum Sample Number n, Confidence Degree r, and Order S (Normal Model)

S \ r	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	0.99
1	15	16	19	21	24	28	32	37	45	58	86
2	34	37	41	44	48	53	58	67	76	93	124
3	54	58	62	66	72	78	85	93	105	125	166
4	74	78	83	88	94	102	109	120	131	152	200
5	94	99	104	110	117	125	134	145	159	181	227
6	113	120	126	132	139	147	156	167	184	210	252
7	134	140	146	154	162	170	179	192	210	233	285
8	154	160	166	175	185	192	205	216	233	259	315
9	173	181	188	196	206	215	226	240	256	282	345
10	192	201	208	218	228	237	249	263	282	310	374
11	214	222	230	239	249	260	270	284	305	335	397
12	233	242	250	260	270	280	293	308	330	361	423
13	254	262	272	281	292	303	315	333	352	386	450
14	273	282	292	303	313	325	339	354	378	409	479
15	293	304	313	324	335	346	362	376	397	434	500

Table 7. Relationship between Minimum Sample Number n, Confidence Degree r, and Order S (Lognormal Model)

S \ r	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	0.99
1	15	16	18	21	24	27	32	37	46	59	88
2	34	37	40	44	49	54	58	67	77	94	126
3	53	58	62	67	72	78	85	93	105	124	160
4	73	79	81	89	94	102	109	119	133	153	195
5	93	99	105	110	118	124	134	143	157	179	226
6	114	119	126	132	139	146	157	169	184	206	253
7	133	140	145	154	162	170	180	192	209	234	286
8	154	160	168	175	185	193	203	217	235	259	316
9	172	180	189	196	205	214	225	241	257	287	344
10	194	200	209	218	228	237	248	262	281	310	368
11	214	221	231	239	249	259	270	288	305	332	394
12	232	242	251	260	270	281	293	309	328	362	419
13	252	261	271	281	291	303	318	331	351	386	447
14	272	283	291	302	314	325	338	354	377	411	475
15	294	302	313	324	334	346	362	378	402	434	501

Determining the Standard Values of Mechanical Properties of Bamboo

The parameter method is mainly based on the statistical mean μ and standard deviation δ of the sample to determine the calculation coefficient K, and the standard value of material strength is jointly determined by the above three. The non-parametric method is to arrange the strength in the sample in order from small to large, and compare the 5% quantile value with the strength data points corresponding to each order to determine the sampling sequence number. The corresponding strength value of the sequence number is the standard value of the bamboo. According to the above analysis, when the parameter method is adopted, the calculation coefficient K is not equal under different probability distribution models and coefficient of variation Cv. When the nonparametric method is adopted, the S value is the same under different probability distribution models and coefficient of variation Cv. When the sample data is not extensive enough, the use of parameter method is easy to lead to the distortion of the results, especially when the number of samples is small. Therefore, it is suggested to use the non-parametric method to determine the standard values of mechanical properties of bamboo.

Table 8. Relationship between Minimum Sample Number n, Confidence Degree r, and Order S (2-P-Weibull Model)

S \ r	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	0.99
1	15	16	18	21	23	28	31	38	46	58	89
2	34	37	41	44	49	54	59	66	77	93	127
3	54	58	62	68	72	78	85	94	105	122	166
4	74	79	82	89	95	101	109	119	131	153	196
5	94	99	105	111	117	124	134	143	158	181	224
6	113	120	125	132	140	147	158	169	182	206	259
7	134	139	147	153	163	171	181	192	209	234	288
8	154	160	167	175	183	193	203	217	233	262	314
9	173	181	188	196	205	216	226	241	258	288	342
10	194	201	209	217	227	238	249	264	283	312	370
11	211	223	231	239	248	258	270	285	304	336	399
12	234	243	251	259	271	282	294	309	329	359	422
13	252	264	271	282	290	302	315	331	352	385	448
14	272	281	293	303	314	324	340	354	376	409	472
15	294	304	312	324	333	344	358	376	399	433	500

Linear function, Exponential function, and Power function are respectively used to fit the sampling sequence number S and minimum sampling number n, and the fitting results were obtained as shown in Table 9. As shown in Table 9, a linear function can be used to fit the relationship between the sampling sequence number S and the minimum sampling number n perfectly; that is, there is a linear correlation between S and n. The linear relation between S and n is defined as $y = ax + b$, where a and b are the calculation parameters. As observed in Table 9, values of a and b are different under different confidence levels. The value parameters a and b are fitted with the confidence r respectively, and the relation shown in Eq. 10 and Eq. 11, and the fitting curve shown in Fig. 16 is obtained. The decision coefficients R^2 of Eq. 10 and Eq. 11 are all higher than 0.98, so it can be seen that Eq. 10 and Eq. 11 can perfectly fit the relationship between calculation parameters and r. Based on the above analysis, the relationship between the sampling sequence number, the minimum sample number, and the confidence of the mechanical properties of bamboo under the nonparametric method can be obtained, as shown in Eq. 12. The standard values of mechanical properties of bamboo obtained by the above methods are shown in Table 10. The values are determined by Eqs. 10 through 12:

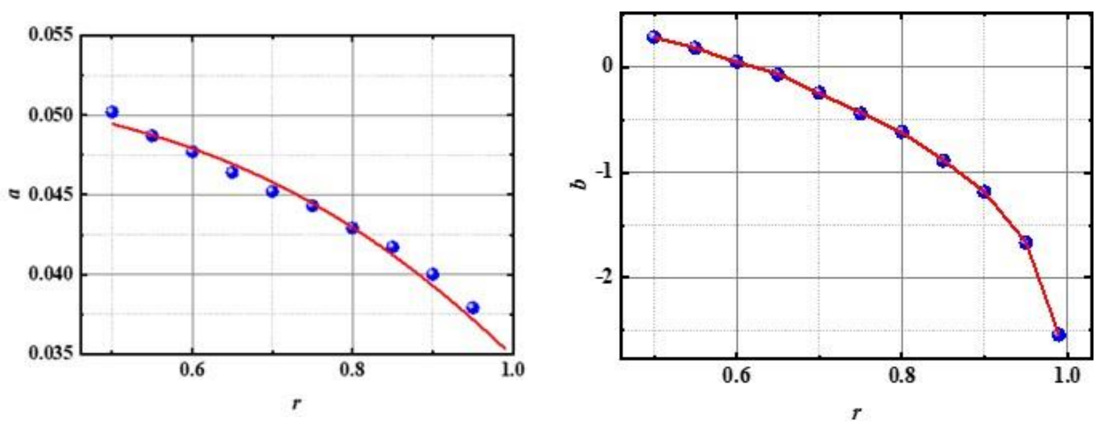
$$a = \frac{0.053}{1+e^{4r-4.64}} \ (R^2 = 0.984) \tag{10}$$

$$b = 0.224\text{-}2.755r^{5.5} \ (R^2 = 0.981) \tag{11}$$

$$S = \frac{0.053n}{1+e^{4r-4.64}} - 2.755r^{5.5} + 0.224 \tag{12}$$

Table 9. Fitting Relation Results

r	Linear		Exponential		Power	
	Relation	R^2	Relation	R^2	Relation	R^2
0.50	$S = 0.0502n + 0.2831$	1	$S = 1.8102e^{0.0032n}$	0.881	$S = 0.0783n^{0.9208}$	1
0.55	$S = 0.0487n + 0.1807$	1	$S = 1.7752e^{0.008n}$	0.885	$S = 0.0699n^{0.9351}$	0.999
0.60	$S = 0.0477n + 0.0499$	1	$S = 1.7359e^{0.0079n}$	0.885	$S = 0.0543n^{0.9763}$	1
0.65	$S = 0.0464n - 0.0699$	1	$S = 1.6987e^{0.0076n}$	0.889	$S = 0.0465n^{0.9973}$	1
0.70	$S = 0.0452n - 0.2435$	1	$S = 1.6451e^{0.0075n}$	0.893	$S = 0.0369n^{1.032}$	1
0.75	$S = 0.0443n - 0.4401$	1	$S = 1.59e^{0.0073n}$	0.895	$S = 0.0276n^{1.0775}$	1
0.80	$S = 0.0429n - 0.6139$	1	$S = 1.5418e^{0.0071n}$	0.897	$S = 0.0213n^{1.1149}$	1
0.85	$S = 0.0417n - 0.8872$	1	$S = 1.4676e^{0.0069n}$	0.902	$S = 0.0149n^{1.1683}$	1
0.90	$S = 0.04n - 1.1847$	1	$S = 1.3921e^{0.0067n}$	0.905	$S = 0.0096n^{1.2317}$	1
0.95	$S = 0.0379n - 1.6648$	1	$S = 1.2818e^{0.0063n}$	0.908	$S = 0.0047n^{1.3338}$	0.999
0.99	$S = 0.0342n - 2.5421$	1	$S = 1.0954e^{0.0057n}$	0.917	$S = 0.0014n^{1.5026}$	0.997



(a) **(b)**

Fig. 16. Relationship between K, r, and n in Normal distribution model: (a) relationship between a and r; and (b) relationship between b and r

Table 10. Standard Values of Mechanical Properties of Original Bamboo

	UCS	UCE	MOR	MOE	UTS	UTE	USS	CCS	CTS
n	13	13	7	6	13	14	9	12	4
f_k	49.79 MPa	11.66 GPa	120.89 MPa	15.64 GPa	122.11 MPa	16.44 GPa	13.60 MPa	25.88 MPa	2.84 MPa

CONCLUSIONS

In this paper, tests of longitudinal grain compression, bending, longitudinal grain tensile, longitudinal grain shear, transverse grain compressive, and transverse grain tensile of original bamboo were conducted to study the influence of parametric and non-parametric methods on the standard values of mechanical properties of original bamboo. The main conclusions are as follows:

1. Ductile failure occurs when bamboo is subjected to longitudinal and transverse compressive resistances, and brittle failure occurs when bamboo is subjected to longitudinal tensile, flexural, transverse shear, and transverse tensile resistances.

2. Using the parameter method, the relationship between the confidence r and the calculation coefficient K, and the coefficient of variation Cv under the Normal model, Lognormal model, and 2-P-Weibull model was studied. The results show that under each distribution model, when Cv is constant, the confidence r increases gradually with the increase of K. When K is constant, the confidence r increases with the increase of Cv. When calculation coefficient K and coefficient of variation Cv are constant, the confidence *r* of the three probability distribution models is sorted as Lognormal model > Normal Model > 2-P-Weibull model. The calculation coefficient K presents a nonlinear increase trend of gradually increasing slope with the increase of confidence r, and a nonlinear decrease trend of gradually decreasing slope with the increase of the number of samples n. When the number of samples exceeds a certain value, K tends to coincide.
3. Under the non-parametric method, when the coefficient of variation Cv is constant, the confidence degree r increases with the increase of sampling sequence number S. When S is constant, r increases with the increase of Cv. When Cv and S are the same, r under the three distribution models is roughly equal. With the increase of sampling S, r presents a nonlinear decreasing trend, which decreases first and then increases. With the increase of the number of samples n, r presents a nonlinear increasing trend of the curve oblique, first increasing and then decreasing. The effect of Cv on the relationship between r and S is negligible.
4. Using the parameter method to study the standard values of mechanical properties of bamboo, the results easily can become distorted, so this paper suggests using the non-parameter method for analysis. The linear relation can perfectly fit the relation between the sampling sequence number S and the minimum sample number n. Based on this, the relation between S, r, and n is proposed. The standard values of UCS, UCE, MOR, MOE, UTS, UTE, USS, CCS, and CTS are 49.79 MPa, 11.66 GPa, 120.89 MPa, 15.64 GPa, 122.11 MPa, 16.44 GPa, 13.60 MPa, 25.88 MPa, and 2.84 MPa, respectively.

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