Relationship between Mechanical Properties and Height-Diameter Ratio of Moso Bamboo

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Systematic tests of longitudinal compression, bending, longitudinal shear, and longitudinal tensile strength of bamboo were conducted to study the variation of mechanical properties and the height-diameter ratio of bamboo. The predictive relations of mechanical properties and height-diameter ratio were fitted by linear regression analysis. The results showed that the mechanical properties of longitudinal compression, bending, longitudinal shear, and longitudinal tensile strength of bamboo increased with the increase of the height-diameter ratio. In this paper, the method of deducing the relationship between mechanical properties and height-diameter ratio of bamboo through the linear fitting relationship between mechanical properties and height-diameter ratio was shown to have high applicability and accuracy for bamboo. This paper has a certain reference value for the evaluation of mechanical properties of bamboo and has a certain practical value for reducing the testing cost.

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Keywords: Moso bamboo; Height-diameter ratio; Mechanical properties; Performance prediction

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INTRODUCTION

Bamboo is a type of green and environmentally friendly building material (Chen *et al.* 2018; Guan *et al.* 2022; Bala and Gupta 2023). Compared with traditional building materials, bamboo has the following advantages: (1) Wide distribution and planting area, short growth cycle (Lo *et al.* 2008; Jiang *et al.* 2015; Li *et al.* 2016; Huang and Sun 2021; Kuang *et al.* 2022); (2) High strength, toughness, and high strength to weight ratio, known as the steel bar in nature; (3) The processing energy consumption is low, and the abandoned bamboo used for construction will naturally degrade without additional treatment, which is conducive to improving the ecological environment. It can be seen that the development potential of bamboo structure is huge. It is conducive to the development of ecological architecture and has great significance for the realization of sustainable development strategy. However, due to the biological characteristics of bamboo, its heterogeneous size, moisture content, poor durability, stress direction, and height to diameter ratio can all lead to different mechanical properties (Made Oka *et al.* 2016; Masood and Khan 2017; Tian *et al.* 2018; Skuratov *et al.* 2021; Zhou *et al.* 2023), which leads to complications in the application of bamboo structure in practical engineering, requiring a lot of bamboo performance testing time and cost.

To predict the mechanical properties of bamboo, experts and scholars have studied and analyzed the correlation between the mechanical properties of bamboo through a series of tests. Liu *et al*. (2021) explored the relationship between the bending strength and elastic modulus of bamboo and the height, wall thickness, and perimeter, and the results showed that the bending strength and elastic modulus of bamboo pieces in different parts had a good correlation with the height, wall thickness, and perimeter. The cited authors derived the relevant fitting formula to predict the mechanical properties of bamboo. Li *et al*. (2014) studied the water content, linear dry shrinkage, air-dry density, flexure strength, flexure elastic modulus, and longitudinal compressive strength of bamboo material of different ages. It was found that the air-dry density, flexural strength, flexural elastic modulus, and longitudinal compressive strength of bamboo increased with the increase of bamboo age, while the raw material's water content, air-dry shrinkage ratio decreased in chord, radial, longitudinal, and full dry shrinkage ratio. Zhou *et al.* (2012) investigated the distribution of vascular bundle and its tensile properties of bamboo, and the results showed that the volume ratio of vascular bundle increased with the increase of bamboo height, and the linear positive correlation between the longitudinal tensile elastic modulus and longitudinal tensile strength of bamboo and the volume ratio of vascular bundle was observed. Lin *et al.* (2019) conducted an experiment on the influence of bamboo joints on the mechanical properties of bamboo, and the results showed that bamboo joints had a significant influence on the compressive strength of bamboo along the grain. Hao *et al.* (2017) conducted experimental research on the mechanical properties of bamboo along the grain direction, and obtained the elastic modulus, compressive strength, and tensile strength of bamboo along the grain direction, as well as the compressive strength and shear strength of bamboo along the grain direction. Up to this point there have been few studies on the prediction of mechanical properties of bamboo structures. Such studies mainly have been based on a small number of sample data to explore the longitudinal tensile and bending properties of bamboo. There is still a lack of relevant studies on the relationship between mechanical properties of bamboo and the height-diameter ratio, and there is a lack of methods to predict mechanical properties of bamboo using the height-diameter ratio.

To explore the relationship between the mechanical properties of bamboo and the height-diameter ratio, and thereby to realize a simple, effective, and practical method for predicting the mechanical properties of bamboo using the height-diameter ratio, the following work was mainly performed for bamboo: (1) Based on a large number of test samples, the longitudinal tensile and longitudinal compressive strength, bending strength, and longitudinal shear strength of bamboo were tested. (2) The correlation between bamboo mechanical properties and height-diameter ratio was fitted by linear regression method, and the correlation prediction formula was given. (3) The prediction formulas proposed in this paper were tested and verified, and the mechanical properties of bamboo can be predicted using dimension measurement tools.

EXPERIMENTAL

Selection of Materials and Production of Specimens

In this paper, China was selected as the sampling site for bamboo. Bamboo trees with a diameter of about 100 mm and an age of 3 to 4 years were cut. In reference to JG/T 199 (2007) and ISO 22157-1 (2004), four types of specimens with mechanical properties, including longitudinal compression, bending, longitudinal shear, and longitudinal tensile were fabricated (Fig. 1). The length-diameter ratio of the longitudinal compression and longitudinal shear specimens was 1. The bending specimen size was 220 mm × 15 mm × t mm; The size of the longitudinal tensile specimen was 330 mm × 15 mm × t mm, where t is the wall thickness (mm) of the bamboo.

(**a**) longitudinal compression (**b**) bending (**c**) longitudinal tension (**d**) longitudinal shear

Fig. 1. Specimen making and loading diagram

Mechanical Properties Test and Calculation

The mechanical property test was conducted with reference to the standard, and the specimen was loaded with a universal testing machine. When formally loaded, the loading rate of the longitudinal compression, longitudinal shear, and longitudinal tensile tests was 0.01 mm/s, and the loading rate of the bending test was 150 N/mm^2 per minute. The formulas that were used for calculating the strength and elastic modulus of the specimen were as follows,

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

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

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

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

where f_{W} is the compressive, shear, and tensile strength of the sample with moisture content W (MPa). E_{W} is the elastic modulus along grain with water content W (MPa). MOR_{W} is the bending strength under water content W (MPa). MOE_{W} is the flexural elastic modulus under water content W (MPa). $P_{\max}$ is the 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 the 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 deflection value of the pure bend section of the specimen under the action of ΔP (mm).

Data Processing

The function drawing software Origin was used to carry out statistical analysis on various mechanical properties of bamboo. The longitudinal compressive strength, longitudinal compressive elastic modulus, flexural strength, flexural elastic modulus, longitudinal tensile strength, longitudinal tensile elastic modulus, and longitudinal shear strength of bamboo were respectively fitted with the height-diameter ratio (H/D), so as to obtain the relevant fitting curve and its fitting relation. The determination coefficient R^2 was used to evaluate the fitting effect. An R^2 value closer to 1 results in a higher goodness of fitting.

RESULTS AND DISCUSSION

Mechanical Property Value Statistics

A total of 60% of the specimens with various mechanical properties were randomly selected for mechanical properties testing, and Origin was used to make statistics on the mechanical properties of the obtained bamboo, and the results shown in Table 1 were obtained.

Table 1 shows that the mechanical properties of bamboo exhibited obvious anisotropic characteristics, among which the longitudinal compressive, longitudinal tensile, and bending properties of bamboo were excellent, while the longitudinal shear properties of bamboo were poor. The flexural strength was slightly smaller than the longitudinal tensile strength, while the longitudinal compressive strength was smaller than the flexural strength and the longitudinal tensile strength.

Table 1. Statistical Results of Mechanical Properties of 60% Bamboo Specimens

Mechanical Property Index	Quantity	Mean Value	Standard Deviation	Coefficient of Variation
UCS	186	58.6 MPa	4.10 MPa	0.07003
UCE	183	14.1 GPa	1.53 GPa	0.10819
MOR	92	132.6 MPa	6.83 MPa	0.05156
MOE	92	17.6 GPa	0.98 GPa	0.05587
UTS	199	150 MPa	10.8 MPa	0.07239
UTE	196	16.3 GPa	1.15 GPa	0.07048
USS	119	15.7 MPa	1.10 MPa	0.06979

Note: *UCS*, *UCE*, *MOR*, *MOE*, *UTS*, *UTE,* and *USS*, respectively, represent the longitudinal compressive strength, longitudinal compressive elastic modulus, flexural strength, flexural elastic modulus, longitudinal tensile strength, longitudinal tensile elastic modulus, and longitudinal shear strength.

Probability Distribution Model

The normal distribution, log-normal distribution, and Weibull distribution were used to perform strength probability fitting for various mechanical properties of bamboo with different height-diameter ratio (*H*/*D*), and the K-S correction test was used to perform goodness of fit test. The probability distribution diagram shown in Fig. 2 and goodness of Fit test table shown in Table 2 were obtained.

According to the probability distribution diagram and Table 2, the normal distribution, log-normal distribution, and Weibull distribution cannot be excluded for the longitudinal compressive strength, flexural strength, flexural elastic modulus, longitudinal shear strength, longitudinal tensile strength, and longitudinal tensile elastic modulus strength of bamboo. The distribution of compressive elastic modulus along grain accords with the normal distribution and Weibull distribution, but does not satisfy the lognormal distribution. The above results are consistent with the literature (Liu *et al.* 2022).

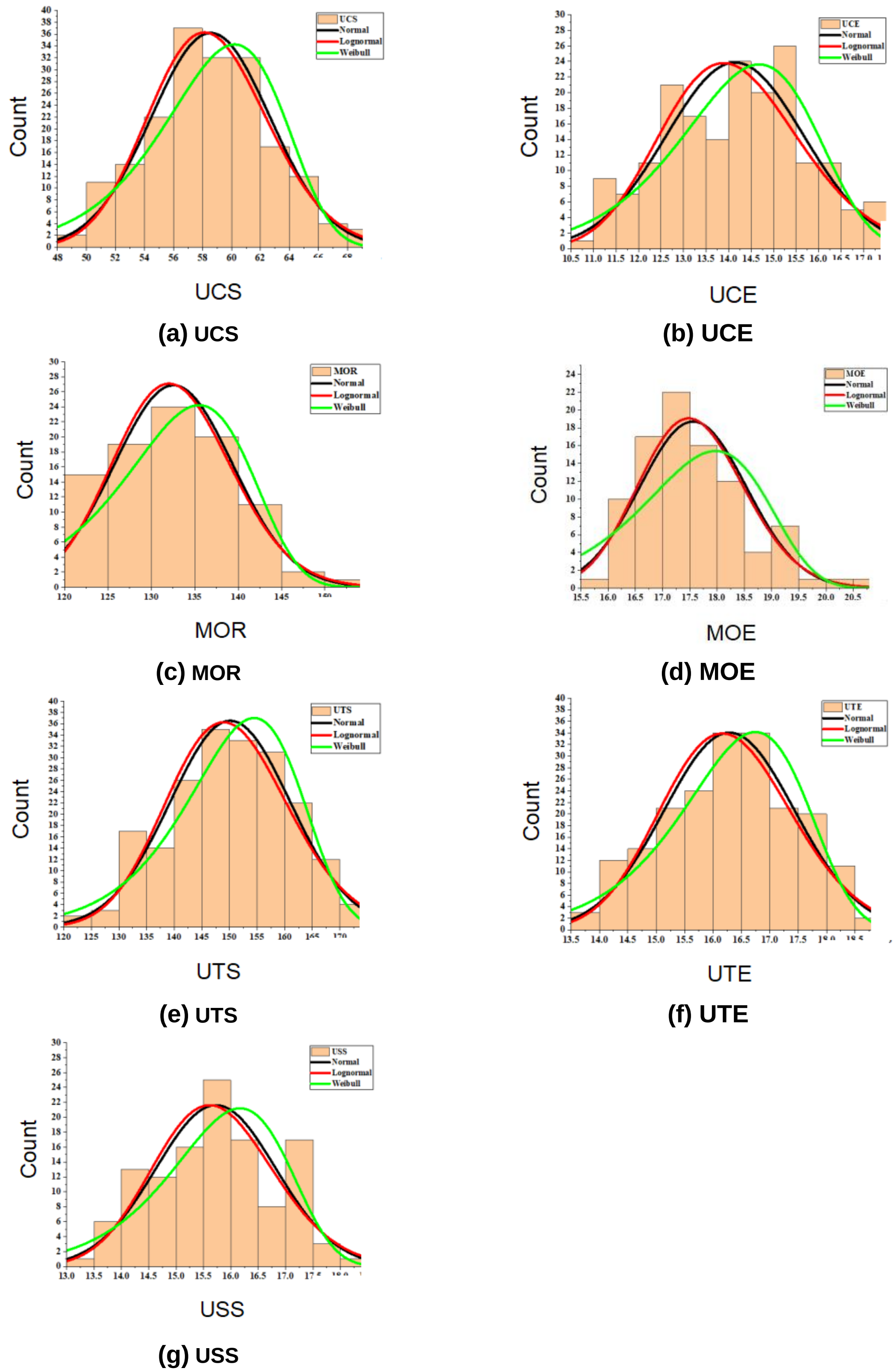

Fig. 2. Experimentally determined probability distributions (histograms) of mechanical properties of specimens compared with three widely used model distributions (fitted smooth curves)

Table 2. Goodness of Fit Test Table

Mechanical Property Index	Distribution	Statistics	P-value	Conclusion at (5%) Level
UCS	Normal	0.03051	> 0.15	Cannot rule out
	Lognormal	0.0315	> 0.15	
	Weibull	0.06094	> 0.1	
UCE	Normal	0.06025	0.10081	
	Lognormal	0.08001	< = 0.01	Exclude
	Weibull	0.05771	> 0.1	Cannot rule out
MOR	Normal	0.0645	> 0.15	
	Lognormal	0.05814	> 0.15	
	Weibull	0.0884	> 0.1	
MOE	Normal	0.07969	> 0.15	
	Lognormal	0.06969	> 0.15	
	Weibull	0.11756	> 0.1	
UTS	Normal	0.04191	> 0.15	
	Lognormal	0.05486	0.14806	
	Weibull	0.06017	> 0.1	
UTE	Normal	0.05061	> 0.15	
	Lognormal	0.05488	> 0.15	
	Weibull	0.06159	> 0.1	
USS	Normal	0.05554	> 0.15	
	Lognormal	0.06715	> 0.15	
	Weibull	0.0782	> 0.1	

Relationship Model Between Mechanical Properties and Height-Diameter Ratio

The software Origin was used to fit *UCS*, *UCE*, *MOR*, *MOE*, *UTS*, *UTE*, and *USS* of bamboo to the height-diameter ratio respectively, thereby obtaining the fitting curve shown in Fig. 3 and the fitting relation shown in Table 3. The fitting effect was evaluated using the coefficient of determination R^2. The results showed that *UCS*, *UCE*, *MOR*, *MOE*, *UTS*, *UTE*, and *USS* were strongly correlated with the height-diameter ratio. The R^2 of *UCE*, *UTS*, and *USS* were all above 0.7, and the fitting effect was relatively better. The longitudinal compressive strength, longitudinal compressive elastic modulus, flexural strength, flexural elastic modulus, longitudinal tensile strength, longitudinal tensile elastic modulus, and longitudinal shear strength of bamboo increased with the increase of the height-diameter ratio. The *UCS*, *UCE*, *MOR*, *MOE*, *UTS*, *UTE*, and *USS* of bamboo can be converted using the relation in the table.

The relationship between the mechanical properties of bamboo and the height-diameter ratio is mainly related to the structure of bamboo. Bamboo is mainly composed of vascular bundle material, which plays the role of bearing and basic organization that plays the role of connecting and transferring load, among which *UCS*, *UCE*, *UTS*, *UTE*, and *USS* of bamboo are mainly linearly and positively correlated with the distribution density of vascular bundle, and the volume ratio of vascular bundle increases with the increase of bamboo height. Therefore, the mechanical properties of bamboo along the grain direction tend to increase with the increase of height-diameter ratio. The *MOR* and *MOE* affecting bamboo are mainly vascular bundles, and they have a linear positive correlation with the distribution density of vascular bundles, so they also show an increasing trend with the increase of height-diameter ratio.

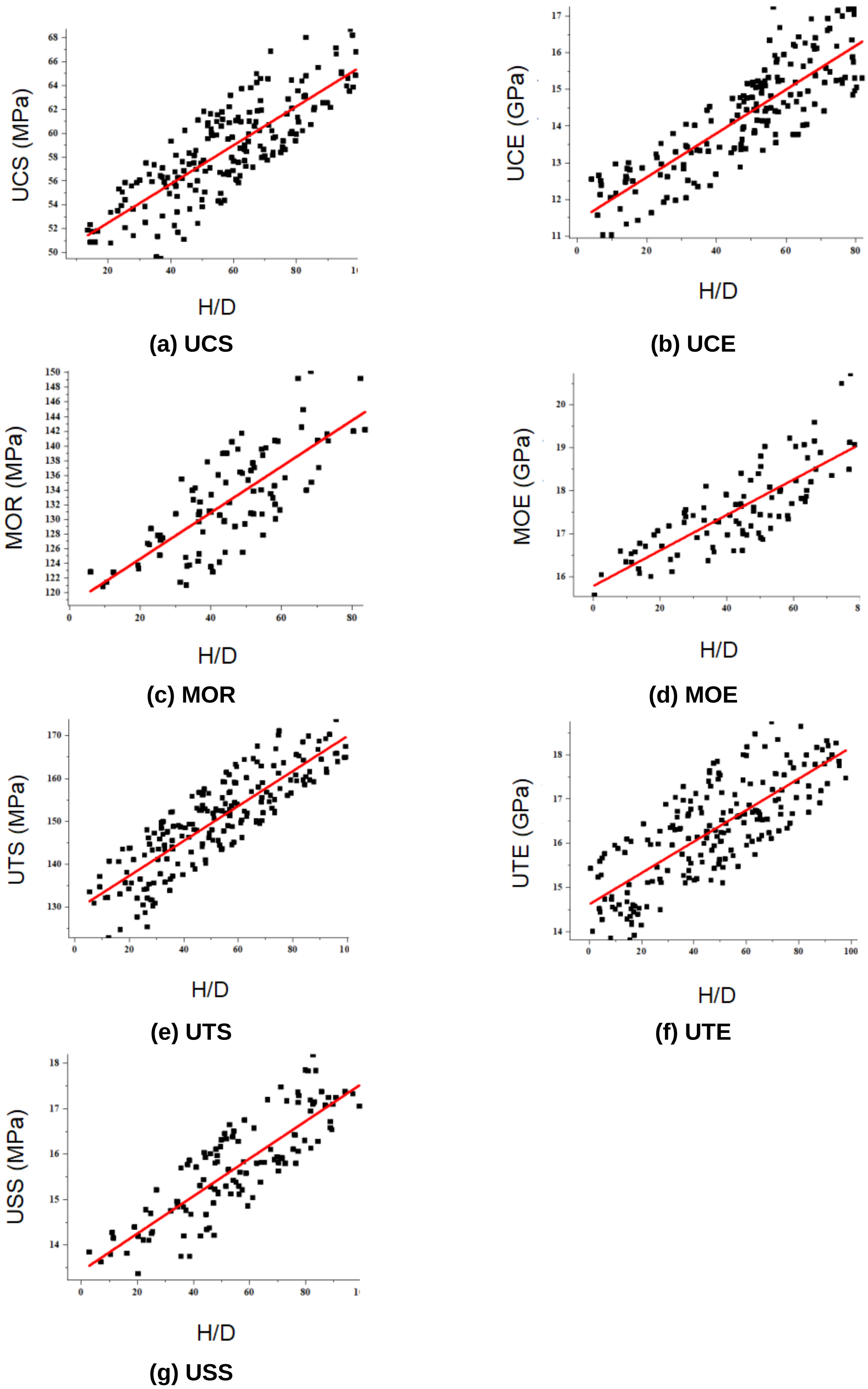

Fig. 3. The fitting curve of mechanical properties and height-diameter ratio of 60% specimens

Table 3. Fitting Relation Between Mechanical Properties and Height-Diameter Ratio

Mechanical Property Index	Relational Expression	R^2
UCS	y = 0.1622x + 49.262	0.6704
UCE	y = 0.0598x + 11.406	0.7220
MOR	y = 0.3148x + 118.31	0.5657
MOE	y = 0.0414x + 15.779	0.6366
UTS	y = 0.4067x + 129.18	0.7278
UTE	y = 0.0356x + 14.614	0.5991
USS	y = 0.0413x + 13.426	0.7052

Model Verification

Based on the fitting results between the mechanical properties of bamboo and the height-diameter ratio, a linear fitting relation between the mechanical properties of bamboo and the height-diameter ratio is proposed in this paper. According to the determination coefficient R^2 of linear fitting between various mechanical properties and height-diameter ratio of bamboo (Table 3), the goodness of fitting between various mechanical properties and height-diameter ratio of bamboo is high. Among them, *UCE*, *UTS*, and *USS* have larger R^2 fitted linearly with height-diameter ratio. In summary, the linear relationship between mechanical properties and height-diameter ratio can be used to deduce the mechanical properties of bamboo, and the measurement of height-diameter ratio is operable in practical application.

To verify the accuracy of the prediction formula in this paper, the height-diameter ratio was taken as the independent variable, and the mechanical properties of the remaining 40% of the mechanical properties of the bamboo specimens were tested. The measured mechanical properties were compared with the corresponding predicted values, and the comparison results were obtained, as shown in Fig. 4. It can be seen from the results in the figure that the predicted results by this method were close to the measured values, indicating that the prediction formula of bamboo mechanical properties obtained in this paper has certain applicability and accuracy, and has certain reference value for the application and development of bamboo structures.

Due to the need to use a large number of bamboo culm materials in the application of original bamboo structure, predicting the mechanical properties of a batch of bamboo culm by a certain mechanical property can save a lot of material and time testing costs. The conversion parameters of bamboo mechanical properties obtained in this paper can provide reference for the prediction of bamboo mechanical properties.

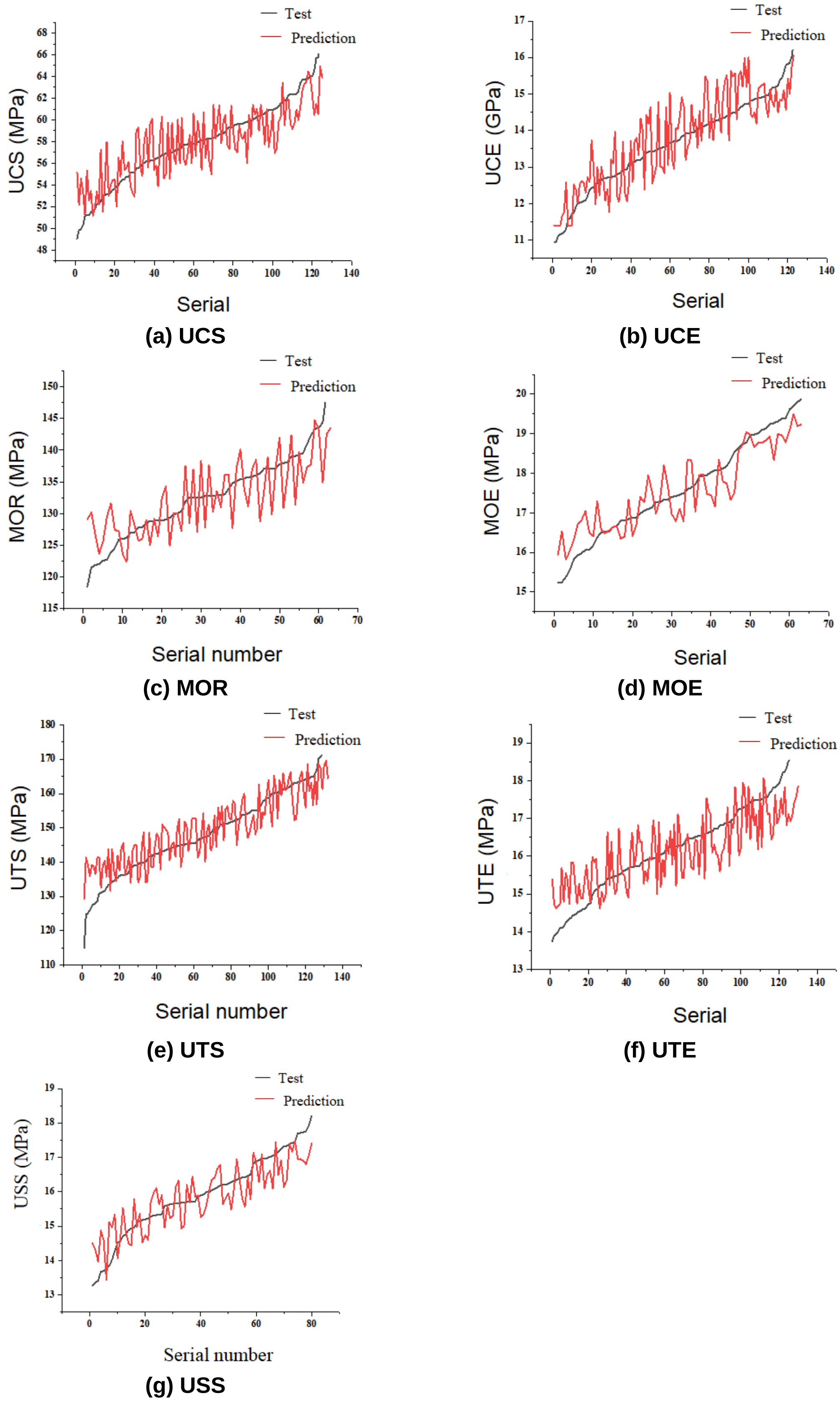

Fig. 4. Comparison of experimental and predicted mechanical properties

CONCLUSIONS

1. The test results showed that the longitudinal compression, longitudinal tensile, and bending properties relative to the grain direction were excellent, while the longitudinal shear properties of the grain were poor. The flexural strength was slightly smaller than the longitudinal tensile strength, while the longitudinal compressive strength was smaller than the flexural strength and the longitudinal tensile strength.
2. The results showed that the longitudinal compressive strength, longitudinal compressive elastic modulus, bending strength, bending elastic modulus, longitudinal tensile strength, longitudinal tensile elastic modulus, and longitudinal shear strength of bamboo all increased with the increase of the height-diameter ratio.
3. The predicted value of the linear fitting relationship between the mechanical properties of bamboo and the height-diameter ratio was compared with the experimental value. The results verified that the prediction formula proposed in this paper can be used as a reference for the prediction of the mechanical properties of bamboo.

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