A Two-variable Model for Predicting the Effects of Moisture Content and Density on the Mechanical Properties of *Phyllostachys edulis* Bamboo

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Phyllostachys edulis bamboo is one of the most valuable bamboo species in the world. It has the following advantages: high strength, light weight, and green, renewable character. In addition, it has a broad application prospect under the background of developing green buildings all over the world. The moisture content and density are the key factors affecting the mechanical properties of bamboos. However, there is no two-variable model of the mechanical properties with respect to the moisture content and density of *P. edulis* bamboo. In this paper, analysis of the compression parallel to the grain, bending, tensile parallel to the grain, and shear parallel to the grain of *P. edulis* bamboo were performed. The relationship between the mechanical properties and the moisture content and density was fitted by a two-variable model. The results show that the two-variable model has good fitting effect. As such, the two-variable model can be used to predict the mechanical properties of *P. edulis* bamboo according to its moisture content and density.

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Keywords: Phyllostachys edulis bamboo; Mechanical properties; Fitting; Prediction

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INTRODUCTION

Bamboo is the fastest growing plant on Earth, taking approximately 4 years to grow (Shastry and Unnikrishnan 2017; Skuratov *et al.* 2021). Bamboo is primarily distributed in the Asia-pacific region, Africa region, and the Americas region. Among them, the Asia-pacific region has the most bamboo species and quantity, especially China. In China, bamboo is primarily distributed in Zhejiang, Hunan, Jiangxi, and other provinces, and *Phyllostachys edulis* bamboo has the widest distribution, the largest amount, and the most applications in engineering. Compared with the scarcity of wood resources, bamboo is very abundant; it also has the following advantages: high strength and rigidity, light weight; and good toughness (Liu *et al.* 2014; Osorio *et al.* 2018; Zhang *et al.* 2019; Gauss *et al.* 2020; Wang and Shao 2020).

As environmental pollution is becoming more and more serious, and the construction industry accounts for the highest proportion of CO_2 emissions, more and more countries and international organizations are calling for and issuing relevant policies to promote the development of green buildings (Jose and Bhirud 2018; Kieu and Schäfer 2020; Hu and Skibniewski 2021). As such, bamboo is more and more widely used in green buildings. The ‘ZCB Bamboo Pavilion’ (Crolla 2017) is a public event space capable of seating 200 people. It is a bending-active gridshell structure that spans 37 meters, is more than 10 meters high, and is wrapped in a lightweight translucent glass-fibre reinforced polymer membrane. Bamboo can also be designed as a truss structure (Paraskeva *et al.* 2017), which consists of bamboo tubes and strips connected by steel clamps. The experimental results show that the truss structure can be used for low cost and prefabricated floor slabs and rooves. Bamboo can also be used to make bridges (Xiao *et al.* 2014), which have broad application prospects in rural and landscape areas.

In order to promote the application of bamboo in architecture, the mechanical properties must be clearly understood. It is of great importance to predict the mechanical properties of bamboo. Presently, research on the prediction of the mechanical properties of bamboo is very limited; most studies are for the prediction for a certain type of mechanical property, and the prediction indexes used are mostly one-variate. For example, Ribeiro *et al.* (2017) carried out bending tests on bamboo stalks and obtained the relationship between the bending strength and bending elastic modulus. Dixon and Gibson (2014) studied the relationship between axial compressive performance and density of *P. edulis* bamboo and fit it using a linear function. Javadian *et al.* (2019) established a prediction model for tensile strength using the diameter of Petung Putih bamboo.

In the prediction indexes of bamboo, density has the strongest correlation with the mechanical properties theoretically (Lo *et al.* 2004; Bahtiar *et al.* 2019). At the same time, the effect of the moisture content on the mechanical properties of bamboo is very important (Xu *et al.* 2014; Chen *et al.* 2018; Jakovljević and Lisjak 2019). It can be considered that density is the property of bamboo itself, and water content is related to the external environment. Therefore, it is of great importance to use the moisture content and density to predict the mechanical properties of bamboo. The established prediction formula can be used to predict the mechanical properties of bamboo by using the physical properties of bamboo. Such an approach which will save a lot of specimens and material costs for mechanical properties test of bamboo. This type of study has important reference value for promoting the application of bamboo structure.

In order to predict the mechanical properties of bamboo, the following tasks were carried out in this paper: (1) tests of the compression parallel to the grain, bending, tensile parallel to the grain, and shear parallel to the grain of Chinese *P. edulis* bamboo were carried out, and the failure modes and process of bamboos were analyzed. (2) The prediction formulas of mechanical properties and physical properties were proposed, and the relationship between mechanical properties and two physical properties was fitted.

EXPERIMENTAL

Materials

A total of 25 samples of 4-year-old *P. edulis* bamboo with a length of 6 m were cut in Chenzhou City, Hunan Province, China. In order to avoid the splitting of the bamboo stalk caused by logging, the cutting position was near the bottom node. After the bamboo stalks were air-dried, four types of specimens were made, *i.e.*, compression parallel to the grain (UC), bending (B), tensile parallel to the grain (UT) and shear parallel to the grain (US), which were distributed uniformly and circulative along the height direction of the bamboo stalks. As shown in Fig. 1, the ratio of the height and diameter of UC and US specimens was 1, according to JG/T standard 199 (2007) and ISO standard 22157-1 (2019). The size of the B specimens was 220 mm × 15 mm × t mm (where t is the wall thickness), and the size of UT specimens was 330 mm × 15 mm × t mm, according to JG/T standard 199 (2007) and ISO standard 22157-1 (2019). After the mechanical property tests, a small specimen, with the size of approximately 20 mm × 20 × t mm, was removed near the failure location to carry out the moisture content and density tests.

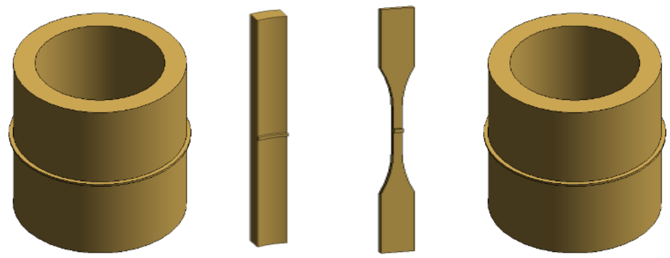


Fig. 1. Schematic diagram of the specimen

Physical and Mechanical Properties

The mechanical properties were tested using an ETM504C universal testing machine (Shenzhen Wancai Test Equipment Co., Ltd., Shenzhen, China). According to JG/T199 (2007) and ISO 22157-1 (2019), the loading rate of the UC, US and UT samples was 0.01 mm/s, and the loading rate of the B samples was 150 N/mm^2 per min. The calculation formula of the mechanical properties, moisture content and density are shown in Eqs. 1 through 6,

$$f = \frac{P_{max}}{A} \quad (1)$$

$$E = \frac{20\Delta P}{A\Delta l} \quad (2)$$

$$MOR = \frac{150P_{max}}{tb^2} \quad (3)$$

$$MOE = \frac{1920000 \cdot \Delta P}{8\delta_m tb^3} \quad (4)$$

$$MC = \frac{m_1 - m_0}{m_0} \times 100 \quad (5)$$

$$\rho = \frac{m_1}{v} \quad (6)$$

where MC is the air dry moisture content (%); f is the strength (MPa) of the UC, US, and UT specimens; E is the elastic modulus (GPa) of the UC and UT specimens; MOR is the bending strength (MPa); MOE is the flexural elastic modulus (GPa); P_{max} is failure load (N); A is the stressed area (mm^2); t is the thickness of the specimen (mm); b is the height of the specimen (mm); P is the difference between the upper and lower loads (N); Δl is the difference (mm) in specimen deformation under the function of the upper and lower loads; δ_m is the deflection value (mm) of the pure bending section of the specimen under the action of ΔP; m_1 and m_0 are the mass (g) of the gas dry and full dry, respectively; ρ is the density (g/cm^3); and V is the dry gas volume (cm^3), which was measured *via* the drainage method.

Data Analysis

The commercial statistical software Origin (Version 8.0, Originlab Co., Northampton, MA) was used to analyze the data, and important statistical indicators, *e.g.*, the mean value, maximum value, minimum value, and standard difference of mechanical properties were obtained. Nonlinear surface fitting was carried out for the mechanical properties by adopting the moisture content and density, and the Poly function, as shown in Eq. 7,

$$f = z_0 + aMC + b\rho + cMC^2 + d\rho^2 + eMC\rho \quad (7)$$

where z_0, *a*, *b*, *c*, *d*, and *e* are parameters.

The determination coefficient (R^2) was used as the index to measure the fitting effect. R^2 is the ratio of the regression sum of squares to the total sum of squares, *i.e.*, the percentage of the dependent variable variability that can be explained by the regression formula. The value range of R^2 is [0,1]. The larger the value is, the better the fitting effect is. If R^2 is greater than 0.7, it indicates a good correlation.

RESULTS AND DISCUSSION

Mechanical Performance Statistics

The compressive strength parallel to the grain (UCS), compressive elastic modulus parallel to the grain (UCE), flexural strength (MOR), flexural elastic modulus parallel to the grain (MOE), tensile strength parallel to the grain (UTS), tensile elastic modulus parallel to the grain (UTE), and shear strength parallel to the grain (USS) of the bamboo samples were calculated (as shown in Table 1), and the probability distribution is shown in Fig. 2. It can be seen from Table 1 that the mechanical properties of the bamboo samples show typical anisotropic characteristics, and the UTS is the highest among these mechanical properties. Figure 2 shows that all the mechanical properties conform to a normal distribution.

Table 1. Mechanical Performance Statistics

	Quantity	Mean Value	Maximum Value	Minimum Value	Standard Deviation
UCS (MPa)	317	58.83	73.98	41.61	6.67
UCE (GPa)	317	13.05	17.74	7.48	2.68
MOR (MPa)	243	131.52	176.99	85.35	16.20
MOE (GPa)	243	16.99	20.45	13.10	3.49
UTS (MPa)	308	145.89	155.52	134.70	6.02
UTE (GPa)	308	16.39	17.68	15.17	4.50
USS (MPa)	228	15.44	16.59	14.12	3.42

Destruction Process and Destruction Pattern

The failure modes of various mechanical properties of bamboo specimens include ductile failure and brittle failure. The test types of mechanical properties for ductile failure include tensile and bending resistance parallel to the grain, and those for brittle failure include tensile and shear resistance parallel to the grain. Typical load-displacement curves obtained from various mechanical properties tests are shown in Fig. 3, and failure modes are shown in Fig. 4. The load-displacement curve of UC specimen can be divided into three stages: elastic section, elastic-plastic section, and failure section. In the elastic section, the load of the specimen increases linearly with the increase of the displacement, and no damage occurs to the bamboo at this time. With the increase of load, the load-displacement curve changes from linear to nonlinear.

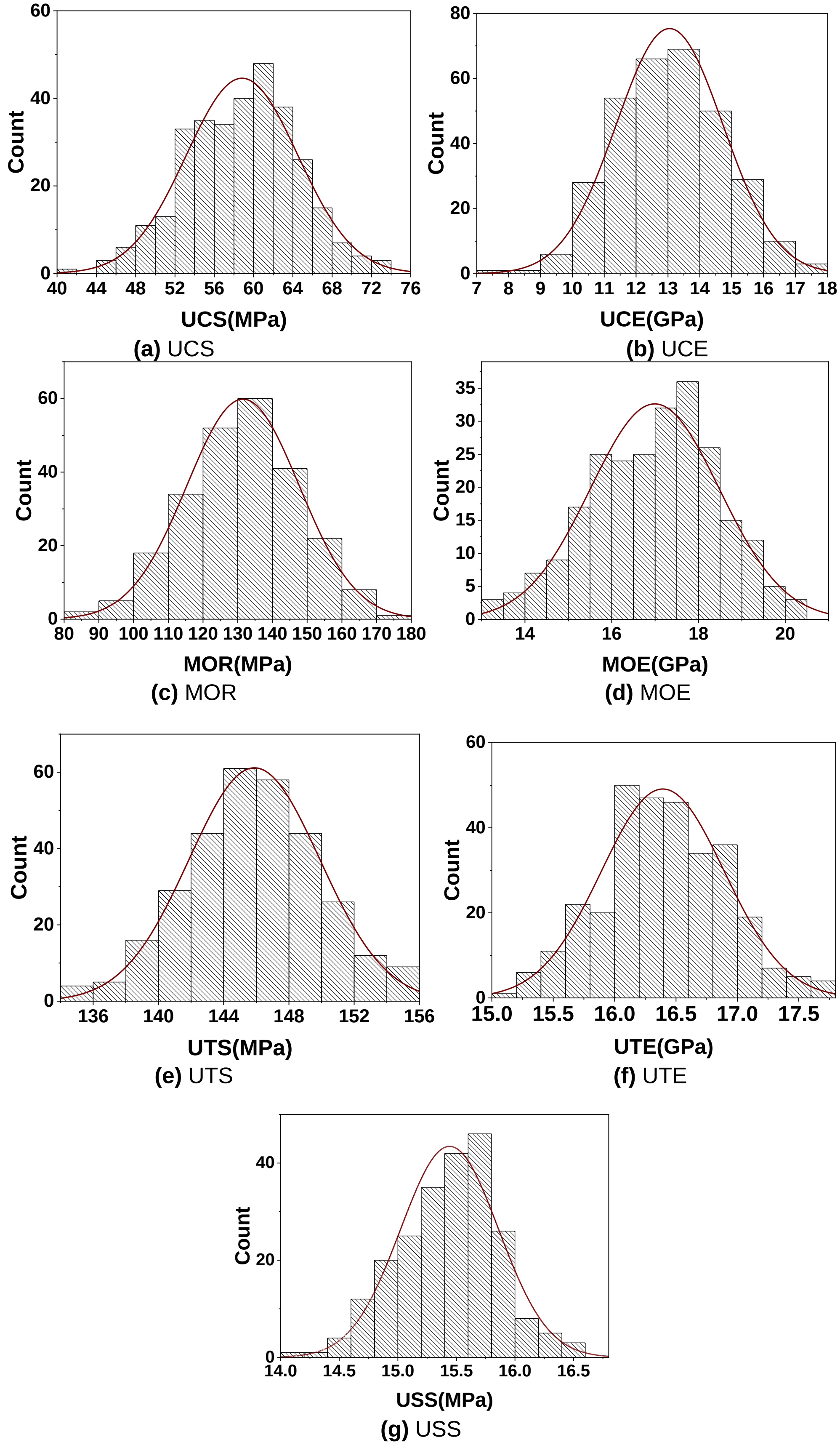


Fig. 2. Probability distribution of the mechanical properties

Compared with the elastic section, the increase of specimen displacement increases gradually with the same load. At this stage, the specimen gradually produces visible buckling deformation. In the failure stage, the specimen was broken due to continuous cracks in the fiber direction (Fig. 4a). The plastic platform of load-displacement curve of the B specimen was obviously shorter than that of the UT specimen. During the loading process, the specimen gradually deformed in flexure and was finally destroyed by fiber fracture in pure bending section (Fig. 4b). The load-displacement curves of UT and US specimens generally showed linear characteristics, that is, the specimens failed without warning. As can be seen from the failure picture, UT specimen fractured in the middle horizontal plane (Fig. 4c), while US specimen failed due to dislocation in the shear plane (Fig. 4d).

In order to better compare the ductility of various specimens, the ductility coefficient of load-displacement curve in Fig. 1 is calculated in Table 1. Table 1 shows that the ductility coefficient of UC specimen reached 2.47, which was the highest among all specimens. B specimen and UT specimen were the next. The ductility coefficient of the US specimen was 0.73, which was the lowest among all specimens. In summary, in the four types of tests of compression resistance, bending resistance, tension resistance and shear resistance parallel to the grain, the compression ductility parallel to the grain was the highest, and the tensile ductility parallel to the grain is the lowest.

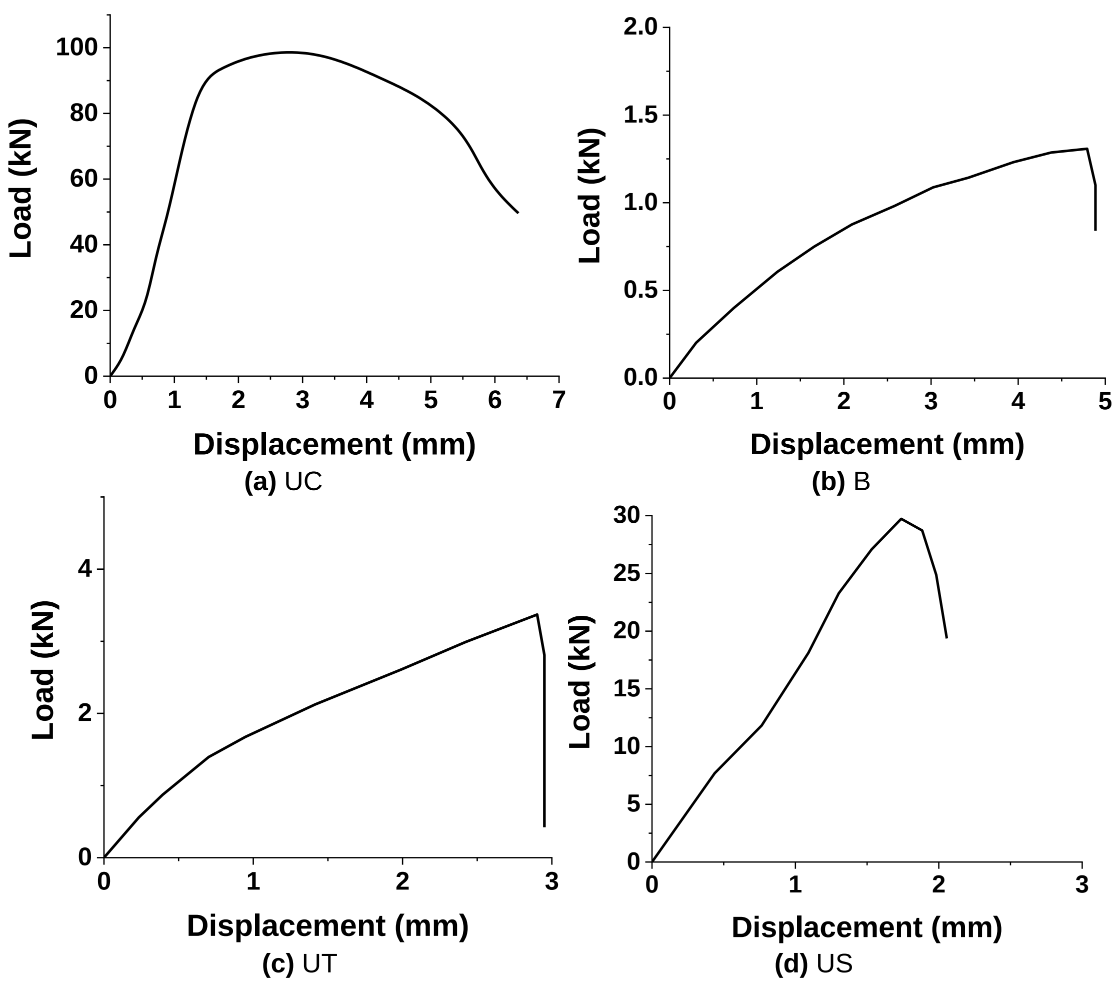
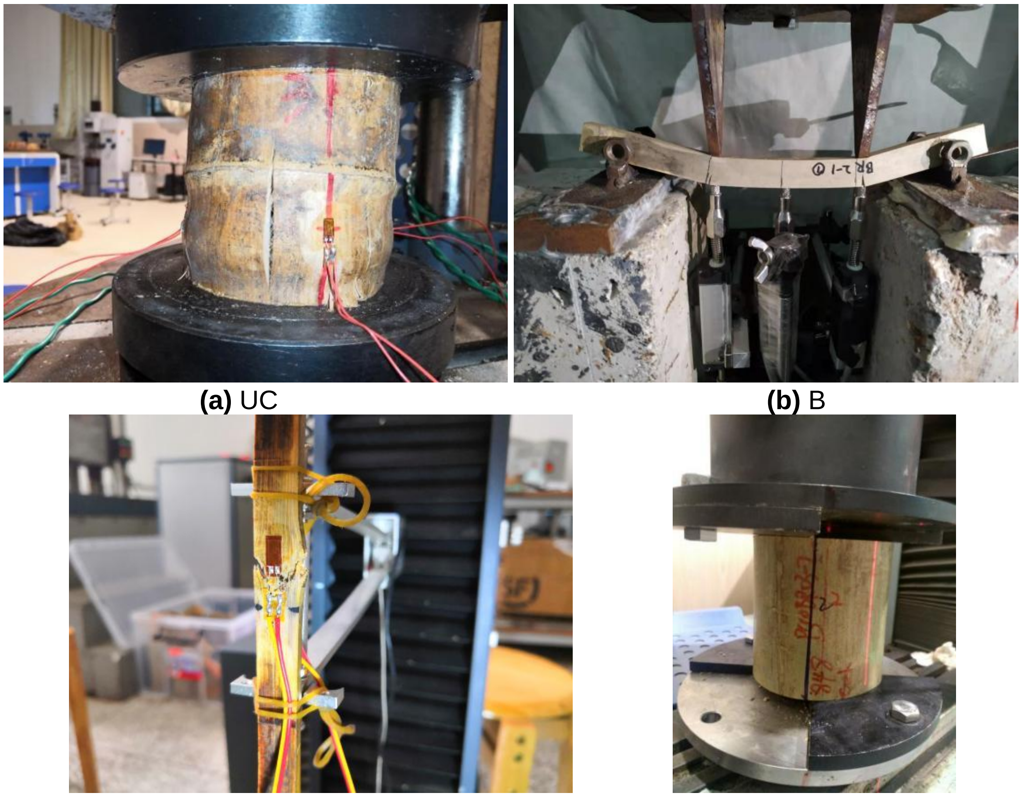


Fig. 3. Typical load-displacement curves



(a) UC **(b)** B

(c) UT **(d)** US

Fig. 4. Typical damage pattern

Table 1. Ductility Coefficient Statistics

	UC	B	UT	US
Ductility coefficient	2.47	1.48	1.25	0.73

Two-variable Model of the Mechanical Properties Considering the Moisture Content and Density

The fitted surface is shown in Fig. 5, and for each mechanical property, the corresponding fitting parameters of the moisture content and density were statistically analyzed (Table 2). It can be seen from Fig. 5 and Table 2 that among the 7 mechanical properties, the R^2 value of UCS, UCE, and UTE fitted with the two physical properties was greater than 0.7, indicating that the above three mechanical properties had a good correlation with water content and density. The R^2 values of UTS, MOR, MOE and USS fitted with the two physical properties were slightly less than 0.7. The mean R^2 value of 7 mechanical and physical properties was 0.7. UTE had the highest fitting correlation, and MOE had the lowest.

Since the mechanical properties of bamboo cannot be obtained at the same time through the testing of one specimen, using Eq. 7 and the parameters in Table 2, the moisture content and density can be used to predict multiple mechanical properties of bamboo. The results of this paper will improve the efficiency of the prediction of the mechanical properties of *P. edulis* bamboo in terms of the test and time costs.

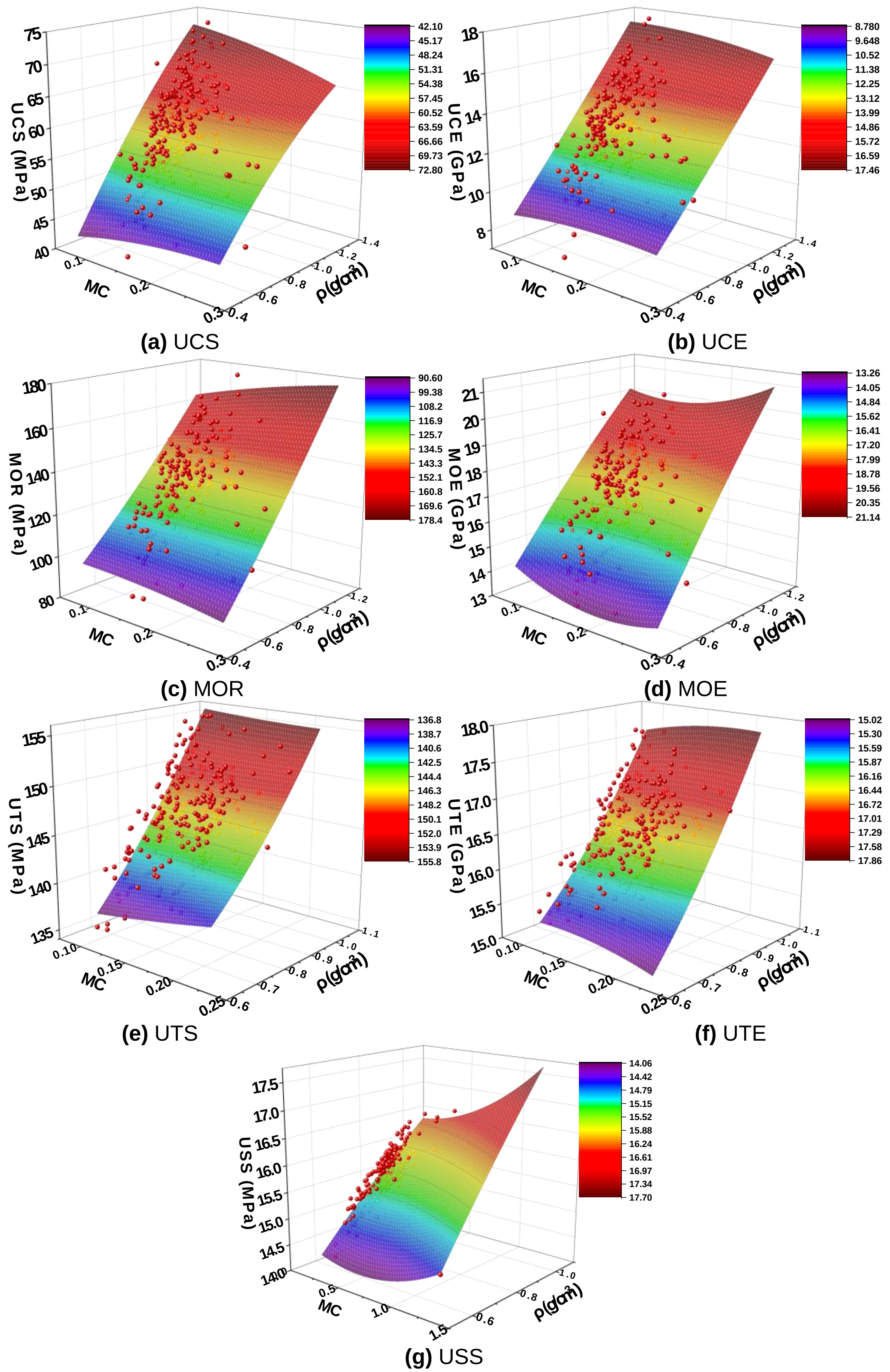


Fig. 5. Fitting surface of the mechanical properties, moisture content, and density

Table 2. Fitting Parameters

	z_0	a	b	c	d	e	R^2
UCS	13.50	65.82	61.30	-68.62	-11.10	-57.08	0.74
UCE	3.35	12.22	10.30	-21.38	0.52	-6.97	0.73
MOR	65.28	-48.70	58.17	-112.64	16.50	130.33	0.69
MOE	11.07	-26.81	10.15	56.35	-1.46	9.56	0.64
UTS	119.16	50.27	5.66	33.33	29.82	-63.14	0.66
UTE	14.43	-0.93	-2.14	-20.46	4.49	8.81	0.78
USS	10.93	-1.98	6.43	0.91	-1.24	1.85	0.69

CONCLUSIONS

In this work, analysis of the compression parallel to the grain, bending, tensile parallel to the grain, as well as shear parallel to the grain of *P. edulis* bamboo was performed. In addition, two-variable models of the compressive strength parallel to the grain, compressive elastic modulus parallel to the grain, flexural strength, flexural elastic modulus, tensile strength parallel to the grain, tensile elastic modulus parallel to the grain, shear strength parallel to the grain, and moisture content and density were fitted by the polynomial functions. The main conclusions are as follows:

1. The failure of bamboo is divided into ductile failure and brittle failure. The compressive and bending resistance parallel to the grain show ductile failure characteristics, while the tensile and shear resistance parallel to the grain show brittle failure characteristics.
2. Among the 7 mechanical properties of bamboo, the fitting coefficients of compressive strength parallel to the grain, compressive elastic modulus parallel to the grain and tensile elastic modulus parallel to the grain with water content and density are greater than 0.7. That is, they have a good correlation with water content and density. The correlation between tensile elastic modulus along grain and two physical properties is the best, while flexural elastic modulus is the worst.
3. The two-variable model in this study can predict the mechanical properties of *P. edulis* bamboo by its moisture content and density, which will strongly promote the application of bamboo in engineering.

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Conflict of Interest Statement

The authors declare that they have no conflict of interest.

Supplementary Materials

Underlying research materials related to this research can be accessed on request from the corresponding author.

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