Prediction of Longitudinal Compressive Physical and Mechanical Properties of Bamboo

Yan Yuan,* and Liming Yang

Some traditional building materials, such as concrete and steel, have a negative impact on the environment. With the in-depth implementation of sustainable development, green materials are gradually being considered, and bamboo is a green high-energy building material. However, there have been few studies on the prediction of mechanical properties of bamboo. In order to predict the longitudinal compressive properties of bamboo, tests were carried out on the longitudinal compressive tests of bamboo. The failure mode was explored, as well as the relationship between the physical and mechanical properties of bamboo. Prediction formulas were developed for the longitudinal compressive properties of bamboo. The results showed that the failure mode of the longitudinal compressive test of bamboo was ductile failure. The wall thickness and diameter of bamboo were found to be positively correlated with height. The longitudinal compressive strength and elastic modulus were positively correlated with height and negatively correlated with wall thickness and diameter. The longitudinal compressive strength and elastic modulus were positively correlated with height. The linear model can be used to fit the relationship between mechanical properties and height. This research provides a reference for the prediction of bamboo properties.

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*Contact information: School of Civil and Architectural Engineering, Zhengzhou University of Science and Technology, Zheng Zhou 450064, China; *Corresponding author: 250716109@qq.com*

INTRODUCTION

As sustainable development continues to gain momentum, some traditional building materials, including masonry, concrete, and steel have increasingly struggled to align with the advancements in green construction practices (Feng *et al.* 2024; Jawaid *et al.* 2024; Li *et al.* 2024). China's "14th Five-Year Plan" also clearly states to pay attention to the economic and social green transformation. The civil engineering industry consumes a lot of energy and produces a lot of environmental pollution. Research and application of new green building materials is an inevitable trend in the sustainable development of the construction industry.

Unlike the aforementioned traditional building materials, wood and bamboo stand out as eco-friendly and renewable options, making them ideal choices for construction. Given the current scarcity of wood resources, bamboo has emerged as a promising new building material. It boasts a short growth cycle, excellent mechanical properties, light weight per unit volume, high toughness, and a high level of comfort (Li *et al.* 2020; Han *et al.* 2023; Lei *et al.* 2024).

At present, bamboo has been used in some projects, such as the bamboo and rattan pavilion of the 2019 Beijing World Horticultural Expo. The bamboo and rattan pavilion uses primarily bamboo structure, which is the original bamboo arch building system. The structure is built by more than 5000 round bamboo pieces, and the main stress structure is the bamboo arch structure, with a span of 32 m, which is one of the largest arched round bamboo buildings without fulcrum in China at present. For example, the turtle classroom in Green School adopts round bamboo structure, which makes the teaching environment comfortable and natural, and is loved by teachers and students. There are numerous bamboo structures, with primary applications spanning large venues, tourist buildings, and more. China places significant emphasis on the development of rural areas. If the promotion and application of this innovative bamboo structure can be extended to rural regions, it holds the potential to tap into a vast market.

In order to make bamboo structure widely used, it is important to master the mechanical properties of bamboo. At present, the research on physical and mechanical properties of bamboo has achieved a series of results. Grosser and Liese (1971) divided bamboo vascular bundles into four basic types, namely open, tight waist, broken waist, and double broken waist, based on the characteristics of the bundles on the transverse section of bamboo. Amada and Untao (2001) found that there was a strong correlation between the fracture toughness of bamboo and the fiber volume fraction. Lo *et al*. (2004) observed the vascular bundle density of bamboo through scanning electron microscopy and carried out compressive tests. The research results showed that a higher vascular bundle density resulted in a higher bearing capacity of bamboo. Xu *et al*. (2014) studied the effect of water content on the mechanical properties of bamboo, and the results showed that the mechanical properties of bamboo decreased significantly when the water content reached 30%. Sá Ribeiro *et al*. (2017) conducted non-destructive testing of bamboo by SWT, obtained the density, elastic modulus, fracture modulus, and other properties of bamboo stalks at different height positions, and established the relationship model between the physical and mechanical properties.

The above research shows that bamboo has excellent mechanical properties. The prediction of mechanical properties of bamboo is an important part of bamboo research. However, there has been a lack of studies on the prediction of mechanical properties of whole bamboo culm. In this work, a relationship between the mechanical and physical properties of bamboo straws is proposed, and it can provide a reference for the prediction of bamboo properties.

EXPERIMENTAL

Bamboo Selection and Specimen Making

The experimental study utilized moso bamboo sourced from Hunan Province, China. The bamboo specimens were approximately four years old and had a moisture content of around 15%. Only bamboo that was free from obvious bending, corrosion, moth damage, cracking, and mildew was randomly harvested from the bamboo forest and subsequently transported to the laboratory for air-drying treatment. From this batch, a random bamboo specimen was selected to undergo a stress test along its grain. The longitudinal compression specimens are shown in Fig. 1, and the ratio of height to diameter of the specimen used was 1.

Fig. 1. Longitudinal compression specimens

Mechanical Properties Test and Calculation

According to the standards JG/T 199 (2007) and ISO 22157:2019 (2019), mechanical properties tests were carried out. Specimens were tested with a universal testing machine to determine various mechanical properties. For formal loading, the loading rate was 0.01 mm/s. The formula for calculating the strength and elastic modulus of the specimen was as follows,

$$UCS_W = \frac{P_{\max}}{A} \tag{1}$$

$$UCE_W = \frac{20\Delta P}{A\Delta l} \tag{2}$$

where UCS_W is the longitudinal compressive strength of the specimen with water content W (MPa). UCE_W is the longitudinal compressive elastic modulus with moisture content W (MPa). $P_{\max}$ is the failure load (N); A is the force area (mm^2); ΔP is the difference between the upper and lower loads (N); Δl is the difference (mm) between the deformation value of the specimen under the upper and lower loads.

Moisture Content Adjustment

After loading the specimen to failure, specimens with a mass of no less than 1.5 g were immediately intercepted near the failure site for water content test. The formula used for the water content calculation is shown in Eq. 5. Because water content has a significant impact on the mechanical properties of bamboo (Zhou *et al.* 2022), the value of mechanical properties was uniformly adjusted to the value under the standard water content (12%) in this study, and the adjustment formula is shown in Eq. 6,

$$W = \frac{m_1 - m_0}{m_0} \times 100 \tag{3}$$

$$UCS = K_f UCS_W \tag{4}$$

$$UCE = K_E UCE_W \tag{5}$$

$$K_f = \frac{1}{1.1 - 0.7e^{-0.15W}} \tag{6}$$

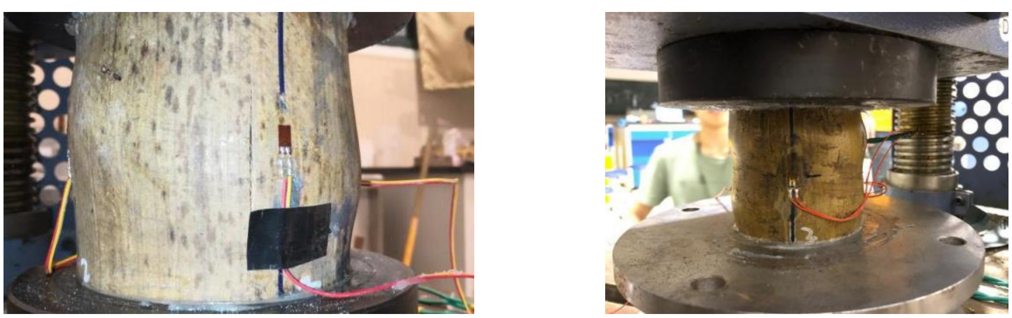
$$K_E = \frac{1}{0.89 + 0.36e^{-0.1W}} \quad (7)$$

where W is the moisture content of air drying (%); m_1 and m_0 are the masses of air dried and fully dried materials, respectively (g). UCS and UCE are the strength or elastic modulus of the specimen under the standard water content (12%). K_f and K_E are the moisture content correction coefficients, which are related to the specific mechanical performance index and moisture content.

RESULTS AND DISCUSSION

Failure Mode

The failure process of bamboo compression test was observed to have the following features: In the initial stage of loading, the specimen was in the elastic stage, and the specimen showed no obvious deformation. With the increase of load, the specimen gradually exhibited buckling deformation. The position of the bulge mainly included the middle and the end (Fig. 2), and most of the bulges occurred in the middle. When the bulging reached a certain degree, the specimen began to crack. In the limit state, the specimen cracked through, and it cracked into several bamboo slices. The failure process of the longitudinal compression of bamboo can be divided into three stages, namely, elastic stage, elasto-plastic stage, and failure stage. In the elastic stage, the deformation of the specimen was small and recoverable, and the load and displacement were linear. In the elasto-plastic phase, the relationship between load and displacement was no longer linear. When the same load was applied, the displacement of the specimen was larger than that of the elastic stage. At this stage, the specimen showed deformation that was visible to the naked eye. The failure mode of the longitudinal compressive test of bamboo was judged to be ductile failure.



(a) Central bulge **(b)** End bulge

Fig. 2. Failure patterns

Eigenvalue Analysis

The height (h), wall thickness (t), diameter (D), compressive strength (UCS), and compressive elastic modulus (UCE) of the specimens were statistically analyzed, and the results obtained are shown in Table 1. As shown, the height of the specimen ranged from 96.2 to 5900 mm, the wall thickness of the specimen ranged from 5.69 to 12.87 mm, and the outer diameter of the specimen ranged from 55.2 to 112.3 mm. The wall thickness and diameter of the specimen decreased with the increase of height. The longitudinal compressive strength of the specimen ranged from 45.4 to 70.8 MPa and decreased gradually with the increase of height. With the increase of wall thickness and diameter, the compressive strength of the specimen decreases gradually. The range of the elastic modulus was 13.2 to 18.5 GPa. With the increase of height, the elastic modulus decreased gradually. With the increase of wall thickness and diameter, the *UCE* values of the specimen decreased gradually. The mean wall thickness and diameter of bamboo culms were 9 mm, 86.9 mm, 57.2 MPa, and 15.5 GPa, respectively. The results show that the bamboo had excellent compressive resistance. Compared to traditional building materials, bamboo has a significantly higher strength-to-weight ratio than concrete and steel. The compressive strength of bamboo is also relatively high compared to wood. Bamboo's short growth cycle is another advantage over wood. Therefore, bamboo can be regarded as an ideal building material and plays an important role in promoting the development of green buildings.

Table 1. Physical and Mechanical Properties Statistics

Specimen Number	*h* (mm)	*t* (mm)	*D* (mm)	*UCS* (MPa)	*UCE* (GPa)
CP-1	96.25	12.87	112.34	45.38	13.19
CP-2	539.87	11.25	106.92	48.91	13.98
CP-3	1022.87	10.36	101.49	50.28	14.18
CP-4	2083.87	9.47	93.29	55.39	14.98
CP-5	3427.29	8.66	85.27	58.29	15.28
CP-6	4183.28	7.29	73.28	62.48	16.39
CP-7	4892.29	6.39	67.29	66.27	17.73
CP-8	5901.97	5.69	55.25	70.79	18.48
Mean value	2768.46	9.00	86.89	57.22	15.53
Standard deviation	2151.03	2.48	20.27	8.91	1.87
Coefficient of variation	0.78	0.28	0.23	0.16	0.12

Relationship Between Physical Properties

From the above analysis, the wall thickness and diameter of bamboo stalk were negatively correlated with the height, while the wall thickness and diameter were positively correlated. The height, wall thickness, and diameter of bamboo were fitted linearly, and the fitting curves and relations are shown in Fig. 3. The figure shows that the fitting determination coefficients R^2 among the physical properties of bamboo were all above 0.964. Thus, there was a strong correlation between the physical properties of bamboo. Through the relationship in Fig. 3, the physical properties of bamboo can also be predicted. If the height of the bamboo stalk from the ground is known, then the wall thickness and diameter of the bamboo stalk at any height can be predicted by the prediction formula shown in Fig. 3. On the premise that the wall thickness or diameter of any place is known, the diameter over the wall thickness can also be predicted.

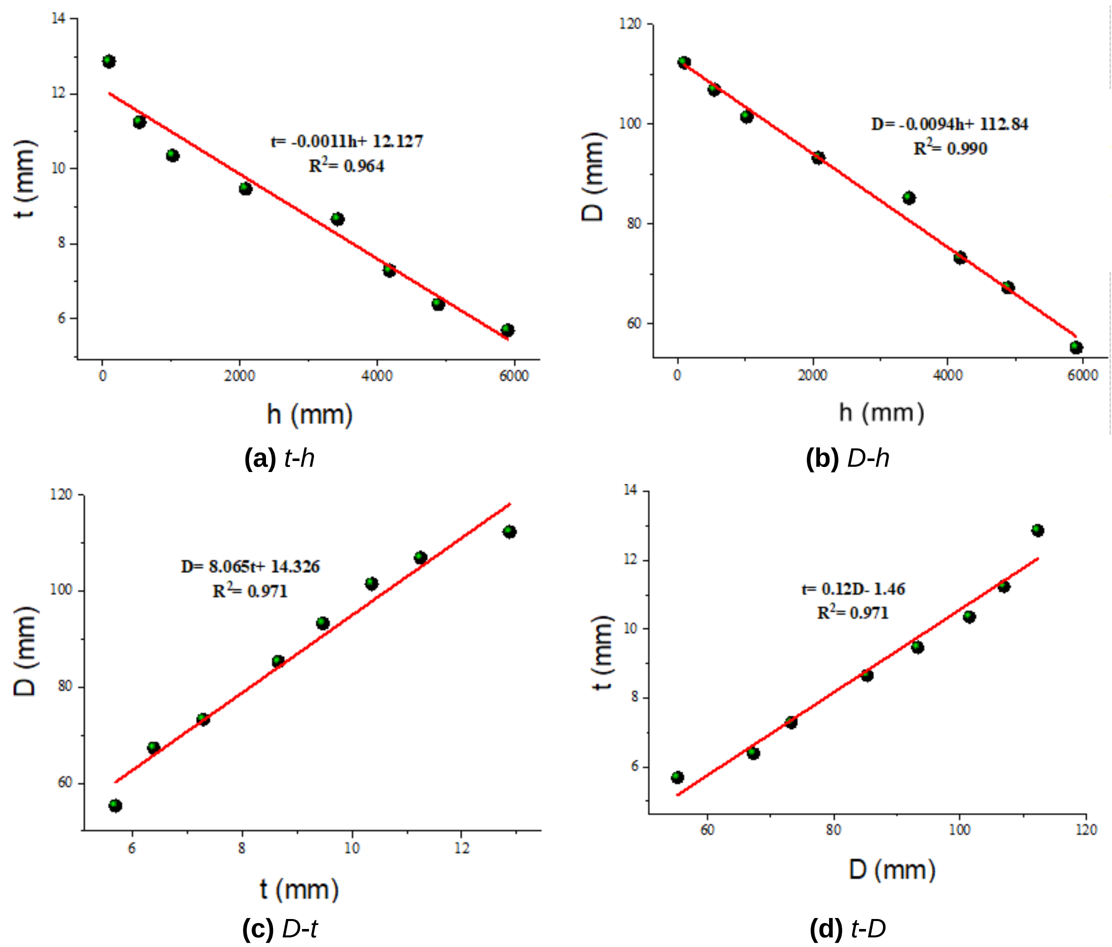


Fig. 3. Fitting curves of physical properties

Relationship Between Mechanical and Physical Properties

It is commonly recognized that the height, wall thickness, and diameter of bamboo can be readily measured using a basic dimensional measuring tool. However, determining the longitudinal compressive strength and elastic modulus of bamboo necessitates conducting experiments. If these properties could be accurately predicted based on height, wall thickness, or diameter, it would significantly reduce the expenses associated with various testing procedures. Linear functions were used to fit the compression strength and elastic modulus of the grain with the height, wall thickness, and diameter, respectively. The fitting curves and fitting relationships obtained are shown in Fig. 4.

Figure 4 suggests that the linear function can better fit the relationship between the longitudinal compressive mechanical properties and physical properties of bamboo, with the lowest coefficient R^2 being 0.951 and the highest coefficient R^2 reaching 0.995. Through the prediction formula shown in Fig. 4, the mechanical properties of bamboo can be predicted based on its physical properties, thus achieving the purpose of saving time, money, and materials, and providing reference for the application of bamboo structural engineering.

There are many reasons for the pattern shown in Fig. 4. From the microscopic level, the internal structure of bamboo is mainly composed of vascular bundles and basic tissues. The higher the vascular bundle density, the higher the mechanical properties of bamboo.

Bamboo from the bottom to the top of the vascular bundle density gradually increased, so the mechanical properties gradually increased. On the other hand, the bottom of the bamboo is wet, and the top of the photosynthesis is strong, so the mechanical properties of the top of the bamboo will be higher than the bottom.

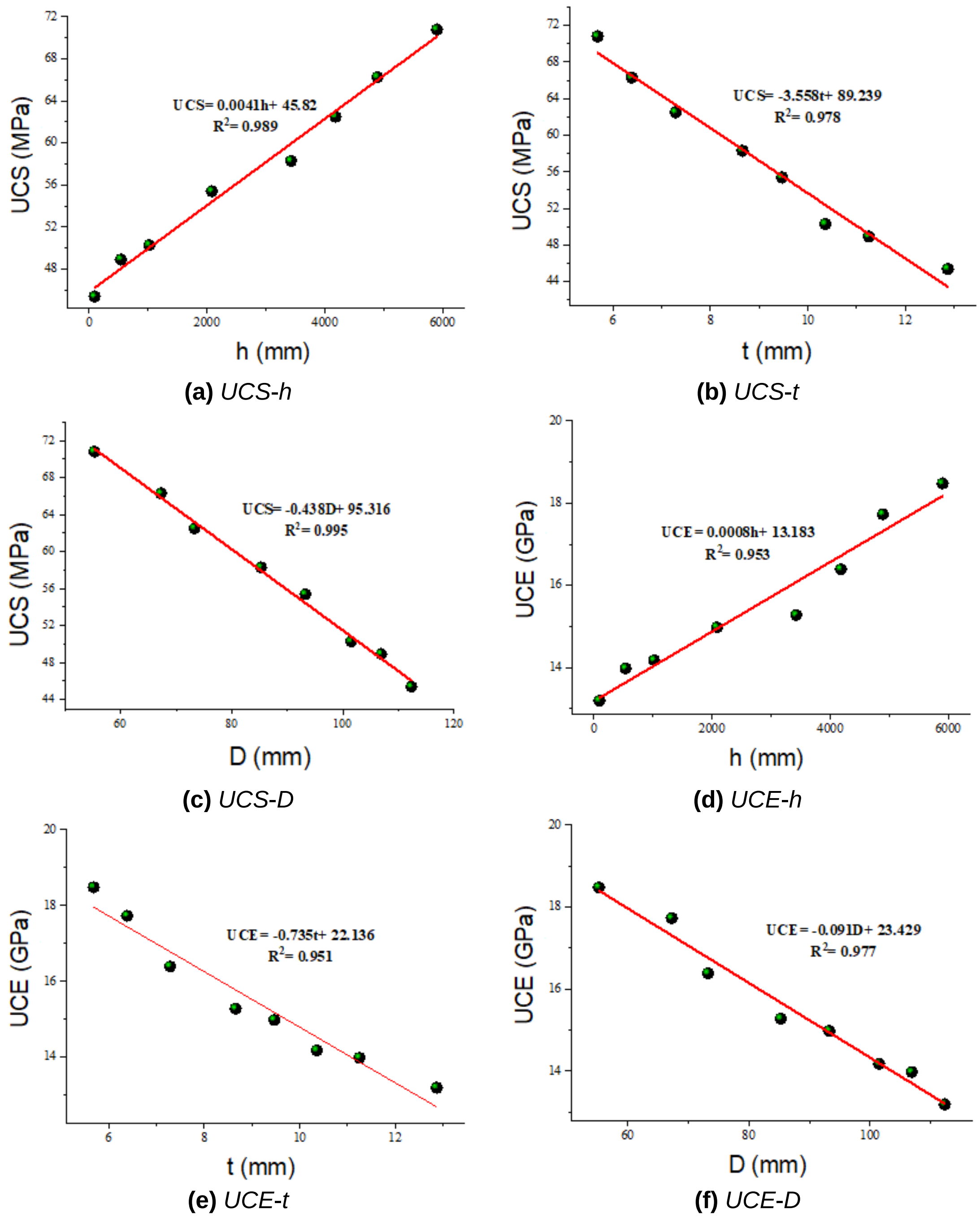
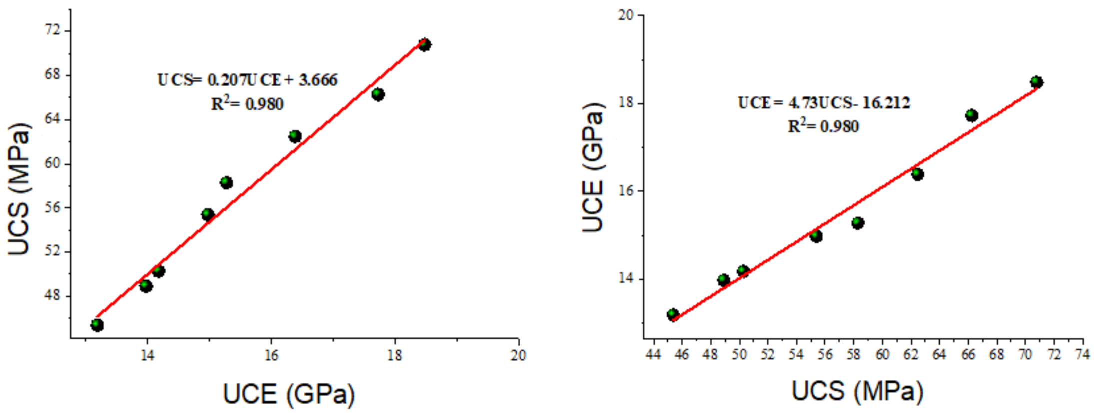


Fig. 4. Fitting curves of mechanical and physical properties

Relationship Between Mechanical Properties

To obtain the relationship between the longitudinal compressive strength and the longitudinal compressive elastic modulus of bamboo, the longitudinal compressive strength and elastic modulus were fitted, and the fitting curve and formula are shown in Fig. 5. It can be seen from Fig. 5 that there was a positive correlation between the longitudinal compressive strength of bamboo and the elastic modulus. That is, the higher the strength of bamboo, the higher is the elastic modulus, and the higher is its elastic modulus and strength. The fitting coefficient R^2 between the longitudinal compressive strength and longitudinal compressive elastic modulus of bamboo was 0.98, indicating a strong correlation.



(a) UCS-UCE **(b)** UCE-UCS

Fig. 5. Fitting curves between mechanical properties

CONCLUSIONS

1. The failure mode of longitudinal compressive tests of bamboo compression was observed to involve middle or end buckling failure. The failure process can be divided into elastic stage, elasto-plastic stage, and failure stage. In general the failure mode was observed to be ductile failure.
2. The average compressive strength and the average compressive elastic modulus were 57.2 MPa and 15.5 GPa, respectively. In summary, the bamboo was shown to have excellent compression resistance.
3. The wall thickness and diameter of bamboo decreased with the increase of height, and the wall thickness and diameter had a positive correlation. The longitudinal compressive strength and elastic modulus increased with the increase of height. However, it decreased with increasing wall thickness and diameter. There was a positive correlation between longitudinal compressive strength and elastic modulus.
4. The relationships among the physical properties of bamboo, between the mechanical properties and the physical properties, and between the mechanical properties of bamboo were established. The fitting relationships could realize the prediction of the physical and mechanical properties of bamboo.

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