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ARTICLE

Prediction of Mechanical Properties of Structural Bamboo and Its Relationship with Growth Parameters

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ABSTRACT

Bamboo is a renewable natural building material with good mechanical properties. However, due to the heterogeneity and anisotropy of bamboo stalk, a large amount of material performance testing costs are required in engineering applications. In this work, longitudinal compression, bending, longitudinal shear, longitudinal tensile, transverse compression and transverse tensile tests of bamboo materials are conducted, considering the influence of the bamboo nodes. The mechanical properties of the whole bamboo stalk with the wall thickness and outer circumference are explored. Through univariate and multiple regression analysis, the relationship between mechanical properties and wall thickness and perimeter is fitted, and the conversion parameters between different mechanical properties are derived. The research results show that the transverse compressive strength of nodal specimen, and transverse tensile strength of nodal and inter-node specimens increase with the increase of wall thickness and outer circumference, but other mechanical properties decrease with the increase of wall thickness and outer circumference. The prediction formula and conversion parameters of bamboo mechanical properties proposed in this research have high applicability and accuracy. Moreover, this research can provide references for the evaluation of bamboo performance and saving test costs.

KEYWORDS

Bamboo; mechanical properties; wall thickness; outer circumference; performance prediction

1 Introduction

Bamboo is a natural, renewable, fast-growing green building material with wide distribution and excellent mechanical properties [1–6]. China is the center of the distribution of bamboo resources in the world, and bamboo is the most commonly used species in structure and has been applied in engineering [7–9]. A clear understanding of the mechanical properties is crucial to the engineering application of structural bamboo. It is also important for steam softening and bamboo flattening technology [10]. Due to the inhomogeneous and anisotropic characteristics of bamboo, the mechanical properties of bamboo with different sizes, directions and heights are not the same, which leads to a large amount of time and cost of bamboo performance test in engineering application.

In order to explore the correlation between bamboo properties and predict the mechanical properties, experiments were carried out to study the correlation between the physical and mechanical properties of bamboo and relevant results were obtained. Sá Ribeiro et al. [11] carried out a bending test of bamboo stalks and obtained a model for predicting bending strength through bending elastic modulus and predicting the elastic modulus and bending strength through the density. Ren et al. [12] and Kumar et al. [13] studied the relationship between the compressive strength, bending strength, tensile strength, and density of bamboo along the grain, and the results showed that the mechanical properties of bamboo have a correlational relationship with density. Dixon et al. [14] studied the relationship between the axial compressive properties of moso bamboo and the density, and the results showed that a linear correlation existed between them. At present, there are few literatures on the prediction of the mechanical properties of bamboo, and some of them are mainly based on a small number of samples to study the tensile, compressive and bending performance indicators along the grain. There is still a lack of research on the relationship between the mechanical properties of moso bamboo materials and growth parameters, conversion model between different mechanical properties of bamboo has not been put forward.

In order to systematically study the mechanical properties of bamboo, predict the mechanical properties through growth parameters, and facilitate the conversion between mechanical properties, this paper mainly carried out the following works on the bamboo materials produced in China: (1) considering the influence of bamboo nodes, a system was developed on moso bamboo longitudinal compression, bending resistance, longitudinal shear, longitudinal tensile, transverse compression, and transverse tensile performance test; (2) the relationship between the mechanical properties of moso bamboo and wall thickness and perimeter was fitted by univariate and multiple regression methods, and the prediction formula was given; (3) the conversion parameters between the various mechanical properties of moso bamboo materials are derived, proposed and verified. In addition, through the prediction formula and conversion method proposed in this paper, the mechanical properties of bamboo can be predicted by using simple size measuring tools.

2 Materials and Methods

2.1 Bamboo Selection and Mechanical Performance Test

The moso bamboo materials used in this research is obtained from Chenzhou, Hunan, China. In a bamboo forest, 160 straight bamboos with the age of 3–4 years, diameters of around 100 mm, and the height of 6 m were randomly collected in December (Fig. 1a), from which 25 samples were selected for mechanical properties tests. The cut bamboos were transported to the test site and stacked in the shading shed. The location of the stacked bamboos was ventilated and irritable to avoid mildew.

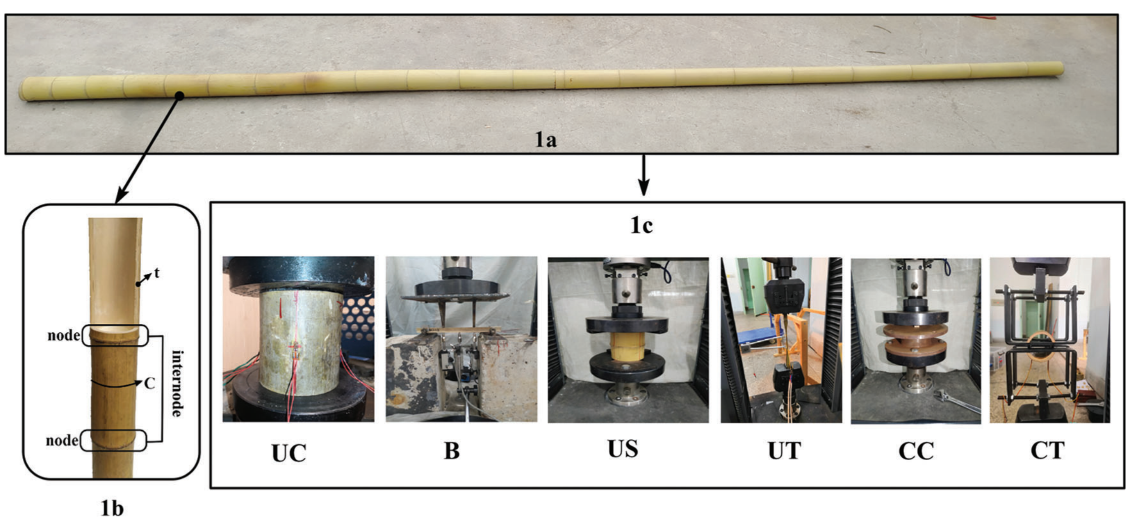

Figure 1: Schematic diagram of material selection and loading

As shown in the Fig. 1b of bamboo structure, t and C are the wall thickness and outer circumference of the bamboo, respectively. The preparation of each specimen is under full consideration of factors such as bamboo nodes and height, and the sampling is based on the principle of uniform distribution of the whole bamboo stalk along the height.

Refer to the standard JG/T199-2007 [15] and ISO 22157-1-2019 [16], six types of specimens of longitudinal compression (UC), bending (B), longitudinal shear (US), longitudinal tensile (UT), transverse compression (CC) and transverse tensile (CT) were made for the investigation of mechanical properties. The ratio of length to diameter of the UC and US specimens is 1, the size of the B specimen is 220 mm × 15 mm × t mm, the size of the UT specimen is 330 mm × 15 mm × t mm, the size of the CC specimen is 15 mm × 15 mm × t mm, and the length of CT specimen is 100 mm.

The mechanical performance tests was carried out according to the standards [15,16]. Universal testing machines were used to load various specimens for mechanical properties as shown in Fig. 1c. During the loading, the UC, US, and UT test loading rate is 0.01 mm/s, the B test loading rate is 150 N/mm^2 per minute, the CC test loading rate is 20 N/mm^2 per minute, and the CT test loading rate is 0.005 mm/s. The formula of the strength and elastic modulus of the specimen is 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 strength of UC, US, UT, CC and CT specimens with the moisture content W (MPa); E_{W} is the elastic modulus along the grain with the moisture content W (MPa); MOR_W is the bending strength with the moisture content W (MPa); MOE_{W} is the flexural modulus of elasticity with the moisture content W (MPa); $P_{\max}$ is the failure load (N); A is the surface area (mm^2); t is the thickness of the specimen (mm); b is the specimen height (mm); ΔP is the difference between the upper and lower limit loads (N); Δl is the difference between the deformation values of the specimen under the upper and lower limit loads (mm); δ_m is the pure bending deflection value of the specimen under the action of ΔP (mm).

2.2 The Adjustment of Moisture Content

After the failure of specimens, a test specimen with a mass of not less than 1.5 g near the damage zone was collected immediately for the moisture content test. The moisture content is calculated according to formula (5). As the moisture content has a significant impact on the mechanical properties of bamboo [17], in this study, the value of the mechanical properties was uniformly adjusted to the value under the standard moisture content (12%). The adjustment formula (6) is shown in equation [15].

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

$$M_{12} = K_W M_W \tag{6}$$

$$K_{\mathrm{W}} = \frac{1}{a + be^{cw}} \tag{7}$$

where, W is the air-dry moisture content (%); m_1 and m_0 are the air-dry and full-dry mass (g), respectively; 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; K_W is the moisture content correction coefficient, which is related to the specific mechanical properties and moisture content. Parameter a, b and c refer to Standard [15].

3 Results and Discussion

3.1 Statistical Analysis of Characteristic Values

Statistics of various mechanical properties of bamboo under standard moisture content (12%) are shown in the box diagram Fig. 2. Excluding the outliers in the box chart, the results are obtained and shown in Tab. 1. It can be seen from the results that the mechanical properties of bamboo show significant anisotropy, and the longitudinal tensile, longitudinal compressive and bending properties are particularly excellent. The longitudinal tensile and longitudinal compressive strengths are significantly greater than the transverse tensile and transverse compressive strengths. The longitudinal tensile strength is slightly greater than the bending strength. The longitudinal tensile and bending strengths are obviously greater than the longitudinal compressive strength. The transverse compressive strength is obviously greater than the transverse tensile strength. Meanwhile, the bamboo nodes have a certain influence on the value of various mechanical properties, especially the mechanical properties in the transverse direction.

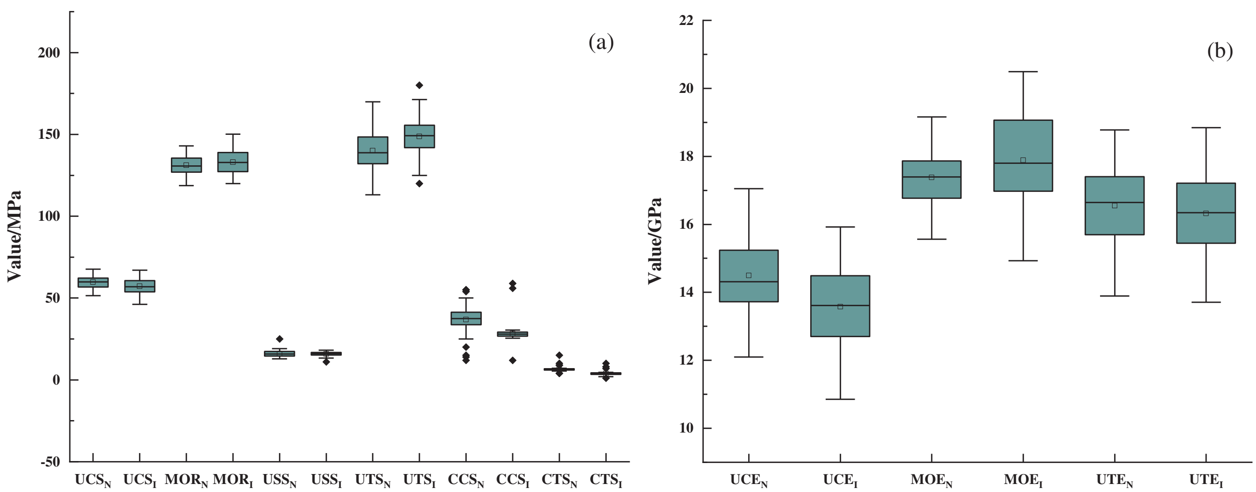

Figure 2: Statistical box diagram of mechanical properties: (a) Strength; (b) Elastic modulus

Table 1: Statistical results of characteristic values of mechanical properties

Mechanical performance index	Quantity	Mean	Standard deviation	Coefficient of variation
UCS_N	74	59.790 MPa	4.129 MPa	0.069
UCS_I	231	57.196 MPa	4.682 MPa	0.082
UCE_N	74	14.498 GPa	1.165 GPa	0.080
UCE_I	231	13.577 GPa	1.179 GPa	0.087
MOR_N	75	130.658 MPa	6.649 MPa	0.046
MOR_I	80	133.129 MPa	7.191 MPa	0.054

(Continued)

Table 1 (continued).

Mechanical performance index	Quantity	Mean	Standard deviation	Coefficient of variation
MOE_N	75	17.380 GPa	0.804 GPa	0.046
MOE_I	80	17.727 GPa	1.365 GPa	0.077
USS_N	61	15.908 MPa	1.621 MPa	0.109
USS_I	144	15.921 MPa	1.095 MPa	0.069
UTS_N	167	140.064 MPa	12.280 MPa	0.088
UTS_I	147	149.174 MPa 9.40926	9.409 MPa	0.063
UTE_N	167	16.548 GPa	1.154 GPa	0.070
UTE_I	158	16.321 GPa	1.182 GPa	0.072
CCS_N	77	37.317 MPa	4.646 MPa	0.125
CCS_I	100	27.928 MPa	1.370 MPa	0.049
CTS_N	47	6.333 MPa	0.489 MPa	0.077
CTS_I	73	3.767 MPa	0.517 MPa	0.137

Note: *UCS*, *UCE*, *MOR*, *MOE*, *USS*, *UTS*, *UTE*, *CCS*, and *CTS* respectively represent the longitudinal compressive strength, the longitudinal compressive elastic modulus, the bending strength, the bending elastic modulus, the longitudinal shear strength, longitudinal tensile strength, longitudinal tensile elastic modulus, transverse compressive strength, and transverse tensile strength. The nodes and inter-nodes are indicated by the subscripts "N" and "I" respectively, and the rests are the same.

3.2 The Relationship between Growth Parameters

Based on the least-squares method, considering the differences between the nodes and the inter-nodes, the linear function, exponential function, and power function are used to fit *t* and *C* to obtain the fitting curve as shown in Fig. 3. The curve and relationship in the figure are the best fitting curves with its relational expression. The fitting relational expressions are shown in Tab. 2. The coefficient of determination R^2 is used to evaluate the fitting effect, and the results show that *t* and *C* have a strong correlation, and from the relationship in Tab. 2, *t* and *C* can be converted.

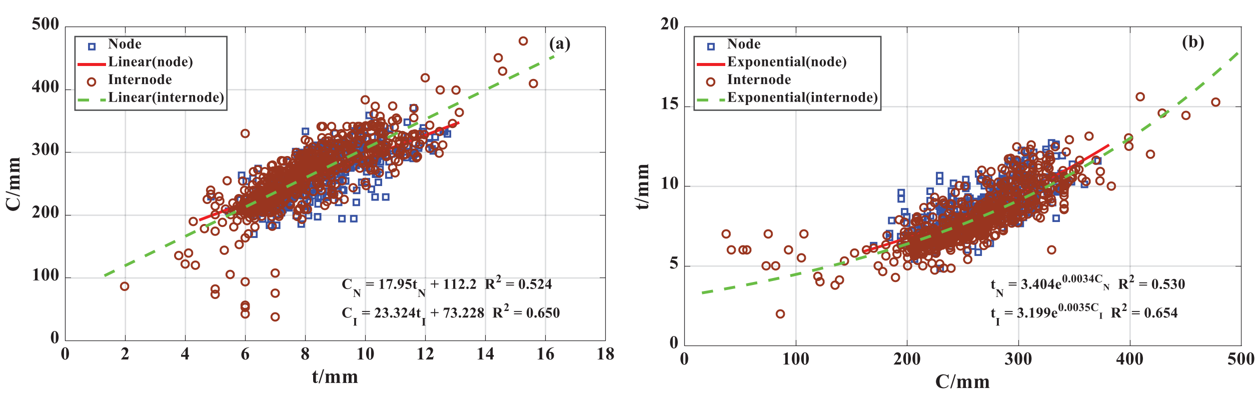

Figure 3: Fitting curve between *t* and *C*: (a) *C*-*t*; (b) *t*-*C*

Table 2: The fitting relationship between *t* and *C*

	Linear		Exponential		Power	
	Relational formula	$\mathbf{R^2}$	**Relational formula**	$\mathbf{R^2}$	**Relational formula**	$\mathbf{R^2}$
C_N-t_N	$C_N = 17.95t_N + 112.2$	**0.524**	$C_N = 147.44e^{0.0677t_N}$	0.510	$C_N = 75.027{t_N}^{0.589}$	0.422
C_I-t_I	$C_I = 23.324t_I + 73.228$	**0.650**	$C_I = 119.37e^{0.0941t_I}$	0.472	$C_I = 50.17{t_I}^{0.7889}$	0.505
t_N-C_N	$t_N = 0.0292C_N + 0.791$	0.524	$t_N = 3.404e^{0.0034C_N}$	**0.530**	$t_N = 0.0616{C_N}^{0.883}$	0.520
t_I-C_I	$t_I = 0.0279C_I + 0.798$	0.650	$t_I = 3.199e^{0.0035C_I}$	**0.654**	$t_I = 0.227{C_I}^{0.641}$	0.505

3.3 The Relationship between Mechanical Properties and Wall Thickness

By equating the *UCS*, *UCE*, *MOR*, *MOE*, *USS*, *UTS*, *UTE*, *CCS* and *CTS* of bamboo materials to *t*, respectively, the fitting curve shown in Fig. 4 and the fitting relationship are obtained and shown in Tab. 3. The results show that the R^2 values fitted by the three functions are relatively close, and the best fitting functions under different fitting materials are different. The longitudinal mechanical properties, the bending resistance, and the *CCS* of the inter-node specimens decrease with the increase of *t*. The *CCS* of node specimen and *CTS* of the node & inter-node specimens increase with the increase of *t*. The result clearly shows that bamboo joints have a significant effect on *CCS* and *CTS*.

The relationship between the mechanical properties of bamboo and *t* shows the above rules and is related to the structure of bamboo. Bamboo is mainly composed of vascular bundles that play a bearing role and basic tissues that connect and transfer loads [18]. With the increase of *t*, that is, with the decrease of bamboo height *h*, the density of bamboo vascular bundles gradually decreases. Because the vascular bundles play a decisive role in the stress along the grain direction, the vascular bundles against the growth direction of bamboo stalk are not orderly arranged and the photosynthesis is weaker, which makes the mechanical properties of bamboo along the grain direction decrease with the increase of *t*. The vascular bundle also plays a major role in bending and transverse compression, so the *MOR* and *CCS* of the inter-node specimens gradually decrease with the increase of *t*. However, due to the polishing treatment of node during the production of CC specimens, the proportion of polished vascular bundles decreases with the increase of *t*. Thus, the *CCS* of the node specimens gradually increase as *t* increases. As the basic tissue plays a major role in the transverse tension, the proportion of basic tissue increases with the increase of *t*, so *CTS* and *t* are positively correlated.

3.4 The Relationship between Mechanical Properties and the Outer Circumference

The relationship between the mechanical properties of bamboo and *C*, and the relationship between the mechanical properties of bamboo and *t* are similar. The fitting results are shown in Fig. 5 and Tab. 4. The mechanical properties along the grain and the *CCS* of the inter-node specimens decrease with the increase of *C*, while the *CCS* of node specimen and *CTS* of the node & inter-node specimens increase with the increase of *C*. Obviously, the bamboo joints have a significant effect on the *CCS* and *CTS* specimens; and the R^2 value and the best fitting function of the same mechanical properties obtained by fitting *t* and *C* are not the same.

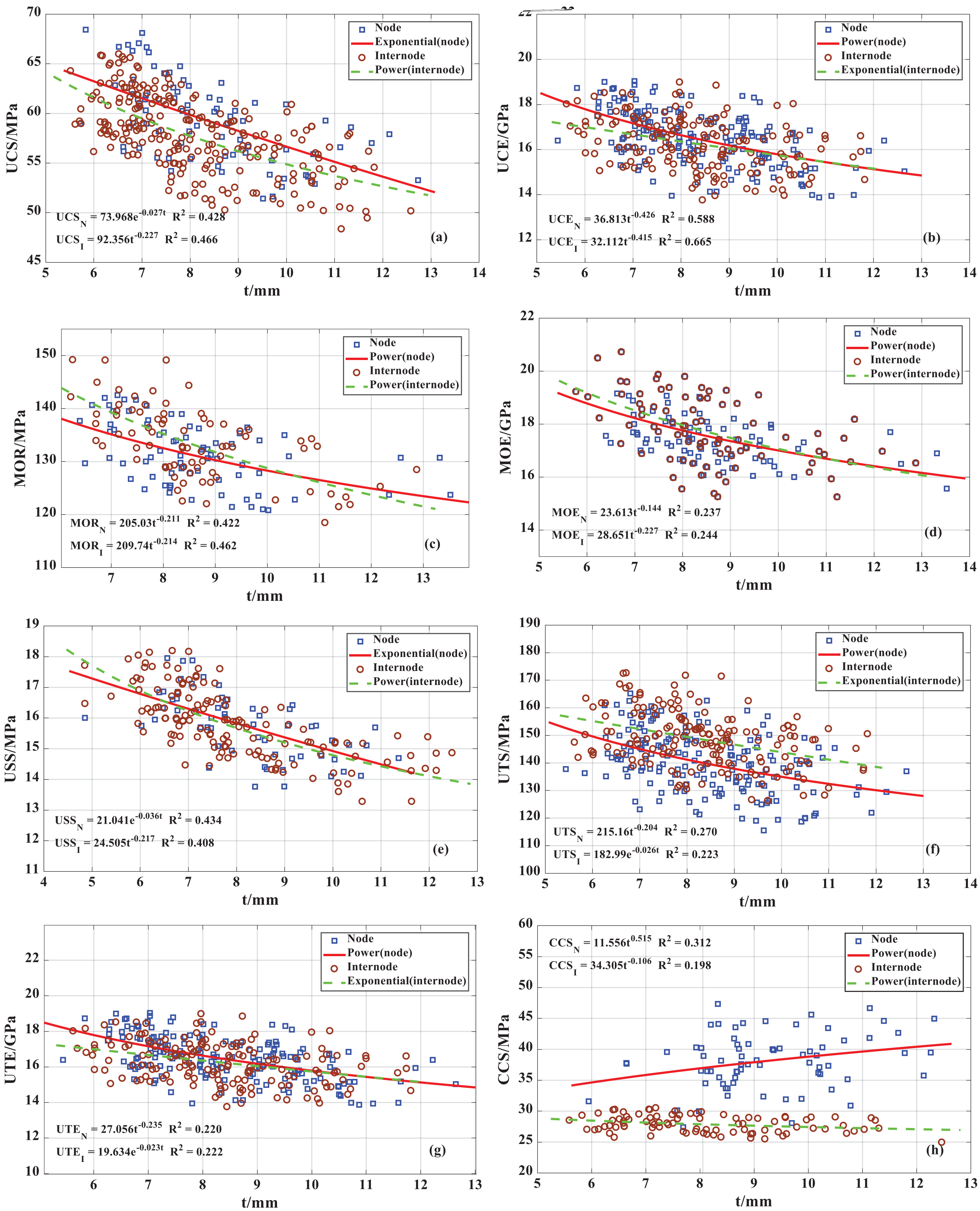

Figure 4: (continued)

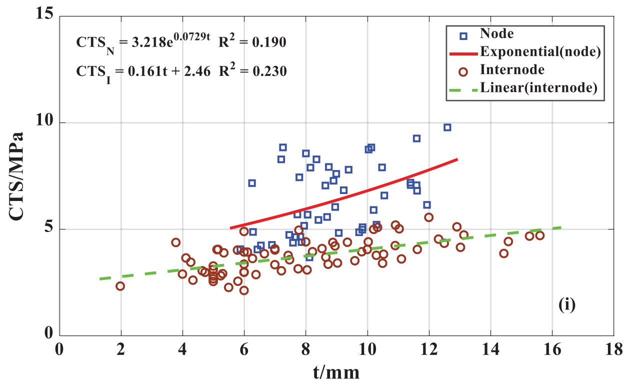

Figure 4: The fitting curve of mechanical properties and *t*: (a) *UCS*; (b) *UCE*; (c) *MOR*; (d) *MOE*; (e) *USS*; (f) *UTS*; (g) *UTE*; (h) *CCS*; (i) *CTS*

Table 3: The fitting relationship between mechanical properties and *t*

	Linear		Exponential		Power	
	Relational formula	**R^2**	**Relational formula**	**R^2**	**Relational formula**	**R^2**
UCS_N-t	$UCS_N = -1.587t + 72.583$	0.421	$UCS_N = 73.968e^{-0.027t}$	**0.428**	$UCS_N = 99.023t^{-0.235}$	0.422
UCS_I-t	$UCS_I = -1.544t + 70.339$	0.462	$UCS_I = 71.807e^{-0.027t}$	0.464	$UCS_I = 92.356t^{-0.227}$	**0.466**
UCE_N-t	$UCE_N = -0.722t + 21.092$	0.560	$UCE_N = 22.545e^{-0.049t}$	0.572	$UCE_N = 36.813t^{-0.426}$	**0.588**
UCE_I-t	$UCE_I = -0.663t + 19.006$	0.650	$UCE_I = 20.285e^{-0.05t}$	0.663	$UCE_I = 32.112t^{-0.415}$	**0.665**
MOR_N-t	$MOR_N = -2.898t + 155.59$	0.394	$MOR_N = 158.16e^{-0.022t}$	0.401	$MOR_N = 205.03t^{-0.211}$	**0.422**
MOR_I-t	$MOR_I = -3.146t + 159.99$	0.437	$MOR_I = 162.77e^{-0.024t}$	0.439	$MOR_I = 209.74t^{-0.214}$	**0.462**
MOE_N-t	$MOE_N = -0.262t + 19.633$	0.220	$MOE_N = 19.78e^{-0.015t}$	0.224	$MOE_N = 23.613t^{-0.144}$	**0.237**
MOE_I-t	$MOR_I = -0.439t + 21.476$	0.227	$MOE_I = 21.829e^{-0.025t}$	0.224	$MOE_I = 28.651t^{-0.227}$	**0.244**
USS_N-t	$USS_N = -0.568t + 20.311$	0.432	$USS_N = 21.041e^{-0.036t}$	**0.434**	$USS_N = 28.869t^{-0.294}$	0.432
USS_I-t	$USS_I = -0.404t + 18.934$	0.397	$USS_I = 19.296e^{-0.026t}$	0.405	$USS_I = 24.505t^{-0.217}$	**0.408**
UTS_N-t	$UTS_N = -3.329t + 168.26$	0.269	$UTS_N = 171.03e^{-0.024t}$	0.268	$UTS_N = 215.16t^{-0.204}$	**0.270**
UTS_I-t	$UTS_I = -3.762t + 179.28$	0.220	$UTS_I = 182.99e^{-0.026t}$	**0.223**	$UTS_I = 230.65t^{-0.212}$	0.217
UTE_N-t	$UTE_N = -0.452t + 20.312$	0.215	$UTE_N = 20.762e^{-0.028t}$	0.214	$UTE_N = 27.056t^{-0.235}$	**0.220**
UTE_I-t	$UTE_I = -0.371t + 19.332$	0.219	$UTE_I = 19.634e^{-0.023t}$	**0.222**	$UTE_I = 24.147t^{-0.189}$	0.217
CCS_N-t	$CCS_N = 2.015t + 17.806$	0.311	$CCS_N = 21.683e^{0.0552t}$	0.304	$CCS_N = 11.556t^{0.515}$	**0.312**
CCS_I-t	$CCS_I = -0.347t + 30.675$	0.152	$CCS_I = 30.462e^{-0.013t}$	0.190	$CCS_I = 34.305t^{-0.106}$	**0.198**
CTS_N-t	$CTS_N = 0.435t + 2.5$	0.182	$CTS_N = 3.218e^{0.0729t}$	**0.190**	$CTS_N = 1.502t^{0.651}$	0172
CTS_I-t	$CTS_I = 0.161t + 2.46$	**0.230**	$CTS_I = 2.572e^{0.0443t}$	0.217	$CTS_I = 1.821t^{0.349}$	0.177

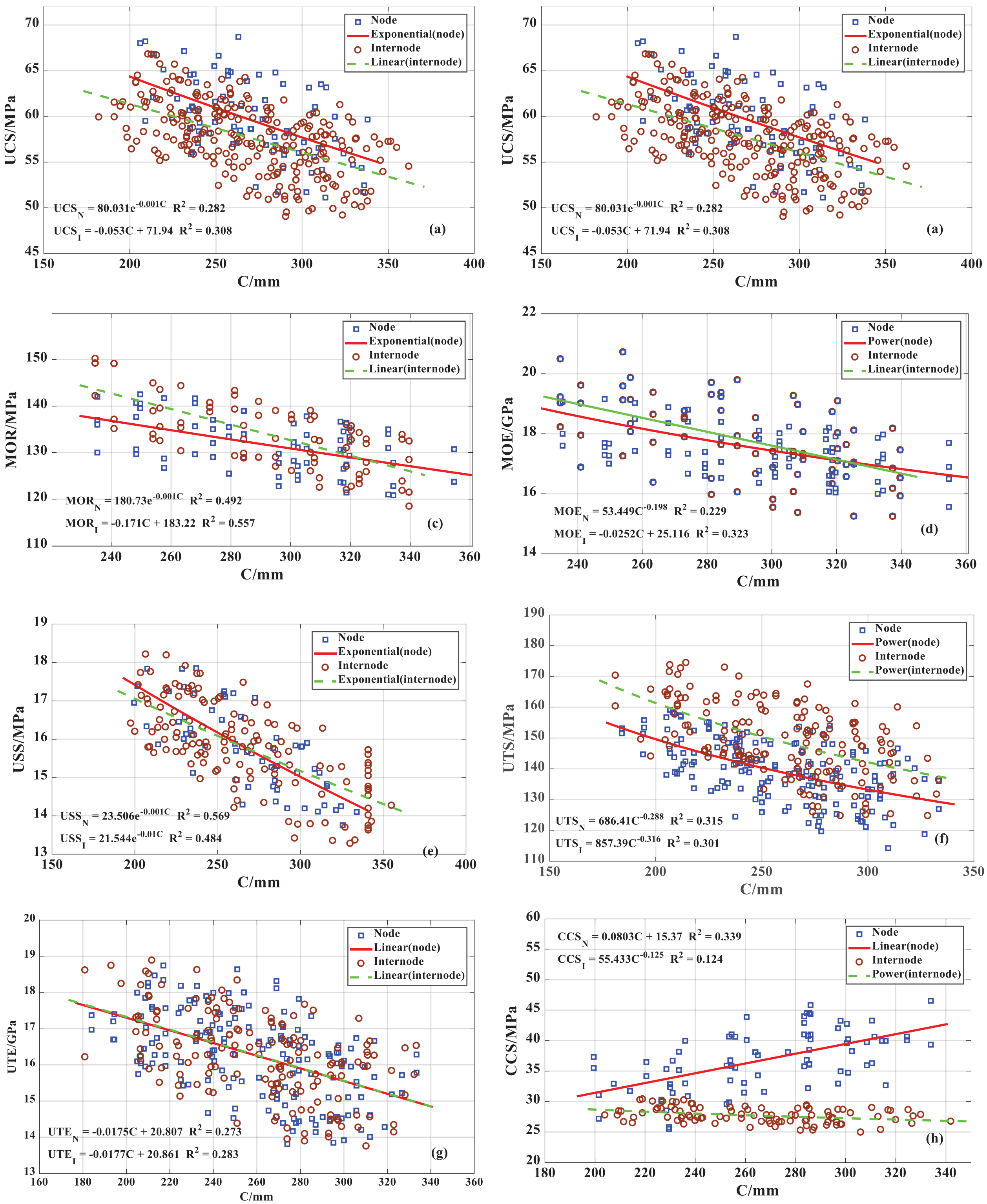

Figure 5: (continued)

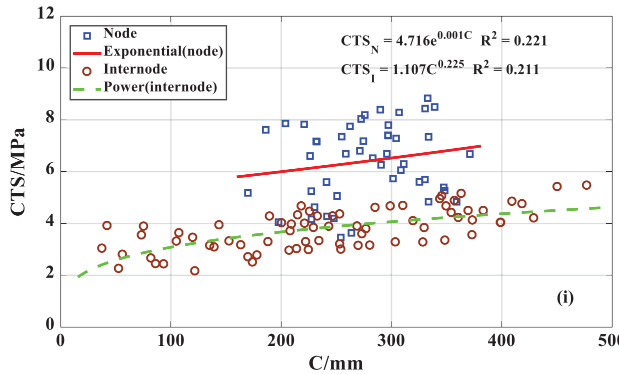

Figure 5: The fitting curve of mechanical properties and *C*: (a) *UCS*; (b) *UCE*; (c) *MOR*; (d) *MOE*; (e) *USS*; (f) *UTS*; (g) *UTE*; (h) *CCS*; (i) *CTS*

Table 4: The fitting relationship between mechanical properties and *C*

	Linear		Exponential		Power	
	Relational formula	**R^2**	**Relational formula**	**R^2**	**Relational formula**	**R^2**
UCS_N-C	$UCS_N = -0.0649C + 77.191$	0.279	$UCS_N = 80.031e^{-0.001C}$	**0.282**	$UCS_N = 309.31t^{-0.295}$	0.281
UCS_I-C	$UCS_I = -0.053C + 71.94$	**0.308**	$UCS_I = 73.744e^{-0.001C}$	0.305	$UCS_I = 226.24C^{-0.245}$	0.307
UCE_N-C	$UCE_N = -0.0257C + 22.546$	**0.524**	$UCE_N = 24.789e^{-0.002C}$	0.519	$UCE_N = 251.19C^{-0.504}$	0.522
UCE_I-C	$UCE_I = -0.0249C + 20.293$	**0.616**	$UCE_I = 22.264e^{-0.002C}$	0.609	$UCE_I = 207.35C^{-0.489}$	0.604
MOR_N-C	$MOR_N = -0.144C + 173.23$	0.490	$MOR_N = 180.73e^{-0.001C}$	**0.492**	$MOR_N = 792.23C^{-0.317}$	0.486
MOR_I-C	$MOR_I = -0.171C + 183.22$	**0.557**	$MOR_I = 193.46e^{-0.001C}$	0.554	$MOR_I = 1050C^{-0.364}$	0.550
MOE_N-C	$MOE_N = -0.0119C + 20.889$	0.228	$MOE_N = 21.233e^{-0.001C}$	0.228	$MOE_N = 53.449C^{-0.198}$	**0.229**
MOE_I-C	$MOE_I = -0.0252C + 25.116$	**0.323**	$MOE_I = 26.744e^{-0.001C}$	0.317	$MOE_I = 174.76C^{-0.404}$	0.318
USS_N-C	$USS_N = -0.0236C + 22.087$	0.566	$USS_N = 23.506e^{-0.001C}$	**0.569**	$USS_N = 137.91C^{-0.389}$	0.556
USS_I-C	$USS_I = -0.0183C + 20.665$	0.481	$USS_I = 21.544e^{-0.01C}$	**0.484**	$USS_I = 92.081C^{-0.317}$	0.481
UTS_N-C	$UTS_N = -0.156C + 179.84$	0.313	$UTS_N = 186.08e^{-0.001C}$	0.310	$UTS_N = 686.41C^{-0.288}$	**0.315**
UTS_I-C	$UTS_I = -0.184C + 196.95$	0.300	$UTS_I = 204.99e^{-0.001C}$	0.298	$UTS_I = 857.39C^{-0.316}$	**0.301**
UTE_N-C	$UTE_N = -0.0175C + 20.807$	**0.273**	$UTE_N = 21.493e^{-0.001C}$	0.273	$UTE_N = 73.683C^{-0.273}$	0.268
UTE_I-C	$UTE_I = -0.0177C + 20.861$	**0.283**	$UTE_I = 21.514e^{-0.001C}$	0.279	$UTE_I = 76.173C^{-0.279}$	0.282
CCS_N-C	$CCS_N = 0.0803C + 15.37$	**0.339**	$CCS_N = 20.025e^{0.0022C}$	0.339	$CCS_N = 1.365C^{0.589}$	0.342
CCS_I-C	$CCS_I = -0.0129C + 31.131$	0.120	$CCS_I = 31.307e^{-5\times10^{-4}C}$	0.119	$CCS_I = 55.433C^{-0.125}$	**0.124**
CTS_N-C	$CTS_N = 0.0056C + 4.866$	0.218	$CTS_N = 4.716e^{0.001C}$	**0.221**	$CTS_N = 1.321C^{0.277}$	0.220
CTS_I-C	$CTS_I = 0.0048C + 2.598$	0.195	$CTS_I = 2.684e^{0.0013C}$	0.204	$CTS_I = 1.107C^{0.225}$	**0.211**

3.5 Multiple Regression Analysis of Mechanical Properties, Wall Thickness, and the Outer Circumference

To compare the effects of multiple regression fitting and univariate fitting, a binary linear function was used to fit the mechanical properties of bamboo with *t* and *C*, and the results were obtained and presented in Fig. 6 and Tab. 5. The comparison of R^2 of the best-fitting relations in Tabs. 3 and 4 and the results in Tab. 5 shows that using *t* to predict *UCS* (including UCS_N and UCS_I), UCE_I, MOE_N, and CCS_I is better, and *C* is used to predict *MOR*, MOE_I, USS_N, *UTS*, UTE_I, CCS_N, and CTS_N, which also has better prediction effects. The use of *t* and *C* bivariate has a better fitting effect for the prediction of UCE_N, USS_I, UTE_N, and CTS_I. In general, the relationship between bamboo material and growth parameter plays a significant role in fitting and analysis [11,14]. Through the univariate and bivariate fitting relations of mechanical properties and growth parameters, simple size measurement tools can be used. In the absence of test conditions, the mechanical properties of bamboo can be tested efficiently and quickly. The best prediction effect can be obtained by using the relationship formula with the highest R^2 value in the univariate and bivariate fitting.

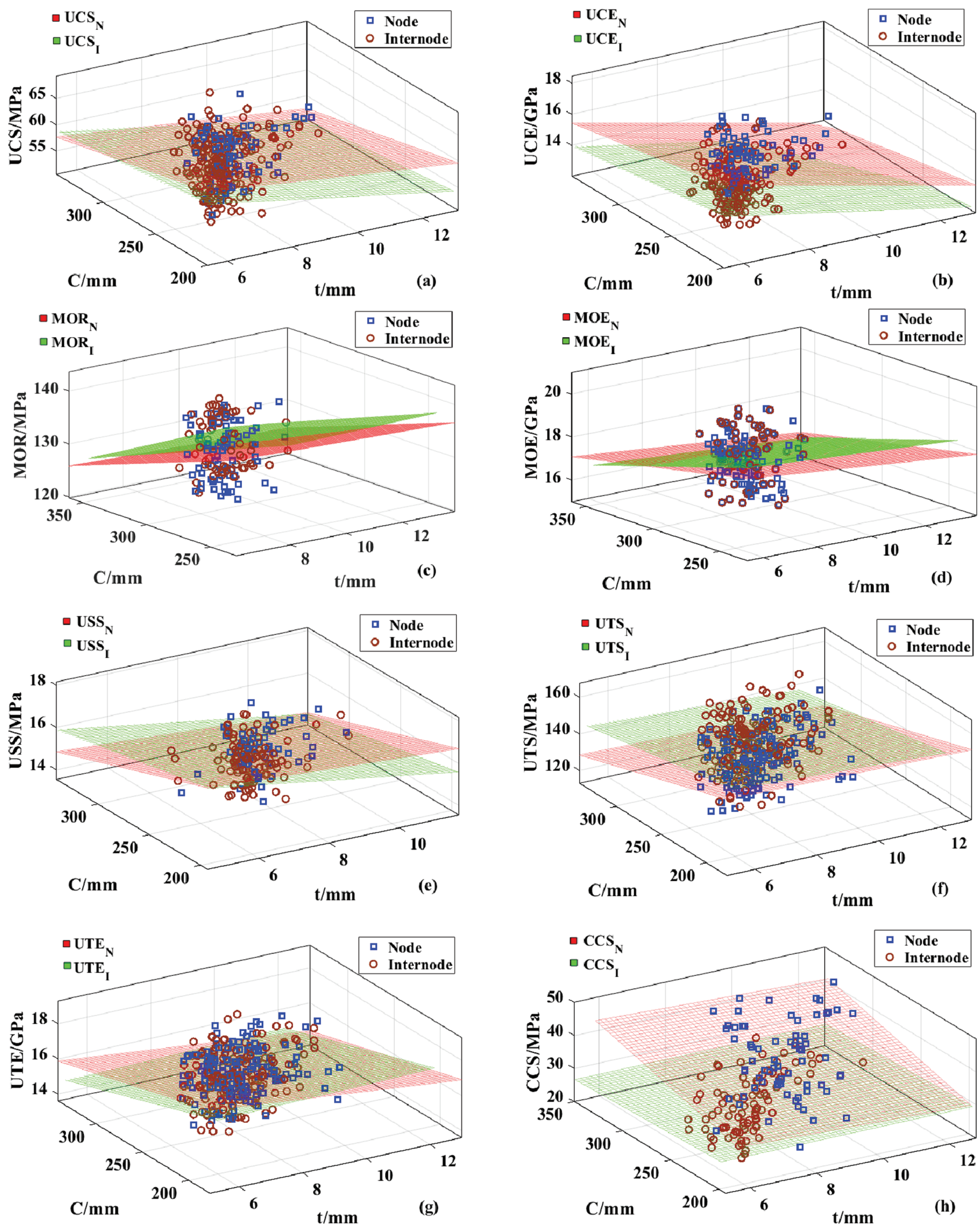

Figure 6: (continued)

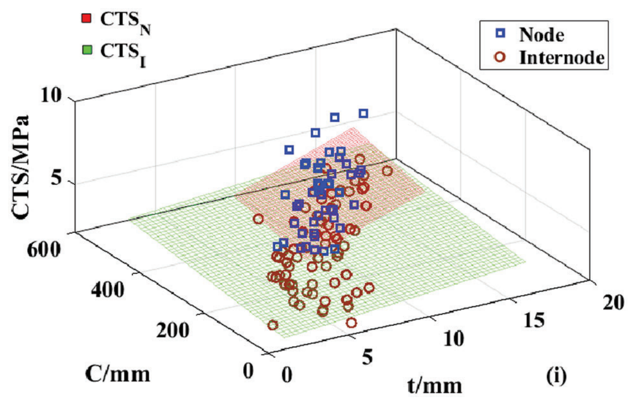

Figure 6: Multiple regression results of mechanical properties and *t*, *C*: (a) *UCS*; (b) *UCE*; (c) *MOR*; (d) *MOE*; (e) *USS*; (f) *UTS*; (g) *UTE*; (h) *CCS*; (i) *CTS*

Table 5: The fitting relationship between mechanical properties and *t*, *C*

Mechanical performance index	Relational formula	R^2
UCS_N	$UCS_N = 77.81 - 0.658t - 0.0482C$	0.373
UCS_I	$UCS_I = 72.57 - 1.031t - 0.0239C$	0.394
UCE_N	$UCE_N = 22.58 - 0.467t - 0.0134C$	0.671
UCE_I	$UCE_I = 19.32 - 0.379t - 0.00969C$	0.636
MOR_N	$MOR_N = 172 - 0.141t - 0.132C$	0.371
MOR_I	$MOR_I = 190.3 + 0.735t - 0.215C$	0.550
MOE_N	$MOE_N = 22.75 + 0.133t - 0.0214C$	0.203
MOE_I	$MOE_I = 25 + 0.372t - 0.0354C$	0.247
USS_N	$USS_N = 21.23 - 0.102t - 0.0174C$	0.465
USS_I	$USS_I = 20.5 - 0.252t - 0.00101C$	0.530
UTS_N	$UTS_N = 185.7 - 0.445t - 0.161C$	0.311
UTS_I	$UTS_I = 181.7 - 0.944t - 0.0971C$	0.198
UTE_N	$UTE_N = 21.94 - 0.183t - 0.0151C$	0.375
UTE_I	$UTE_I = 20.69 - 0.0351t - 0.0181C$	0.267
CCS_N	$CCS_N = 19.93 - 0.409t - 0.081C$	0.305
CCS_I	$CCS_I = 31.47 - 0.00534t - 0.0133C$	0.117
CTS_N	$CTS_N = 1.929 - 0.335t - 0.00525C$	0.210
CTS_I	$CTS_I = 2.44 - 0.0842t - 0.00262C$	0.454

3.6 The Relationship between the Mechanical Properties of Nodes and Inter-Nodes

Based on the fitting results between the mechanical properties and *t* & *C* in this research, a method is proposed to derive the relationship between the mechanical properties of bamboo through the linear fitting relationship between the mechanical properties and the growth parameters. The average value of the determination coefficient R^2 of the linear fitting of various mechanical properties of bamboo with *t*

(Tab. 3) is 0.333, and the average value of the determination coefficient R^2 for linear fitting with *C* (Tab. 4) is 0.356. Among the 18 linear fitting relationships between mechanical properties and growth parameters, the larger values of R^2 of *t* and *C* are 6 and 12, respectively. Generally, the linear relationship between mechanical properties and *C* is used to derive the relationship between the mechanical properties of bamboo, and the operability of measuring *C* is also stronger in practical engineering. Based on the linear relationship between the mechanical properties of the node and inter-node specimens and *C*, the relationship between the mechanical properties of the node and inter-node specimens at the same position of the bamboo is deduced and shown in Tab. 6.

Table 6: The relationship between the mechanical properties of bamboo nodes and internodes

Mechanical performance index	Node-internode	Internode-node
UCS	$UCS_N = 1.225UCS_I - 10.902$	$UCS_I = 0.817UCS_N + 8.903$
UCE	$UCE_N = 1.032UCE_I + 1.601$	$UCE_I = 0.969UCE_N - 1.551$
MOR	$MOR_N = 0.842UCE_I + 18.939$	$MOR_I = 1.188UCE_N - 22.491$
MOE	$MOE_N = 0.472UCE_I + 9.008$	$MOE_I = 2.118UCE_N - 19.12$
USS	$USS_N = 1.29USS_I - 4.563$	$USS_I = 0.775USS_N + 3.538$
UTS	$UTS_N = 0.848UTS_I + 12.861$	$UTS_I = 1.179UTS_N - 15.169$
UTE	$UTE_N = 0.898UTE_I + 0.182$	$UTE_I = 1.011UTE_N - 0.184$
CCS	$CCS_N = -6.225CCS_I + 209.154$	$CCS_I = -0.161CCS_N + 33.6$
CTS	$CTS_N = 1.167CTS_I + 1.835$	$CTS_I = 0.857CTS_N - 1.573$

3.7 Conversion Parameters of Mechanical Properties

It is impossible to measure multiple mechanical properties of test specimens at the same time, and the relationship between the mechanical properties plays a vital role in the establishment of the mechanical property evaluation system of bamboo. The establishment of the relationship between the mechanical properties can greatly reduce the consumption and testing of materials cost. To solve this problem, a linear relationship between mechanical properties and *C* is used to derive the relationship between multiply mechanical properties. Eq. (7) is the conversion formula between mechanical properties.

$$M_2 = \eta M_1 + \theta \tag{7}$$

where, M_1 and M_2 are mechanical performance indicators.

η and θ are defined as the conversion parameters of bamboo mechanical properties, as shown in Tabs. 7 and 8 for details. Since a large number of bamboo stalk materials are used in the application of the original bamboo structure, predicting the mechanical properties of a batch of bamboo stalks through a certain mechanical property can save a lot of materials, time and test costs. Also, the conversion parameters can provide a reference for the prediction of the mechanical properties of bamboo.

3.8 Verification of Prediction Formula

In order to verify the accuracy of the proposed prediction formula, UCS_I is used as an independent variable, and the measured values of the mechanical properties of bamboo in the literature [12,19–21] are compared with the predicted values obtained in Tab. 8. The comparison results are summarized in Tab. 9. It can be seen that the predicted results by the proposed method are relatively close to the measured values of experiment, indicating that the prediction formula and conversion parameters of mechanical properties of moso bamboo obtained in this research have certain applicability and accuracy, and are useful for the application of bamboo structure.

Table 7: Conversion parameters of mechanical properties of bamboo node specimens

Parameter	M_2/M_1	UCS_{N2}	UCE_{N2}	MOR_{N2}	MOE_{N2}	USS_{N2}	UTS_{N2}	UTE_{N2}	CCS_{N2}	CTS_{N2}
	UCS_{N1}	1	0.396	2.219	0.183	0.364	2.404	0.27	–1.237	–0.086
	UCE_{N1}	2.525	1	5.603	0.463	0.918	6.07	0.681	–3.125	–0.218
	MOR_{N1}	0.451	0.178	1	0.083	0.164	1.083	0.122	–0.558	–0.039
	MOE_{N1}	5.454	2.160	12.101	1	1.983	13.109	1.471	–6.748	–0.471
η	USS_{N1}	2.75	1.089	6.102	0.504	1	6.61	0.742	–3.403	–0.237
	UTS_{N1}	0.416	0.165	0.923	0.076	0.151	1	0.112	–0.515	–0.036
	UTE_{N1}	3.709	1.469	8.229	0.68	1.349	8.914	1	–4.589	–0.32
	CCS_{N1}	–0.808	–0.32	–1.793	–0.148	–0.294	–1.943	–0.218	1	0.07
	CTS_{N1}	–11.589	–4.589	–25.714	–2.125	–4.214	–27.857	–3.125	14.339	1
	UCS_{N1}	0	–8.021	1.959	6.735	–5.982	–5.704	–0.007	110.878	11.527
	UCE_{N1}	20.256	0	46.902	10.449	1.383	42.985	5.455	85.815	9.779
	MOR_{N1}	–0.883	–8.371	0	6.573	–6.303	–7.826	–0.245	111.97	11.603
	MOE_{N1}	–36.733	–22.567	–79.544	0	–19.34	–93.999	–9.912	156.327	14.696
θ	USS_{N1}	16.452	–1.506	38.462	9.752	0	33.841	4.429	90.522	10.107
	UTS_{N1}	2.373	–7.081	7.224	7.17	–5.12	0	0.633	107.941	11.322
	UTE_{N1}	0.027	–8.011	2.018	6.74	–5.973	–5.64	0	110.844	11.524
	CCS_{N1}	89.613	27.465	200.793	23.167	26.604	209.7	24.157	0	3.794
	CTS_{N1}	133.584	44.877	298.356	31.229	42.594	315.393	36.013	–54.405	0

Table 8: Conversion parameters of mechanical properties of bamboo internode specimens

Parameter	M_2/M_1	UCS_{I2}	UCE_{I2}	MOR_{I2}	MOE_{I2}	USS_{I2}	UTS_{I2}	UTE_{I2}	CCS_{I2}	CTS_{I2}
	UCS_{I1}	1	0.47	3.226	0.475	0.345	3.472	0.334	0.243	–0.091
	UCE_{I1}	2.129	1	6.867	1.012	0.735	7.39	0.711	0.518	–0.193
	MOR_{I1}	0.31	0.146	1	0.147	0.107	1.076	0.104	0.075	–0.028
	MOE_{I1}	2.103	0.988	6.786	1	0.726	7.302	0.702	0.512	–0.19
η	USS_{I1}	2.896	1.361	9.344	1.377	1	10.055	0.967	0.705	–0.262
	UTS_{I1}	0.288	0.135	0.929	0.137	0.099	1	0.096	0.07	–0.026
	UTE_{I1}	2.994	1.407	9.661	1.424	1.034	10.395	1	0.729	–0.271
	CCS_{I1}	4.109	1.93	13.256	1.953	1.419	14.264	1.372	1	–0.372
	CTS_{I1}	–11.042	–5.188	–35.625	–5.250	–3.813	–38.333	–3.688	–2.688	1

(Continued)

Table 8 (continued).

Parameter	M_2/M_1	UCS_{I2}	UCE_{I2}	MOR_{I2}	MOE_{I2}	USS_{I2}	UTS_{I2}	UTE_{I2}	CCS_{I2}	CTS_{I2}
	UCS_{I1}	0	–13.505	–48.888	–9.089	–4.175	–52.804	–3.164	13.621	9.113
	UCE_{I1}	28.746	0	43.858	4.579	5.751	46.994	6.436	20.618	6.51
	MOR_{I1}	15.153	–6.386	0	–1.885	1.057	–0.199	1.896	17.309	7.741
	MOE_{I1}	19.117	–4.524	12.79	0	2.426	13.563	3.22	18.274	7.382
θ	USS_{I1}	12.091	–7.825	–9.879	–3.341	0	–10.829	0.874	16.564	8.018
	UTS_{I1}	15.21	–6.359	0.185	–1.858	1.077	0	1.915	17.323	7.736
	UTE_{I1}	9.475	–9.054	–18.318	–4.584	–0.903	–19.91	0	15.927	8.255
	CCS_{I1}	–55.963	–39.797	–229.447	–35.698	–23.498	–247.089	–21.854	0	14.182
	CTS_{I1}	100.626	33.77	275.774	38.756	30.57	296.54	30.441	38.113	0

Table 9: Comparison of prediction results between literature and this paper

Literature	Mechanical performance index	Measured value in literature/MPa	The predicted value of this article/MPa	Absolute error
	Bottom partUCS_I	69.1	–	–
	Bottom part MOR_I	158.2	174.029	10.01%
	Bottom part UTS_I	185.1	187.111	1.09%
	Centralpart UCS_I	70.9	–	–
[13]	Centralpart MOR_I	170.3	179.835	5.60%
	Centralpart UTS_I	194.9	190.361	2.33%
	Upper part UCS_I	76.3	–	–
	Upper part MOR_I	184.6	197.256	6.86%
	Upper part UTS_I	212.6	212.110	0.23%
[19]	UCS_I	54	–	–
	UCE_I	11930	11875	0.46%
[20]	UCS_I	59.46	–	–
	MOR_I	132.46	142.930	7.90%
[21]	UCS_I	56.4	–	–
	MOR_I	150.96	133.058	11.86%
	UTS_I	154.24	143.017	7.28%

4 Conclusions

(1) In this research, the mechanical performance tests of bamboo were carried out for longitudinal compression, bending, longitudinal shear, transverse compression and transverse tension. In addition, the mechanical characteristic values of bamboo nodes and inter-nodes specimens were statistically analyzed. The results show that the mechanical properties of bamboo show significant anisotropy. The longitudinal tensile and compressive strengths are obviously greater than the transverse tensile and compressive

strengths, and the longitudinal tensile strength is slightly greater than the bending strength. The longitudinal tensile and bending strengths are obviously greater than the longitudinal compressive strengths, and the transverse compressive strength is obviously greater than the transverse tensile strength. However, the bamboo nodes have a certain influence on the value of various mechanical properties, especially the mechanical properties in the transverse direction.

(2) The Linear function, Exponential function and Power function were used to fit the performance indicators and growth parameters (wall thickness and outer circumference) of bamboo. It is concluded from the results that longitudinal mechanical properties, bending, and the transverse compressive strength of inter-node specimens decrease with the increase of wall thickness and outer circumference, while transverse compressive strength of nodal specimen and transverse tensile strength of nodal and inter-node specimen increase with the increase of wall thickness and outer circumference.

(3) There is a good correlation between the growth parameters, mechanical properties and the univariate and bivariate fitting of growth parameters. It is better to use wall thickness to predict the longitudinal compressive strength, the compressive elastic modulus of the inter-nodes, the bending elastic modulus of the nodes and the transverse compressive strength of the inter-nodes. On the other hand, it is better to use the outer circumference for the prediction of bending strength, the inter-node bending elastic modulus, node longitudinal shear strength, the inter-node longitudinal tensile strength, the node transverse compressive strength and node transverse tensile strength. The bivariate linear function of wall thickness and outer circumference is effective in predicting the longitudinal compressive elastic modulus of the node specimen, the longitudinal inter-node shear strength, the node longitudinal tensile elastic modulus and the inter-node transverse tensile strength.

(4) Comparing the fitting effects of mechanical properties by using wall thickness and outer perimeter, the linear fitting relationship between mechanical properties and outer perimeter is used to derive the bamboo mechanical property conversion parameter, which provides a reference for the prediction of the mechanical properties of bamboo. By comparing with the relevant results in literatures, the applicability and accuracy of the prediction formula and conversion parameters proposed in this work are verified.

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