

# Transverse Compressive Stress-Strain Relationship of Bamboo: Development of a Constitutive Model

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Bamboo is a green and renewable building material having high economic value, high yield, and good mechanical properties. In this study, a total of 160 bamboo samples were tested, and the transverse stress-strain curves and the characteristic values of bamboo were analyzed. The relationship between the thickness, diameter, transverse compressive strength, and transverse compressive elastic modulus of bamboo and with its height was established. The transverse stress-strain constitutive relationship of bamboo was proposed. The results showed that the transverse compressive failure modes of bamboo mainly include bending failure and baroclinic failure. The transverse compressive stress-strain curves of bamboo can be divided into elastic stage, elastoplastic stage, and failure stage. Bamboo wall thickness, diameter, transverse compressive strength, and transverse compressive elastic modulus have strong correlation with height. Based on the stress-strain curves of normalized processing, a transverse compressive stress-strain constitutive model of bamboo achieved high fitting goodness.

DOI: 10.15376/biores.21.3.5878-5886

Keywords: Bamboo; Transverse compression; Test; Stress-strain curves

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## INTRODUCTION

Today, with natural resources becoming increasingly tight and environmental protection becoming a global consensus, both the scientific and industrial communities are seeking and developing high-performance and sustainable building materials that minimize ecological impact. Bamboo, as a unique biomaterial in nature, stands out among numerous renewable resources with its rapid growth, high strength, high toughness, low density, and good environmental adaptability, such that it has become a highly regarded green building materials (Babu and Chandrasekhara 2023; Pieter and Utomo 2023; Zhang *et al.* 2023). At present, a series of achievements have been made in research on the mechanical properties of bamboo. Dixon and Gibson (2014) established the relationship between the axial bending performance and the axial compressive strength of bamboo. Sa Ribeiro *et al.* (2017) established a relationship model between the density and dynamic elastic modulus of bamboo and its strength and stiffness. Akinbade *et al.* (2017) studied the distribution gradient of mechanical properties at different axial positions by using the modified flat ring bending test method.

Scholars have conducted in-depth research on the influencing factors of the mechanical properties of bamboo, mainly including different parts of bamboo, bamboo age, site conditions, and other factors. Research has found that the mechanical properties of the upper part of the same bamboo are better than those of the lower part. In the same cross-section, the mechanical properties of the green part of the outer bamboo are better than those of the yellow part of the inner bamboo (Chen *et al.* 2019; Yuan *et al.* 2022; Phongphinitana *et al.* 2025). Furthermore, the tissue of new bamboo is tender, and its tensile, compressive strength, stiffness, *etc.* will all increase with the growth of bamboo age, and then gradually decline (Engler *et al.* 2012). In terms of the specific indicators of mechanical properties, past research in this area covers multiple aspects such as compressive strength, tensile strength, bending strength, and elastic modulus (Liu and Chen 2019; Shu *et al.* 2022; Zhao *et al.* 2025). The compressive and tensile strengths of bamboo can be described as excellent, with relatively high values. The elastic modulus of bamboo is relatively high compared to wood, showing good anti-deformation ability. In addition, bamboo has good impact toughness and fatigue performance, can absorb a large amount of impact energy, and it can maintain good integrity when repeatedly subject to loads.

In order to improve the mechanical properties of bamboo, scholars have also conducted a large number of modification and strengthening studies (Azeez *et al.* 2018; Su *et al.* 2021; Xiao *et al.* 2022; Zheng *et al.* 2023). The surface of bamboo has been treated by physical or chemical methods, such as heating, compression, and anti-corrosion treatment, to enhance its hardness, wear resistance, and insect resistance. Meanwhile, bamboo has been combined with other materials, such as bamboo-wood composites and bamboo-plastic composites, to form new types of composite materials, further enhancing their mechanical properties and durability (Chen *et al.* 2018; Hu *et al.* 2020; Fan *et al.* 2024).

However, to fully realize the engineering application value of bamboo, it is necessary to have an in-depth understanding of its mechanical behavior characteristics, especially its constitutive relationship – that is, the complex relationship between stress and strain of the material during the process of force application. Bamboo, as a kind of natural biomaterial, has a complex internal structure composed of multiple layers of cell walls, and there are significant mechanical differences between each layer and within the cell walls. This leads to bamboo showing a high degree of heterogeneity and anisotropy macroscopically. This complex mechanical property makes it difficult to directly apply the constitutive models of traditional homogeneous and isotropic materials to bamboo, thereby limiting the accurate prediction of its mechanical properties and the in-depth expansion of its engineering applications. Therefore, establishing a constitutive model that can accurately reflect the mechanical properties of bamboo has become a key scientific issue for promoting the engineering application of bamboo and facilitating the development of green building materials. In construction engineering, excessive transverse compression of bamboo is a common phenomenon. Hence, it is necessary to study the transverse compressive constitutive model of bamboo. In this study, the transverse compressive test of bamboo was carried out, the failure mode of transverse compression of bamboo was explored, the stress-strain curves of transverse compression of bamboo were analyzed, and a model for the stress-strain constitutive relationship of transverse compression of bamboo was developed.

## EXPERIMENTAL

### Materials and Methods

#### *Preparation of specimens*

To explore the transverse compression of all-bamboo poles, samples were taken from different height parts of the bamboo poles. The bamboo seeds for this study were produced in Jiujiang City, Jiangxi Province. They were 4 years old, and the variety was *Phyllostachys edulis*. The moisture content was approximately 12% for all of the specimens. The sampling height range was approximately 10 m. Transverse compressive specimens of bamboo were made at every 0.5 m in height. Eight specimens were taken at each height position. The total number of specimens in this test was 160. The transverse compressive production of bamboo was carried out in accordance with the standard JG/T 199-2007 (2007). The size of the transverse compressive specimen of bamboo was 15 mm × 15 mm ×  $t$  mm, where  $t$  refers to the thickness of the culm wall. The dimensions are measured with a caliper, and the measurement accuracy is 0.1 mm.

### Loading Scheme

The transverse compressive strength test of bamboo was conducted with reference to the standard JG/T 199-2007 (2007), and the test loading was carried out using a universal testing machine with a loading rate of 20 N/mm<sup>2</sup> per minute. The calculation formula for the transverse compressive strength of bamboo is as follows,

$$f_{cc} = \frac{P_{\max}}{lt} \quad (1)$$

where,  $f_{cc}$  represents the transverse compressive strength (MPa) of bamboo,  $P_{\max}$  is the ultimate load (N);  $l$  is the length (mm) of the specimen;  $t$  represents the thickness (mm) of the specimen.

There are mainly three algorithms for calculating the elastic modulus: ① Calculate at the point corresponding to 0.4 times the peak strain, and the elastic modulus  $E_1 = \sigma_{0.4} / 0.4\varepsilon$ ; ② Calculate at the point corresponding to 0.4 times the peak stress, the elastic modulus  $E_2 = 0.4\sigma / \varepsilon_{0.4}$ ; ③ Perform linear fitting on the curve where the peak stress is lower than  $0.4\sigma$ , and the slope of the straight line obtained is  $E_3$ . In this study, the elastic modulus adopted the average value of the three, that is,  $E = (E_1 + E_2 + E_3) / 3$ .

### Destruction Process and Mode

In the transverse compressive test of bamboo, the following three main failure modes were observed:

#### *Bending failure mode*

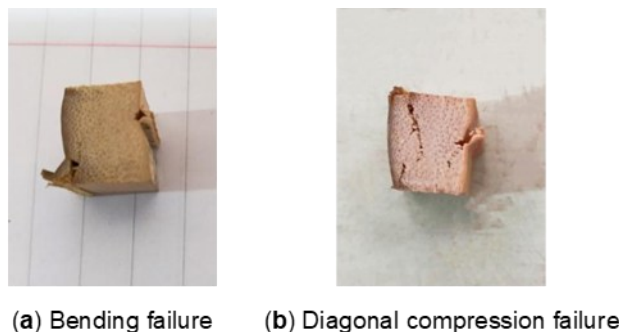
In this mode, due to their curved wall structure, bamboo specimens tend to form cracks along the vertical direction when subjected to lateral pressure, and they gradually bend until they break (Fig. 1a). The entire failure process exhibits the typical ductile characteristics of elasticity, elastoplasticity, and the failure (descent section). The initial stage is the elastic stage, followed by the elastoplastic stage accompanied by plastic deformation. When the pressure exceeds the limit, the specimen enters the failure stage.

### *Diagonal compression failure mode*

For some specimens, during loading, due to the frictional force of the loading surface, cracks are generated and expand along the diagonal direction, resulting in failure (Fig. 1b). The reasons for this mode may be related to factors such as the friction characteristics of the specimen surface, loading conditions, and material properties. The uneven stress distribution caused by friction is the key inducement.

### *Other failure modes*

In addition to the above two main modes, various failure phenomena such as the separation of bamboo green and bamboo flesh, and the crushing at the end of the specimen may also be observed during the test. The emergence of these patterns is often closely related to factors such as the uneven distribution of vascular bundles within bamboo materials and stress concentration caused by specimen design.



**Fig. 1.** Failure patterns

## **RESULTS AND DISCUSSION**

### **Stress-Strain Curves**

The transverse compressive stress-strain curves of bamboo describe the relationship between stress and strain when bamboo is subjected to a pressure perpendicular to the direction of its fibers (*i.e.*, transverse compression). Figure 2 shows the average stress-strain curves of all specimens at each height. The stress-strain curve of the transverse grain compressive strength of bamboo can be divided into the following stages:

#### *Elastic stage*

In the initial stage of loading, there is a linear relationship between the stress and strain of bamboo, meaning that it obeys Hooke's Law. During this stage, the bamboo's response to stress is immediate and recoverable, and no obvious permanent deformation occurs. When the stress is removed, the strain will also completely disappear and return to the original state. This stage reflects the elastic property of bamboo's transverse compression.

#### *Elastoplastic stage*

As the stress continues to increase, bamboo begins to enter the elastoplastic stage. At this stage, the relationship between stress and strain is no longer linear, and the bamboo begins to undergo plastic deformation. That is, the deformation will not fully recover after

the stress is removed. The internal structure of bamboo undergoes irreversible changes, such as the formation and expansion of microcracks. At this stage, the load-bearing capacity of bamboo gradually increases, but the rate of increase gradually slows down.

### Failure stage

When the stress reaches the transverse compressive strength limit of the bamboo, the bamboo will suddenly fail. At this point, the stress will rapidly decrease, while the strain will continue to increase. This stage indicates that the bamboo has lost its ability to continue bearing pressure and may be accompanied by obvious sounds. At this stage, the stress-strain curve of bamboo shows a sharp downward trend.

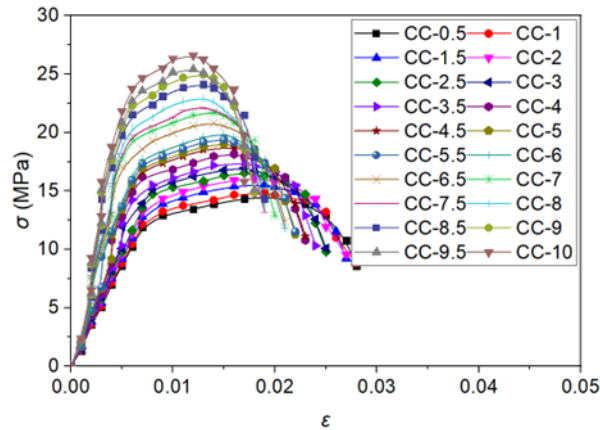


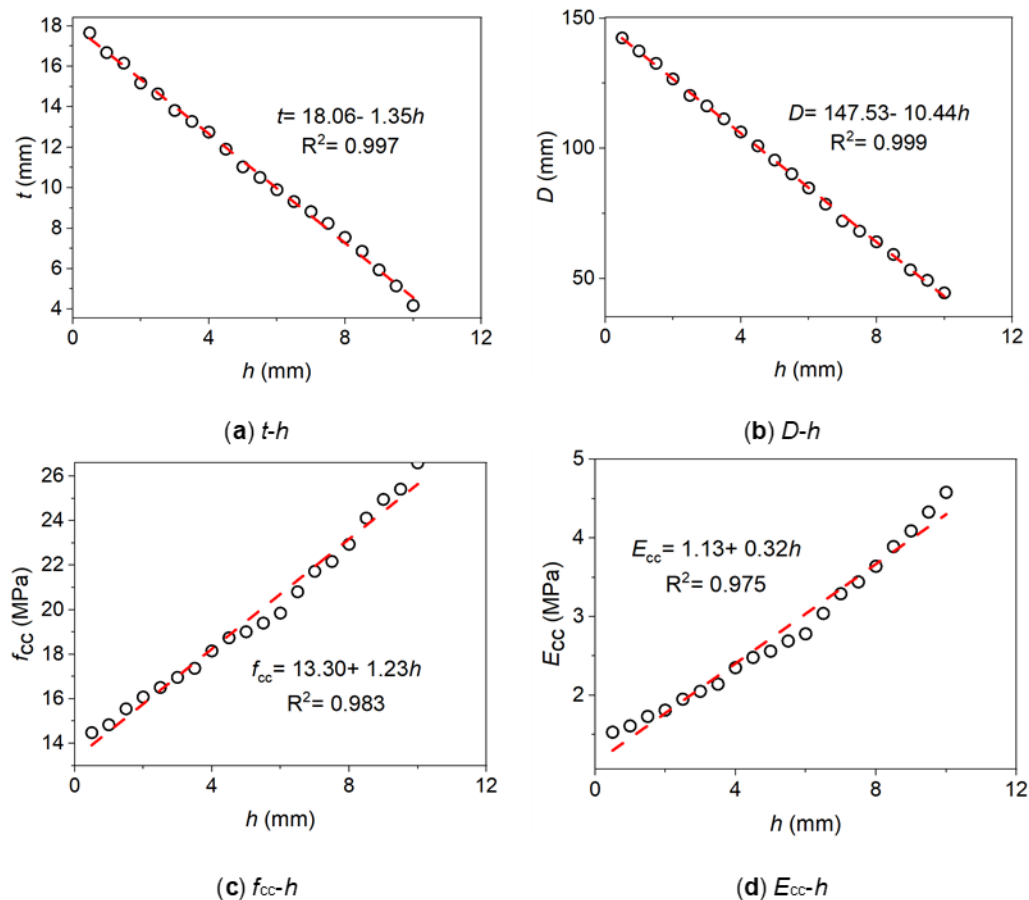
Fig. 2. Stress-strain curves

Table 1 shows the statistics of the transverse compressive characteristic values of bamboo.

**Table 1.** Transverse Compressive Characteristic Values of Bamboo

Number	$h$ (mm)	$t$ (mm)	$D$ (mm)	$f_{cc}$ (MPa)	$E_{cc}$ (GPa)
CC-0.5	0.5	17.66	142.43	14.48	1.53
CC-1	1	16.68	137.42	14.83	1.61
CC-1.5	1.5	16.16	132.66	15.55	1.73
CC-2	2	15.18	126.68	16.08	1.81
CC-2.5	2.5	14.64	120.34	16.51	1.95
CC-3	3	13.82	116.28	16.96	2.05
CC-3.5	3.5	13.28	111.34	17.37	2.14
CC-4	4	12.75	106.31	18.15	2.35
CC-4.5	4.5	11.91	100.95	18.74	2.48
CC-5	5	11.03	95.54	19.01	2.56
CC-5.5	5.5	10.51	90.20	19.40	2.69
CC-6	6	9.90	84.80	19.85	2.78
CC-6.5	6.5	9.32	78.58	20.81	3.04
CC-7	7	8.82	72.09	21.73	3.29
CC-7.5	7.5	8.24	68.22	22.17	3.44
CC-8	8	7.55	64.12	22.94	3.64
CC-8.5	8.5	6.86	59.27	24.12	3.89
CC-9	9	5.94	53.35	24.96	4.09
CC-9.5	9.5	5.15	49.33	25.42	4.33
CC-10	10	4.18	44.50	26.60	4.58

The average of the values of 8 specimens at each height position is taken. According to Table 1, linear fitting was conducted on the wall thickness ( $t$ ), diameter ( $D$ ), transverse compressive strength ( $f_{cc}$ ), transverse compressive elastic modulus ( $E_{cc}$ ), and height ( $h$ ) of bamboo materials respectively, and the fitting results shown in Fig. 3 were obtained. As can be seen from Fig. 3, the wall thickness and diameter of bamboo decreased with the increase of height, while the transverse compressive strength and transverse compressive elastic modulus gradually increase with the increase of height. The determination coefficient  $R^2$  for fitting using the linear relationship was always above 0.9, indicating that the wall thickness, diameter, transverse compressive strength and transverse compressive elastic modulus of bamboo had a strong correlation with height.



**Fig. 3.** The fitting results of transverse compressive characteristic values of bamboo

### Constitutive Relation

The transverse compressive stress-strain curves of bamboo were normalized. The stress was proportional to the peak stress  $\sigma_{c0}$ , and the strain was proportional to the peak strain  $\varepsilon_{c0}$ . The average normalized curve is shown in Fig. 4, which indicates that the peak point of the transverse compressive stress-strain curve of the bamboo after normalization treatment was (1,1). Before the peak point is the ascending stage, and after the peak point is the descending stage. The following model was adopted to describe the transverse compressive stress-strain constitutive relationship of bamboo:

$$y = \frac{3.35x - 2.16x^2}{1 + 1.35x - 1.16x^2} \quad (2)$$

where,  $x = \varepsilon/\varepsilon_{c0}$ ,  $y = \sigma/\sigma_{c0}$ . According to the fitting results, the fitting determination coefficient  $R^2$  of the above constitutive model reached 0.97, indicating that the constitutive model proposed in this study had high accuracy.

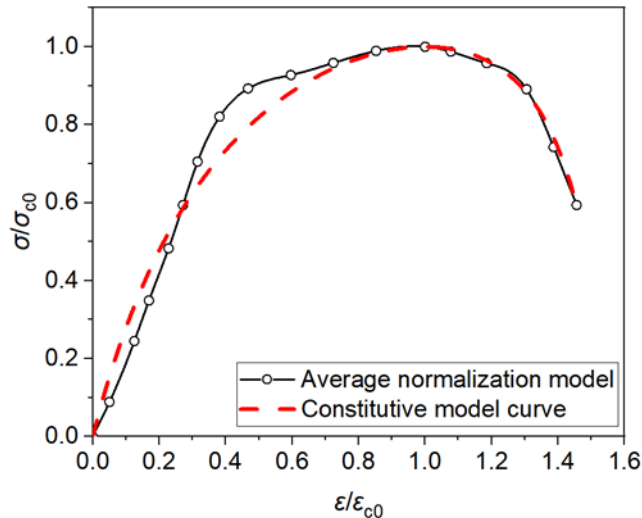


Fig. 4. Normalized stress-strain curves and constitutive model

## CONCLUSIONS

In this study, the transverse compressive tests of various bamboo poles were carried out, the transverse compressive failure modes of bamboo were explored, the stress-strain curves were plotted, characteristic values were analyzed, and the transverse compressive stress-strain constitutive relationship of bamboo materials was proposed. The main conclusions are as follows:

1. The failure modes of the transverse compression of bamboo samples mainly included the bending failure mode and the diagonal compression failure mode. The transverse compressive stress-strain curves of bamboo could be divided into the elastic stage, the elastoplastic stage, and the failure stage.
2. The determination coefficients of the wall thickness, diameter, transverse compressive strength, and transverse compressive elastic modulus of bamboo fitted by linear relationship and height were all above 0.9. The wall thickness, diameter, transverse compressive strength, and transverse compressive elastic modulus of bamboo exhibited a strong correlation with height.
3. The stress-strain curves were normalized, and a stress-strain constitutive relationship with a higher goodness of fit was proposed, with a determination coefficient reaching 0.97.

## ACKNOWLEDGMENTS

The authors are grateful for the support of the Key Research Project of Higher Education Institutions in Henan Province of China: [Grant Number 23B560012].

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Article submitted: September 12, 2025; Peer review completed: October 25, 2025;  
Revised version received: October 28, 2025; Accepted: December 25, 2025; Published:  
May 8, 2026.

DOI: 10.15376/biores.21.3.5878-5886