Time-varying Deterioration of Bamboo Mechanical Properties

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Bamboo is a type of fast-growing and renewable natural resource that is an ideal building material. In this study, the longitudinal tensile, longitudinal compressive, flexural, longitudinal shear, transverse tensile, and transverse compressive stress-strain and strength properties of bamboo with a period of 240 days were conducted to study the time-varying deterioration performance of bamboo. The results showed that the mechanical properties of bamboo decreased gradually with the passage of time. The transverse compressive strength deteriorated the most, and the longitudinal tensile strength deteriorated the least. After 240 days of tests, bamboo CCS decreased by 52.5% and UTS decreased by 25.4%. Formulas to predict deterioration of mechanical properties were put forward and validated. It was found that the nodes of bamboo influenced its mechanical properties. The deterioration degree of the test specimens with nodes was slightly higher than that of the test specimens without nodes. These findings provide evidence about the deterioration mechanism of bamboo and are significant for promoting the development of bamboo architecture.

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INTRODUCTION

Bamboo, a green material that has been living in harmony with nature since ancient times, has been widely used in the field of construction for a long time. As a rapidly growing and renewable natural resource, bamboo not only provides a wealth of inspiration and choices for architectural design, but it also promotes the practice of sustainable development concepts in the construction industry. In architecture, bamboo is cleverly used in many ways. As a structural material, specially treated bamboo, such as bamboo plywood, bamboo bunches, *etc*., can withstand high levels of pressure and tension, and is used to build bridges, pavilions, and even multi-storey residential frames (Made Oka *et al*. 2016; Huang *et al*. 2017; Chen *et al*. 2018; Wei *et al*. 2020; Wang *et al*. 2021; Bala and Gupta 2023). The characteristics of light weight and high strength make bamboo buildings exhibit good seismic performance in the face of natural disasters, such as earthquakes, and provide safe shelters for residents (Zhou *et al*. 2012; Tian *et al*. 2018; Lin *et al*. 2019). In the decoration and detail design, bamboo adds a unique oriental charm to the space with its natural texture, warm color, and fresh breath. Whether used as wall decoration, partition screen, or furniture, bamboo can be well integrated into a variety of design styles to create a peaceful and elegant living atmosphere (Jiang *et al*. 2015; Crolla 2017; Skuratov *et al*. 2021). In addition, bamboo also plays an important role in green buildings because of its good air permeability and humidity regulation. It can regulate the indoor microclimate and reduces the use of air conditioning, thus reducing energy consumption and carbon emissions. In the pursuit of low-carbon life today, bamboo architecture has undoubtedly become a favorable choice for both environmental protection and aesthetics.

Research on the mechanical properties of bamboo is the foundation to promote the development of bamboo architecture. In recent years, scholars have studied the mechanical properties of bamboo and produced a series of research results. Ribeiro *et al*. (2017) evaluated the flexural properties of bamboo and obtained the relationship between the flexural properties. Liu *et al*. (2021) examined 9 mechanical properties of bamboo, studied the relationship between mechanical properties and physical properties of bamboo, proposed the prediction formulas of mechanical properties of bamboo, and established the relationship between mechanical properties of bamboo. Zhou *et al*. (2022) studied the longitudinal tensile and compressive properties, analyzed the stress-strain curve of bamboo, and proposed a stress-strain constitutive model of bamboo. Kuang *et al*. (2023) analyzed the strength design value of bamboo by testing the flexural performance and provided a reference for the application of bamboo structures. A systematic study on the physical and mechanical properties of bamboo was carried out, and the influence of humidity on the physical and mechanical properties of bamboo was analyzed (Jakovljevic *et al*. 2019). Gauss *et al*. (2020) put forward methods and approaches to solve the problem of bamboo's easy degradation and provided references for bamboo’s anti-degradation and anti-mildew properties. The strength classification of bamboo through experimental research was also explored, and a foundation for the selection of bamboo buildings was laid out (Bahtiar *et al*. 2019).

Up to this point, there have been few studies on the time-varying degradation of bamboo mechanical properties. Bamboo deteriorates in the natural environment for the following reasons: (1) Mold erosion: mold can invade the interior of the bamboo and absorb the nutrients of the bamboo through its mycelium, resulting in a decline in the quality of the bamboo. There are many kinds of molds, such as *Arthrospora*, *Trichoderma*, *etc.*, which are easy to grow in a humid and warm environment and have a significant impact on the deterioration of bamboo (Liu 2012). (2) Insect decay: Insect decay is another important cause of bamboo deterioration. Insects eat inside the bamboo, forming holes and directly destroying the structure and strength of the bamboo. (3) Cracks: Bamboo is susceptible to various stresses in the natural environment, such as temperature changes, humidity changes, *etc*., resulting in cracks. Cracks not only affect the beauty of bamboo, but they also weaken its mechanical properties and accelerate the deterioration process (Shao and Wang 2018). (4) Climate factors: the alternating action of rain and sunlight is easy to crack bamboo, which accelerates the infiltration of rain and the breeding of mold, further affecting the performance of bamboo. In addition, extreme climate such as drought, floods, *etc*., will also promote the deterioration of bamboo (Huang *et al*. 2021). (5) Human factors: human activities such as excessive logging and irrational utilization will also have an impact on the deterioration of bamboo. Excessive cutting will lead to the decrease of bamboo forest resources and affect the regeneration ability of bamboo. However, improper utilization may cause damage to bamboo in the process of processing, storage and use, and accelerate its deterioration process. To sum up, bamboo deteriorates in the natural environment for a variety of reasons, including mold erosion, insects, cracks, climatic factors, and human factors. In order to prolong the service life of bamboo, it is necessary to take effective protective measures, such as strengthening the management of bamboo forest, rational cutting and utilization of bamboo, anti-degradation, and insect-prevention treatment. In this study, six kinds of mechanical property tests of bamboo were carried out to characterize such changes, and the mechanical properties of bamboo were studied for 240 days. The stress-strain curves of bamboo were analyzed, the prediction formulas of bamboo strengths were put forward according to the deterioration law of bamboo mechanical properties, and the influence of bamboo nodes on bamboo deterioration was investigated.

EXPERIMENTAL

Materials

The moso bamboo selected in this study was produced in Yunnan Province, China. Bamboo stalks without obvious bending and damage were selected for felling, and the bamboo age was 4 years. A total of 245 bamboo trees were felled. First, the felled bamboo was air-dried in a ventilated and dry laboratory, and the moisture content of the bamboo after air-dried treatment was about 15%. Specimens suitable for evaluation of mechanical properties were fabricated and tested following JG/T 199-2007 (2007) and ISO 22157-2019 (2019) standards. In this study, the longitudinal tensile, longitudinal compressive, flexural, longitudinal shear, transverse tensile, and transverse compressive properties of bamboo were examined. The longitudinal tensile strength (UTS), longitudinal compressive strength (UCS), flexural strength (MOR), longitudinal shear strength (USS), transverse tensile strength (CTS), and transverse compressive strength (CCS) of bamboo were obtained by experiments. The size of the specimen used for longitudinal tensile test was 330 mm × 15mm × *t* mm (*t* is the wall thickness), whereas the ratio of height to diameter of the specimens employed in longitudinal compressive and the longitudinal shear tests was 1. The size of the bamboo bending test specimen was 220 mm × 15 mm × *t* mm, the length of the effective section of the transverse tensile test specimen was 26 mm, and the size of the transverse compressive test specimen was 15 mm × 15 mm × *t* mm. Each specimen is shown in Fig. 1. Detailed dimensions of the specimen are shown in JG/T 199-2007 (2007) and ISO 22157-2019 (2019). The time-varying deterioration performance of all types of specimens was studied. A total of 240 days of tests were conducted, and the strength test was conducted every 20 days, and 3 specimens were tested in each test.

(a) UTS **(b)** UCS and USS **(c)** MOR **(d)** CTS **(e)** CCS

Fig. 1. The specimens

Mechanical Properties Tests

The longitudinal tensile, longitudinal compressive, and longitudinal shear tests were conducted at the loading rate of 0.01 mm/s. The loading rate of bamboo bending test was 150 N/mm^2 per minute. The transverse tensile test was loaded to break at 0.005 mm/s. The transverse compression test was uniformly loaded to failure at a loading rate of 20 N/mm^2 per minute.

RESULTS AND DISCUSSION

Stress-strain Curves

Figure 2 shows the stress-strain curves of various mechanical properties of bamboo obtained through the tests of 0, 120, and 240 d.

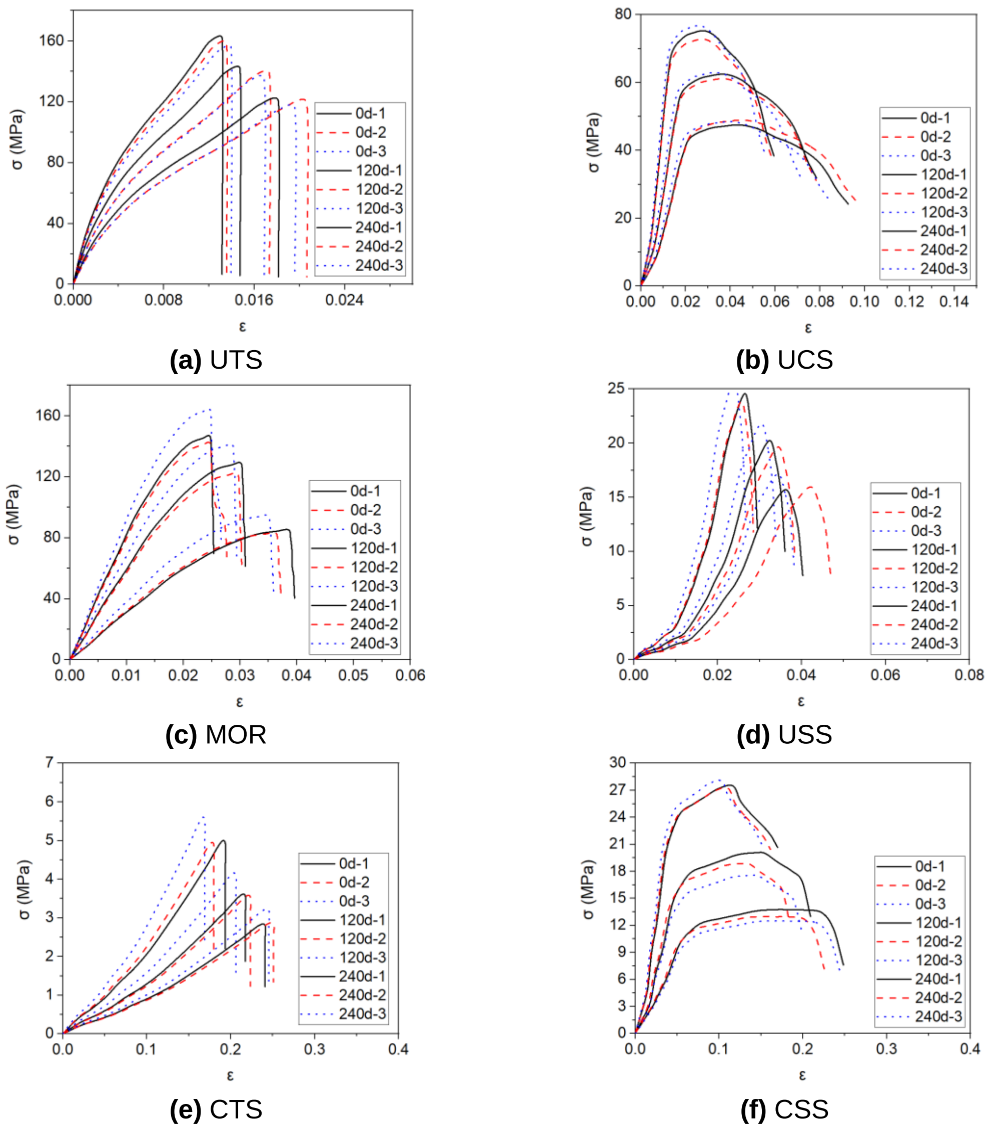

Fig. 2. Stress-strain curves

These results revealed the following:

(1) The failure modes of various mechanical properties of bamboo were different. The stress-strain curves of the longitudinal tensile, flexural, longitudinal shear, and transverse tensile tests of bamboo suddenly decreased after reaching the peak stress, but the stress-strain curves of the longitudinal compressive and transverse compressive tests of bamboo did not exhibit this phenomenon. This shows that the longitudinal tensile, flexural, shear, and transverse tensile tests represented brittle failure modes, while the longitudinal compressive and transverse compressive tests followed ductile failure modes. It can also

be seen from Fig. 2 that the failure modes of various mechanical properties of bamboo at different time points were consistent. For example, the longitudinal tensile test showed a brittle failure mode at 0 d and a brittle failure mode at 240 d, and the longitudinal compressive resistance showed ductile failure mode at any time point.

(2) Bamboo is a typical anisotropic material, and the values of its mechanical properties are very different. Among the 6 mechanical properties tested in this study, the longitudinal tensile strength was the largest and the transverse tensile strength was the smallest. From the microscopic point of view, bamboo is mainly composed of vascular bundles and basic tissue. The vascular bundle mainly bears the applied force, and the basic tissue connects the vascular bundle into the material as a whole. Therefore, in the longitudinal tensile test, bamboo is mainly played by vascular bundle, and vascular bundle has higher strength, so bamboo has higher longitudinal tensile strength. As far as transverse tensile strength is concerned, it is mainly the basic tissue that plays a role, so the transverse tensile strength of bamboo is low.

(3) With the passage of time, the mechanical properties of bamboo decreased. That is, the deterioration degree of bamboo became increasingly more serious with the passage of time. Therefore, the protection of bamboo is an important issue in the application of bamboo structure. Usually, the bamboo is pretreated by chemicals or coating methods, to protect it. Commonly used chemicals to protect bamboo include tung oil, coal tar, asphalt, resin, *etc*., following soaking, cooking, and other methods.

Rule of Time-varying Deterioration

The strength changes in the mechanical properties of bamboo for 240 days were studied to assess the law of time-varying deterioration in the properties. Figure 3 shows the time-varying deterioration rule of various mechanical properties of bamboo, in which all data were linearly fitted. The mean values of UTS, UCS, MOR, USS, CTS, and CCS of bamboo at 0 d were 158.6 MPa, 74.9 MPa, 147.6 MPa, 24.8 MPa, 5.18 MPa, and 27.6 MPa, respectively. Among the mechanical properties of bamboo, UTS and MOR were the largest, UCS was also higher, and other strength indexes were lower. As shown in Fig. 3, with the passage of time, all mechanical properties of bamboo showed a trend of gradual decline. When bamboo is exposed to the natural environment, its mechanical properties deteriorate over time. This is related to changes in environmental factors such as temperature and humidity. From the microscopic level, the degradation of physical and mechanical properties of bamboo was likely caused by mold decomposition of cellulose, hemicellulose, and lignin (Li *et al*. 2015). The mean values of UTS, UCS, MOR, USS, CTS, and CCS of bamboo at 240 d were 118.3 MPa, 48.2 MPa, 84.3 MPa, 16.3 MPa, 2.98 MPa, and 13.1 MPa, respectively. The mean values decreased 25.4%, 35.6%, 42.9%, 34.3%, 42.4%, and 52.5%, respectively, when compared to the starting values. The deterioration of transverse compressive strength of bamboo was the highest, and that of longitudinal tensile strength was the lowest.

The values of various mechanical properties of bamboo were fitted at different time points. Figure 3 shows that the degradation laws of various mechanical properties of bamboo were well fitted with a linear relationship, and the coefficients of determination were all higher than 0.9. According to the fitting results, the mechanical properties of bamboo showed a linear decline trend over time. Following the fitting formulas shown in Fig. 3, the degradation law of various mechanical properties of bamboo can be predicted. In this study, these formulas were used to predict the strength values of each mechanical property on day 365. The calculated strength values of UTS, UCS, MOR, USS, CTS, and CCS of bamboo at 365 d were 93.4 MPa, 34.5 MPa, 93.4 MPa, 13.1 MPa, 1.44 MPa, and 4.00 MPa, respectively. Compared with the beginning, they were reduced by 41.1%, 53.9%, 36.7%, 47.0%, 72.8%, and 85.5%, respectively.

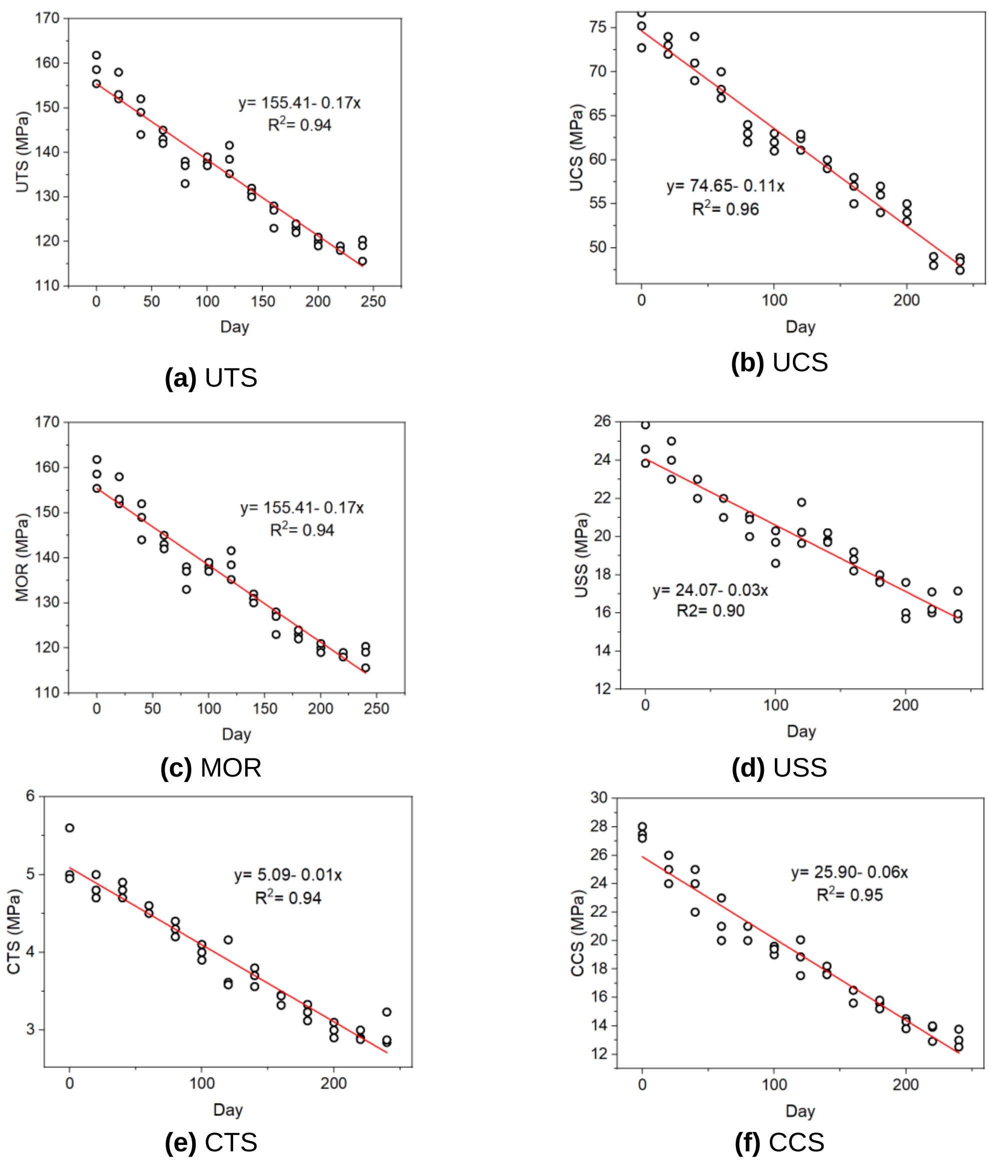

Fig. 3. Rule of time-varying deterioration

Influence of Bamboo Nodes

To explore the influence of bamboo nodes on the deterioration of various mechanical properties of bamboo, this study conducted strength tests on a group of specimens with bamboo nodes and recorded the strength values of the specimens with nodes at 0 d and 240 d respectively, as shown in Fig. 4. It can be seen from the results of Fig. 4 that strength deterioration occurred over time in both test specimens with and without bamboo nodes. The strength values of UTS, MOR, and USS without bamboo nodes were greater than those with nodes, while the strength values of UCS, CTS, and CCS with nodes were greater than those without bamboo nodes. The above results are mainly related to the microstructure of bamboo. Taking the longitudinal tensile strength as an example, the distribution of vascular bundles in the bamboo node is relatively crooked, and compared with the linear arrangement of the non-bamboo node, this structure is more prone to stress concentration when stressed, resulting in the reduction of the longitudinal tensile strength. The strength values of UTS, UCS, MOR, USS, CTS, and CCS with bamboo nodes at 0 d were 156.3 MPa, 78.3 MPa, 142.1 MPa, 22.3 MPa, 6.2 MPa, and 29.3 MPa, respectively. The values at 240 d were 101.3 MPa, 52.4 MPa, 78.3 MPa, 14.3 MPa, 3.3 MPa, and 15.0 MPa, respectively. The strengths at 240 d decreased 35.2%, 33.2%, 44.9%, 36.0%, 46.3%, and 48.9%, respectively, compared with that at day zero. Overall, the deterioration degree of the bamboo specimens with bamboo nodes was slightly higher than that without nodes.

It is of profound value and significance to study the degradation of bamboo properties. It is not only related to the safety and durability of bamboo structural engineering, but also directly affects the social economic operation and the safety of people's lives, and is also a key link to promote the progress of material science. By deeply exploring the degradation mechanism of bamboo in complex environment, it is possible to scientifically predict and effectively delay the decline of bamboo performance, provide accurate guidance for engineering maintenance, and reduce resource waste and economic loss caused by material failure. In addition, this research promotes the development of new high-performance, long-life materials, providing a solid material science foundation for the implementation of sustainable development strategies.

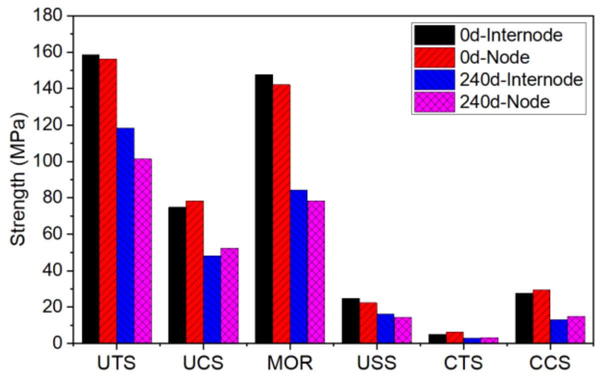

Fig. 4. Comparison of the deterioration of bamboo specimens with and without nodes

CONCLUSIONS

In this study, six mechanical properties of bamboo were tested, and degradation behaviors became better understood.

1. Through analyzing the stress-strain curves, it was found that the longitudinal tensile, flexural, shear, and transverse tensile tests of bamboo indicated brittle failure modes, and the longitudinal compressive and transverse compressive tests were ductile failure modes.

2. A 240-day time-varying degradation study of 6 mechanical properties of bamboo showed that the mechanical properties of bamboo decreased gradually with the passage of time. This was related to changes in environmental factors such as temperature and humidity. The deterioration of transverse compressive strength

was the highest and that of longitudinal tensile strength is the lowest. The formulas obtained by fitting the relationship between strength and time can be used to predict the strength of bamboo.

3. In addition, the effect of bamboo nodes on the time-varying deterioration of bamboo mechanical properties were also investigated. The results showed that the deterioration degree of the specimens with nodes was slightly higher than that of the specimens without nodes.

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