Assessing the Creep Performance of Full-scale Bamboo Scrimber Columns

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Bamboo scrimber is a kind of artificial processing material with high compressive strength, large size, natural texture, and wide application. It is made by rolling and de-fibering bamboo into a loose reticulate bundle, which is unbroken transversely, and loosely interlaced in the longitudinal direction, followed by drying, gluing, assembling, and hot pressing. In this study, to better understand the application value of bamboo scrimber in construction engineering, the performance of axially compressed solid columns that have been completed with three full-scale solid bamboo scrimber columns of 100 mm width, 100 mm height, and 2000 mm length were subjected to creep tests for 3 months. The specimens J1, J2, and J3 were designed to carry the long-term load of 0.2, 0.4, and 0.6 times the short-term test failure load of the same batch of specimens, respectively. The experimental study found that the bamboo scrimber columns could not bear 0.6 times of the short-term test failure load P_u, and that temperature and humidity greatly influenced creep of the specimens. Finally, a creep constitutive equation was established using a three-parameter model, and the equation matched well with the creep test data.

Keywords: Bamboo scrimber column; Creep test; Creep constitutive equation

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INTRODUCTION

Bamboo scrimber is a type of engineered bamboo that owes its origins to the wood scrimber processing technology invented by Australian scientist John Douglas Coleman in 1973 (Shang *et al.* 1998). It consists of a square or rectangle plate with high strength, large size, and natural bamboo texture made from long, cross-linked, loose reticular fiber bundles— maintaining the original arrangement of fibers— dried at low temperatures to less than 12% moisture content. These are then made by the parallel lay-up, glued, and hot pressed. Bamboo scrimber has the preferred characteristics of the high utilization rate of bamboo, good physical and mechanical properties, appealing aesthetics, and cost-effective commercial as well as reliable construction material (Li *et al.* 2001).

As a polymer composite material, bamboo scrimber has rheological properties, meaning its structure will undergo creep deformation under long-term loads. To avoid excessive creep and to understand the compressive creep performances of bamboo scrimber columns, it is necessary to subject them to axial compression creep tests. Since there is little published research on the creep performance of bamboo scrimber columns, this study has referred to related research methods used for assessing wood creep.

In the 1960s, Armstrong (Armstrong *et al.* 1960, 1961) proposed that changing the moisture content would influence the creep properties of wood. Later, Bhatnagar (1964) pointed out that the relationship between creep strain and stress in the wood was a linear function when the stress in the specimen was less than or equal to a certain value, and when it exceeded that value, the relationship was non-linear. Schniewind (1967) found that the periodic variations of relative humidity and temperature in the environment led to significant reductions in the average time of small beams of Douglas fir to failure at a given load level. In the 1970s, the concept of mechanical adsorption creep was proposed (Grossman 1976). Consequently, the relationship between wood deformation and the time at which the water content, temperature, or circulation conditions under stress are changed was suggested for the first time. Leicester (1971) introduced a creep interpretation model for mechanical adsorption characteristics. Bazant (1985) had proposed that wood is a linear viscoelastic material under the stress limit and constant temperature as well as humidity conditions.

Chinese scientists also have conducted much research on wood creep. In 1989, the compression rheological properties of oak wood cross-grain and white poplar-planed flakes were reported (Shi and Wang 1989; Wang 1989). At the same time, Liu and Li (1989, 1996a) presented a viscoelastic model for wood creep, later reporting on the creep characteristics of several major tree species. One notable study proposed that resin pH affects the creep properties of particleboard (Wang 1990). Other reports describe the creep characteristics of *Phyllostachys pubescens* under various stress levels, and temperature and moisture content (Xu *et al.* 2007), and a discussion of rheology applications to research on wood composite materials, namely particleboard, plywood, medium-density fiberboard, veneer laminated wood, paper wood composite board, and wood-plastic composite material (Hu *et al.* 2008). Ma *et al.* (2008) reviewed the rheological properties of wood and composite materials, and prospected for further research on wood rheology in the future, including the accelerated characterization of wood long-term rheological properties based on time-temperature-stress equivalence principle and the application of the genetic algorithm in wood rheological research.

Creep of a full-scale glued bamboo bridge strengthened by carbon fiber-reinforced plastics (CFRP) has been observed for 3.5 years by Xiao *et al.* (2013). The ensuing analysis revealed the rule of creep deformation during the period. After the uniform load was removed, a subsequent short-term damage test showed that CFRP not only improved the mechanical performance of bamboo beams but also met the requirements of strength and durability in practical engineering. Using a self-developed creep device, Wang (2007) and Zhou (2009) carried out tensile and compression creep tests of LVL (laminated veneer lumber) under various load levels, analyzed the influencing factors of creep constitutive model of LVL, and established a relationship between creep strain and time. A user material subroutine (UMAT) has been developed for creep calculation using commercial software ABAQUS, and has been used to numerically simulate the effect of long-term deformation and creep on the stability of wood arches and reticulated shells. Liu *et al.* (2016) selected three sets of full-scale LVL columns made from poplar LVL for a 1-year creep test. That study showed that creep deformation mainly includes elastic, viscous, and viscoelastic deformations, with changes in temperature and humidity having a considerable influence on creep deformation. A constitutive creep equation was established, and the simulated value coincided well with the test data. A tensile and compressive creep test of full-scale model bamboo scrimber provided information of these properties under ideal conditions (Wu 2015), as did another a creep test conducted on bamboo scrimber beams (Li *et al.* 2015).

Thus far, the creep tests of bamboo scrimber columns, both in China and abroad, are less and limited to the scale model under ideal conditions. The creep law established by the scale model is quite different from that of the full-scale model (Liu *et al.* 2016). In this paper, the long-term compression of full-scale bamboo scrimber columns was studied in detail to reveal the creep behavior rules of such columns and to explore potential applications of full-scale bamboo scrimber columns for building structures.

EXPERIMENTAL

Methods and Materials

The specimens were produced by Jiangxi Chun Hong Bamboo Technology Co., Ltd. (Jiangxi Province, China). The size of bamboo scrimber columns used was 100 mm × 100 mm × 2000 mm (width × height × length). The physical and mechanical properties of the same batch of bamboo scrimber specimens before the long-time loading test were determined. According to these results, bamboo scrimber had an air-dried density of 1.204 g/cm^3, average moisture content of 6.6%, compressive strength along the grain of 57.35 MPa, standard compressive strength along the grain of 55.47 MPa, elastic modulus along the grain of 1180 MPa, and a Poisson ratio of 0.384. From a previous (Liu *et al.* 2020) axial compression test of the same batch of bamboo scrimber columns, the failure load of the specimens under axial compression was 340 kN. In this study, the creep load of specimens J1, J2, and J3 was set at 0.2, 0.4, and 0.6 times more of the failure load value, respectively, as shown in Table 1. With the 0.6 times stress ratio, two specimens were loaded twice.

Table 1. Compression Creep Load of Bamboo Scrimber Columns

Specimens	Stress Ratio	Creep Stress (MPa)	Creep Load (KN)
J1	0.2	6.8	68
J2	0.4	13.5	135
J3	0.6	20.5	205

Design of Loading Device

To study the creep performance of the specimens under long-term loading, a new type of self-balancing device for creep test was designed based on the research of Liu *et al.* (2016). A schematic of the loading device is shown in Fig. 1. The jack at the bottom loads the device, and the applied load passed through the foot steel plate, spring, middle steel plate, the pressure sensor, and top steel plate, and finally it was borne by the specimen. After the value in pressure sensor reached specified load, the foot steel plate's position was fixed with a nut. In this loading process, the compressive deformation was produced in the spring. When the pressure sensor reads down and pressure in the specimen decreased due to axial and lateral deformations under the long-time load, then the spring elongated, and replenished the pressure. The function of the spring was to maintain a stable load.

Experimental Scheme and Measuring Point Arrangement

The experiments were performed according to China's current code for the design of timber structures GB 50005-2003 (2005) and ASTM D198 (2015), in the Mechanics Laboratory of Yangzhou University (Yangzhou, China). The creep test started on June 27, 2017, and ended 3 months later, on September 27, 2017.

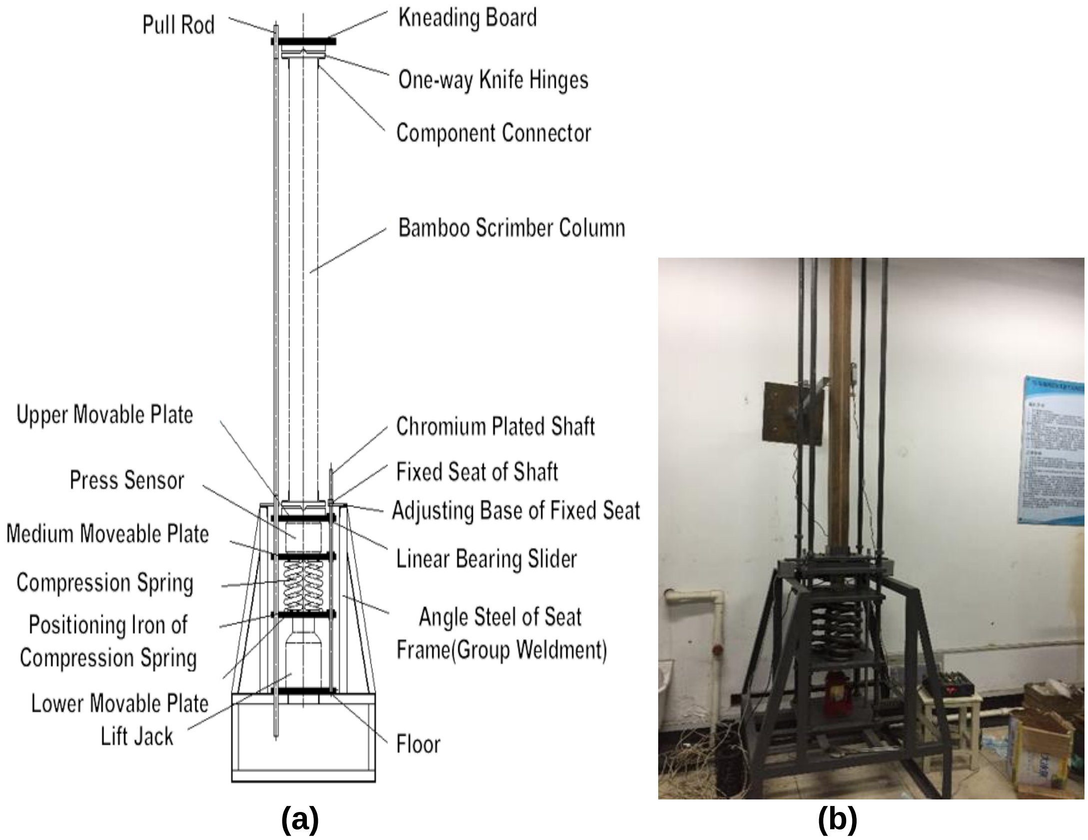


Fig. 1. Test setup: (a) Device design drawing; and (b) test device

The main purpose of this paper was to study the effect of long-term load on the creep behavior of bamboo scrimber columns. Because this test time was in the summer, all doors and windows were kept closed and curtains were drawn to avoid direct sunlight. This was done to simulate a relatively constant temperature and relative humidity environment. Meanwhile, the indoor temperature and relative humidity were measured and recorded on a daily basis.

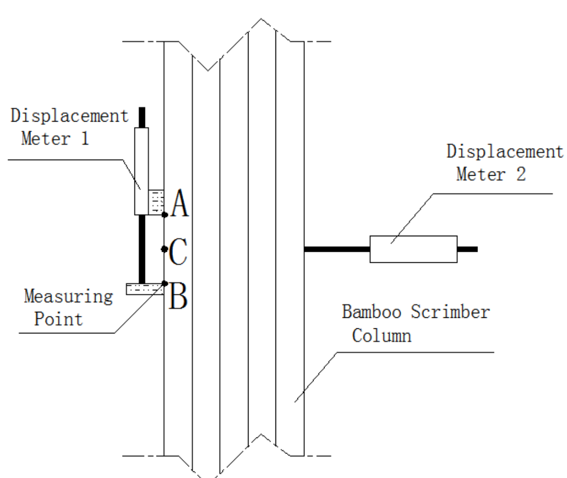


Fig. 2. Arrangement of measure point layout

The two ends of each specimen were hinged with one-way knife hinges. Before loading, a geometric alignment of the specimen, lifting jack, spring, and pressure sensor was made to prevent initial peculiarities and to ensure that all layers of the steel plate were horizontal and could slide up and down freely.

Wire displacement meters were placed in the middle of a specimen, and the axial creep and lateral deflection values of each specimen were recorded manually. Specifically, during the first week of loading, test data were recorded every 3 h, and then four times a day. The measure point layout and the creep test were executed as shown in Fig. 2.

RESULTS AND DISCUSSION

Temperature and Humidity Record

The temperature and relative humidity changes during the test are shown in Fig. 3. From the figure it can be found that the ambient temperature of the test room was approximately 22 to 26 °C. The temperature increased somewhat during the period of the 40^{th} to 60^{th} day owing to the external high temperature in the environment. The relative humidity decreased a little in the first 40 days, and then it remained at 60% to 66% in the 20^{th} to 40^{th} days. The relative humidity cycle was 63% to 73% during the 40^{th} to 90^{th} days of the experiment because of the heat and humidity of the rainy season in Yangzhou.

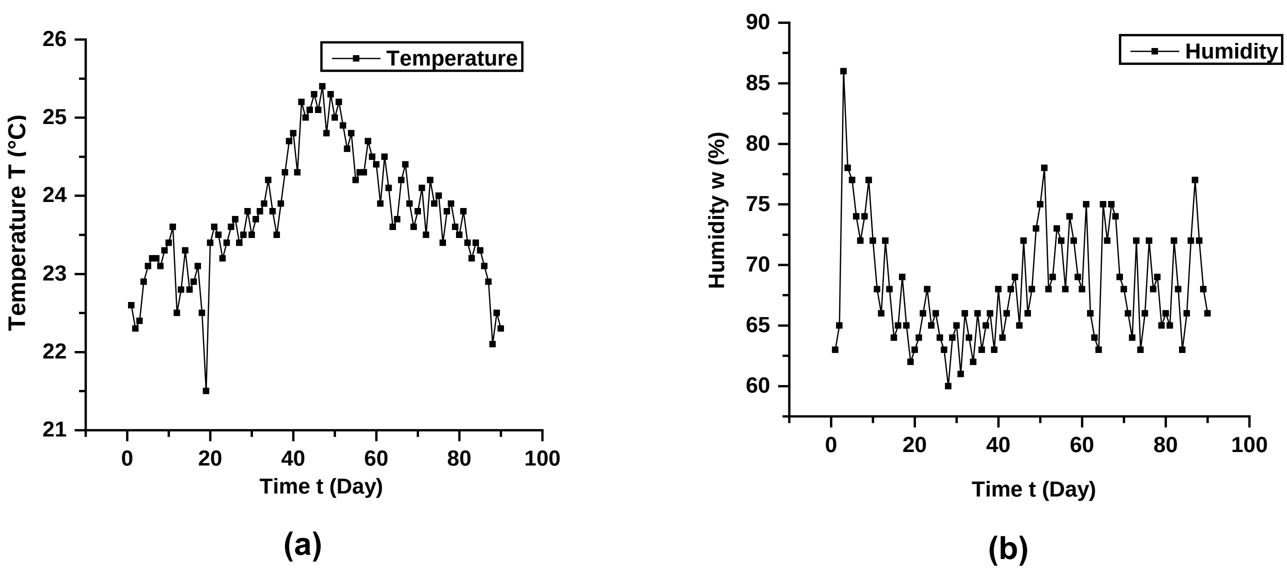


Fig. 3. Change of temperature and humidity: (a) Temperature time curve in test environment; and (b) Humidity time curve in test environment

Experimental Phenomena

Three sets of experimental devices were used to carry out long-term load tests with three stress ratios at the same time, and only one specimen was used for creep tests with each stress ratio. In the axial compression creep test of 0.6 times stress ratio, the specimen failed on the third day after loading. As a result, to eliminate the accidental error of test specimen and make the test result more reliable, the second 0.6 times stress ratio experiment was conducted with a specimen of the same size, which also was destroyed suddenly on the 8th day of loading (Fig. 4). These results indicated that the full-scale solid bamboo scrimber column would not bear large long-term loads because of the various finger connection positions, and the quality of plate surface gluing. The maximum long-term load of full-scale solid bamboo scrimber column was suggested to be less than 0.6 times the ultimate load.

(a) (b)

Fig. 4. Failure modes of the bamboo scrimber columns: (a) the 0.6 times stress ratio experiment; and (b) the second 0.6 times stress ratio experiment of specimens

The long-term loading tests from the other two stress ratios were carried out until the end of the tests, and only one specimen was used for creep tests with each 0.2 times stress ratio and 0.4 times stress ratio.

Creep Strain

Figure 5 shows the creep deformation of a full-scale solid bamboo scrimber column under the stress levels of 0.2 times and 0.4 times. The two specimens did not enter the third stage of creep (Liu *et al.* 2016), namely, the non-convergence creep stage. The creep of the bamboo scrimber column can be divided into two stages: the first is the transition creep stage, in which the strain imposed increases with time, but the rate of increase gradually slows; the second is the constant creep stage, named such because the strain remained generally stable. Both specimens entered the steady-state of creep around day 50, after which it was mostly stable. From Fig. 5, it can be seen that the creep strain of the specimens under 0.2 and 0.4 times stress level had similar changes with the increase of time. Comparing the two creep curves, evidently, the creep deformation of the specimen increased correspondingly with its increased load, which is consistent with the findings of Itani *et al.* (1986).

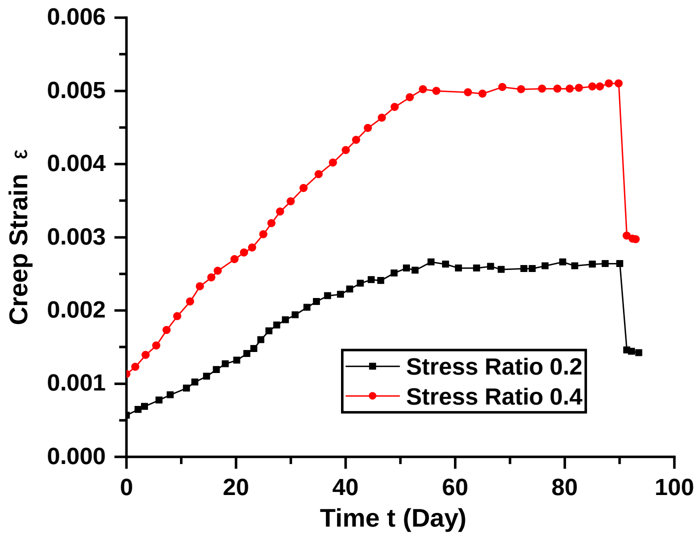


Fig. 5. Creep strain–time curve of bamboo scrimber columns

The creep properties of the bamboo scrimber column under the 0.4 times stress level were further analyzed. Figure 6 depicts the strain change during unloading, and the solid-line curve after unloading expresses the creep recovery, which happened in a relatively short time. A sudden drop then appears in the strain curve, representing the elastic recovery deformation (ε_e) of the specimen after unloading. There was also evidence of viscoelastic deformation (ε_{de}) and viscous deformation (ε_V) in the residual deformation of the specimen. According to work by Sheng (2015), with more time elapsed since unloading, ε_{de} can be gradually restored, whereas ε_V is permanent deformation. It is reasonable to speculate on the creep strain curve that went unrecorded during unloading (see the dashed line in Fig. 6).

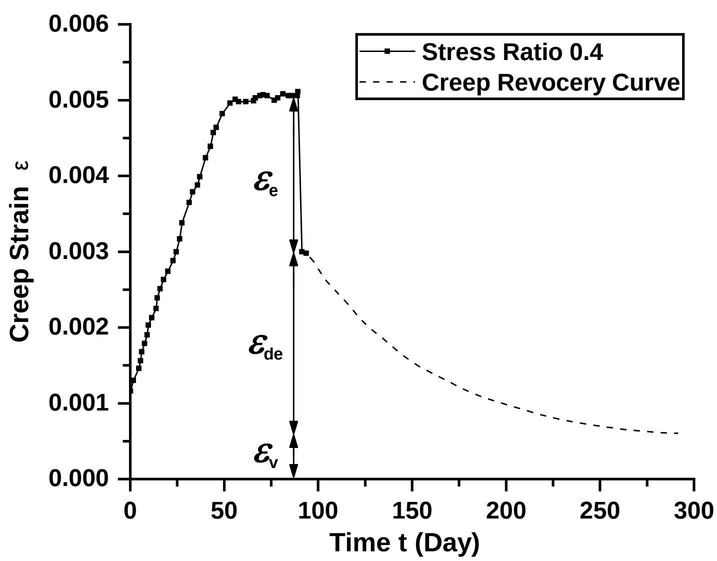


Fig. 6. Unloading creep strain-time curve with the stress ratio of 0.4x

To study the relationship between creep strain and temperature and relative humidity of bamboo scrimber column, the creep strain data of specimen with a stress ratio of 0.4 in 60 to 80 days were analyzed. Figure 7a shows the creep strain-temperature relationship when the relative humidity was approximately 68%, and Fig. 7b shows the creep strain-humidity relationship when the temperature was approximately 24 °C. From Figs. 6 and 7, it can be found that the fluctuation of temperature and relative humidity had a certain influence on creep strain. The creep strain increases with the increase of temperature and relative humidity, which is consistent with the research in reference (Liu *et al.* 2016).

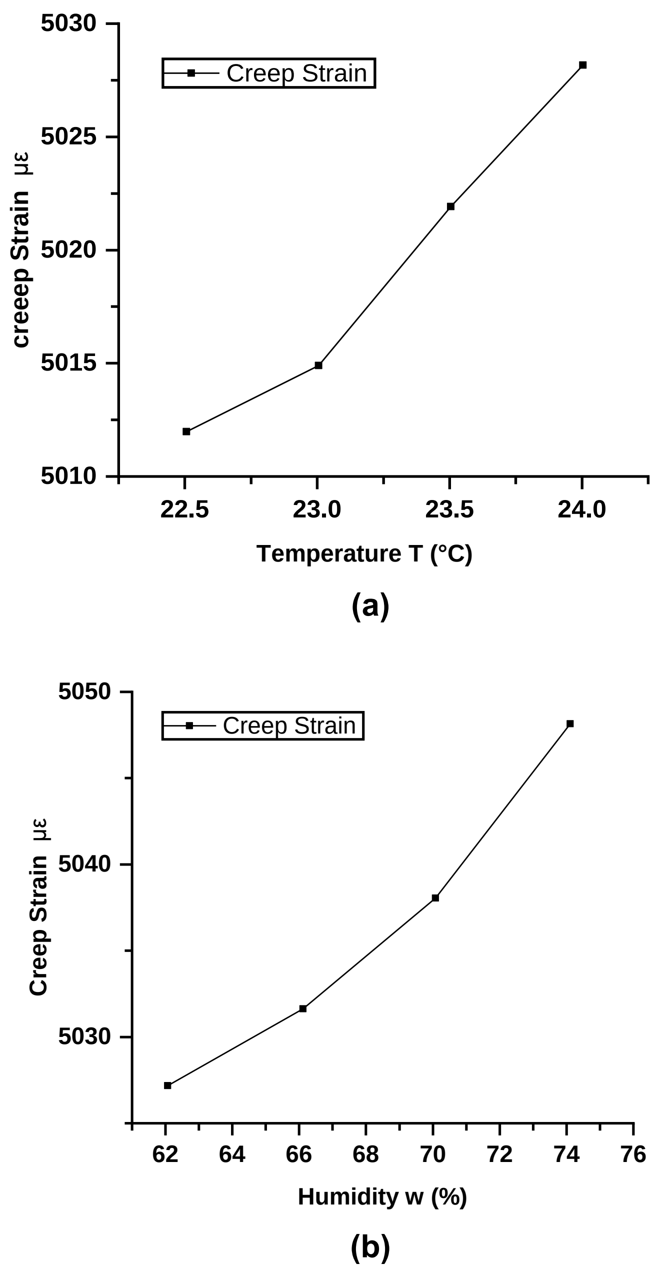


Fig. 7. Bamboo scrimber column with the stress ratio of 0.4 ×: (a) Creep strain–temperature relationship and (b) creep strain–humidity relationship

Lateral Deflection

Figure 8 shows the time *versus* lateral deflection curve of the bamboo scrimber column under the 0.2 and 0.4 times stress level. There were similarities in the creep deflection of the two groups of specimens, and the lateral deflection of both columns would enter the stable stage at *ca.* 20 to 30 days. In the middle and later stage of the experiment, the indoor relative humidity changed more than before, and the lateral deflection of bamboo scrimber column also fluctuated due to the wet and hot rainy environment. In addition, the influence of temperature and relative humidity cycle on lateral deflection of bamboo scrimber columns is similar as that on creep strain, which is not going into much detail here. From Fig. 9, it can be found that the lateral deflection of bamboo scrimber columns was small and is mainly an elastic type of deformation.

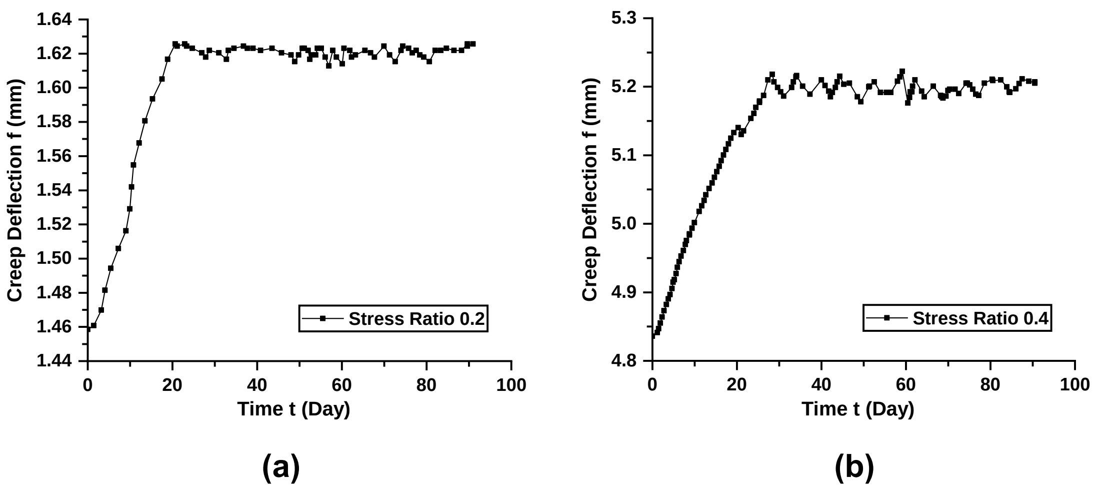
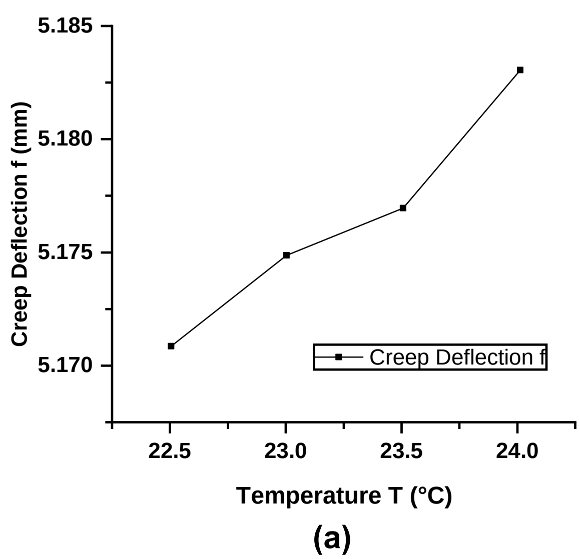
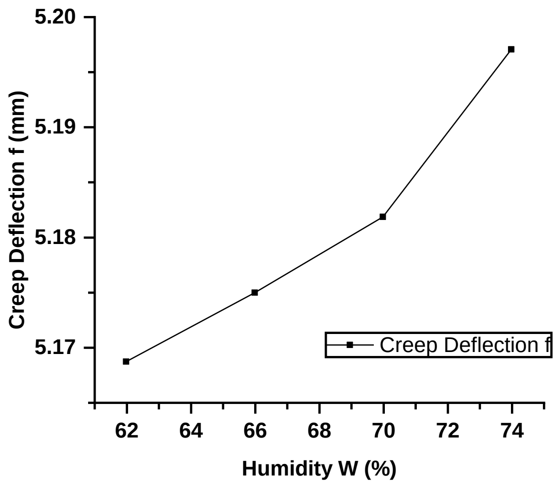


Fig. 8. Creep deflection–time curve: (a) 0.2 times stress ratio curve of bamboo scrimber columns; (b) 0.4 times stress ratio curve of bamboo scrimber columns





(b)

Fig. 9. Influence of temperature and humidity on creep strain: (a) creep deflection–temperature relationship of bamboo scrimber column with the stress ratio of 0.2x; (b) creep deflection–humidity relationship of bamboo scrimber column with the stress ratio of 0.4x

In summary, it can be found that both temperature and relative humidity affect the creep strain and lateral deflection of bamboo scrimber columns. Therefore, the influence factors of temperature and humidity should be considered when studying the creep mechanism of bamboo scrimber columns.

Theoretical Analysis and Discussion

The creep of the bamboo scrimber column is a long-term process, and the two creep stages mentioned above are common in engineering. Therefore, the two creep stages of the bamboo scrimber column are mainly discussed and analyzed. Sheng (2015) had fitted a constitutive equation of laminated veneer lumber specimens made from poplar according to a three-parameter model, the Burger model, and a classical creep model. That comparative study showed that the three-parameter constitutive equation could be applied to improve engineering practices. Here, the creep constitutive model of the bamboo scrimber column based on this three-parameter solid model was established using the least square regression method and considering the influence of temperature and relative humidity. The three-parameter model was made up of a Kelvin model and a spring in series (Fig. 10). The creep expression of the model is calculated as follows,

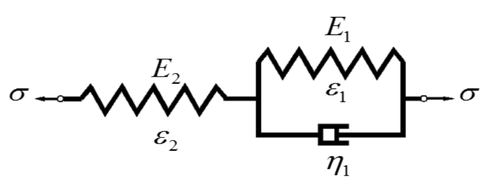


Fig. 10. Three- parameter solid model with creep for bamboo scrimber column

$$\varepsilon(t)=\frac{\sigma_0}{E_2}+\frac{\sigma_0}{E_1}\left(1-e^{\frac{-t}{\tau_1}}\right) \tag{1}$$

where σ_0 is a constant compressive stress, and $\tau_1 = \eta_1/E_1$, E_1, E_2, and η_1 are the elastic coefficients and viscosity coefficient incorporating environmental relative humidity and temperature.

To predict the creep behavior of this model, Eq. 1 was organized into the following forms,

$$\varepsilon = A + Be^{Ct} \tag{2}$$

where t is creep time (days), while A, B, and C are constants related to materials used as parameters for fitting the equations, where:

$$A = \frac{\sigma_0}{E_1} + \frac{\sigma_0}{E_2},\ B = -\frac{\sigma_0}{E_1},\ C = -\frac{E_1}{\eta_1} \tag{3}$$

Fridley *et al.* (1992) considered the change process of humidity and temperature when determining the elastic coefficient and viscosity coefficient in Burger model, and obtained a transformation equation group. In this paper, the Burger model transformation equations of Fridley *et al.* (1992) are used for reference. The humidity correlation coefficient w and the temperature coefficient correlation coefficient θ are introduced into the three parameter model,

$$\begin{aligned} E_1(w,\theta) &= E_{1s}\left(1 + D_1 w + D_2 w^2 + D_3\theta + D_4\theta^2\right) \\ E_2(w,\theta) &= E_{2s}\left(1 + D_5 w + D_6 w^2 + D_7\theta + D_8\theta^2\right) \\ \eta_1(w,\theta) &= \eta_{1s}\left(1 + D_9 w + D_{10} w^2 + D_{11}\theta + D_{12}\theta^2\right) \end{aligned} \tag{4}$$

where E_{1S}, E_{2S}, and η_{1s} are the elastic and viscous coefficients in the three parameter model, and they are also the elastic and viscous coefficients of the reconstituted bamboo column at the beginning of the test. D_1 through D_{12} are the model constants, w are the relative humidity correlation coefficients, θ are the temperature correlation coefficients, and E_1, E_2, and η_1 are the elastic coefficients and viscosity coefficients of the historical process considering the humidity and temperature.

Moisture content and temperature are known to affect the mechanical properties of wood. For the four-element model defined previously, the values of E_1, E_2, and η_1 must be adjusted for their hygrothermal state. To accomplish this, two non-dimensional factors are introduced as follows,

$$w = \frac{M - M_0}{M_0} \tag{5}$$

$$\theta = \frac{T - T_0}{T_0} \tag{6}$$

where M denotes humidity reading (%), M_0 represents reference humidity reading (%), T is temperature reading (°C), and T_0 denoted reference temperature reading (°C).

The initial creep ε_0 of bamboo scrimber column is given as,

$$\varepsilon_0 = \frac{P_i}{AE} \tag{7}$$

where ε_0 is initial elastic strain(mm), P_i is the determined creep load (KN), A is the section size of a specimen (mm), and E is the elastic modulus (GPa). As the size of the specimen, P_i and E have been known, substituting P (340 kN) and E (11810 MPa) into Eq. 7 yields the initial strain upon the specimen (Table 2).

Table 2. Initial Strain of Bamboo Scrimber Columns

Stress Ratio	Initial Strain ε_0
0.2	0.000584
0.4	0.001160

By bringing the initial strain value into Eq. 2, ORIGIN (a kind of scientific drawing and data analysis software) is used to obtain the creep fitting equation of bamboo scrimber (Table 3).

Table 3. Initial Strain of Bamboo Scrimber Columns Fitting Equation of Creep of Bamboo Scrimber Columns

Stress Ratio	Fitting Equation	Fitting Degree (R^2)
0.2	$\varepsilon_0 = \varepsilon_{0.2}\left(4.95-4.42e^{-0.03227t}\right)$	0.97213
0.4	$\varepsilon_0 = \varepsilon_{0.4}\left(4.86-4.17e^{-0.02943t}\right)$	0.98180

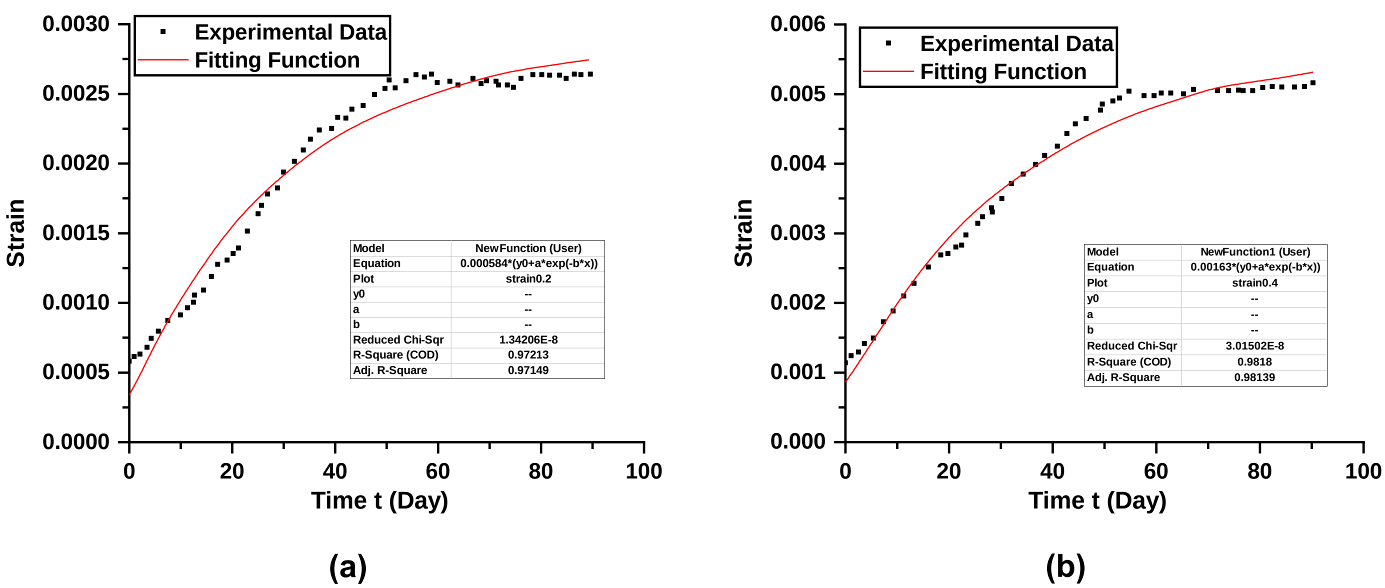


Fig. 11. Comparison of the three-parameter fitting equation with experimental values: (a) test with stress ratio = 0.2×; (b) test with stress ratio = 0.4×

The correspondence between the fitting equation and the values from the creep test experiment was generally good (Fig. 11). This good agreement with the test values means the equation adequately reflects the creep changes that occur in bamboo scrimber columns. The creep load of the specimen with a stress ratio of 0.2× was 135 kN, and that of 0.4× was 205 kN. The 100 kN to 200 kN is the common bearing capacity interval in building construction. Therefore, according to the creep curve and fitted equation, the constitutive creep formula of full-scale bamboo scrimber column is given as follows,

$$\begin{aligned} &\varepsilon = \varepsilon_0\left(A + Be^{-0.03085t}\right) \\ &A = -0.45n + 5.04 \\ &B = 1.25n - 4.67 \end{aligned} \tag{8}$$

where ε_0 is initial elastic strain, *A* and *B* are equation coefficients, *T* is time (days), and *n* is the stress ratio. This formula was derived from the test results based on an environment of 20 °C to 28 °C (temperature) and 60% to 85% (humidity). Further empirical tests are necessary to check the applicability of full-scale bamboo scrimber column in colder and drier areas.

CONCLUSIONS

From the above research, the following conclusions can be obtained.

1. The stress ratio of long-term load of bamboo scrimber columns should be less than 0.6.
2. From the creep curve of bamboo scrimber column, it can be seen that in the first stage of creep, the creep deformation increased with elapsed time. In the second stage, however, the creep deformation tended to stabilize and the lengthwise dimension reached a stable value; hence, the overall creep curve also conformed to the creep properties of general bamboo material. Under different load levels, the changes of lateral deflection of the two groups of specimens were similar. Humidity had a greater impact on the lateral deflection of the bamboo column, and the deflection value fluctuated. However, the lateral deflection of the whole bamboo scrimber column was very small and mainly involved elastic deformation.
3. The creep deformation of the specimens was basically stable at day 50 and onwards. When the temperature and humidity in the environment changes, the measured data will produce some fluctuation, but the creep value is stable in general. The change of creep under different temperature and humidity conditions indicates that bamboo scrimber is a kind of hygroscopic material that is easily influenced by its local environment.
4. Considering the influence of environmental humidity and temperature, the temperature coefficient and humidity coefficient were substituted into a three-parameter model, and the compression creep constitutive equation of recombined full-scale bamboo column was solved by fitting. When the temperature and humidity change, the process of creep strain and creep deflection are observed from macroscopic point of view. The research on the creep mechanism of recombined bamboo helps to promote the application of bamboo scrimber column in civil engineering.

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