

Article

Creep Performance and Life Prediction of Bamboo Scrimber under Long-Term Tension in Parallel-to-Grain

Caimei Liu ¹, Xizhi Wu ^{1,2,*} , Xiubo Liu ¹ and Xianjun Li ¹

¹ College of Materials Science and Engineering, Central South University of Forestry and Technology, Changsha 410082, China; liucaimei2005@126.com (C.L.); liuxiubosz@163.com (X.L.); lxjmu@163.com (X.L.)

² Guangzhou Tech-Long Packaging Machinery Co., Ltd., Guangzhou 510530, China

* Correspondence: wuxizhi2006@126.com

Abstract: Creep performance is a crucial factor that must be considered in structural design. This paper aims to investigate the creep failure mode, creep strain, creep compliance, and other creep properties of bamboo scrimber under long-term tension in parallel-to-grain. To establish a general creep life prediction method for the full stress level of the bamboo scrimber, a multi-branch Kelvin–Voigt model, a generalized Maxwell model, and a creep finite element simulation were employed. The results showed that the creep strain curve of bamboo scrimber included the unsteady creep stage and the stable creep stage, but not the accelerated creep stage. When the stress ratio was less than 0.3, the residual strength decreased gradually. Below 70% of the ultimate load capacity, the creep characteristics of the bamboo scrimber were linear viscoelastic, and the creep compliance was generally independent of the load level. The creep finite element model of bamboo scrimber could accurately calculate the creep deformation of specimens. Based on this creep finite element model and creep failure rules, a life prediction model for the full stress level of bamboo scrimber was established, which could accurately predict the creep life. This paper provides theoretical guidance for the creep design of bamboo scrimber in engineering structures.

Keywords: bamboo scrimber; finite element; creep; life prediction; linear viscoelasticity



Citation: Liu, C.; Wu, X.; Liu, X.; Li, X. Creep Performance and Life Prediction of Bamboo Scrimber under Long-Term Tension in Parallel-to-Grain. *Forests* **2023**, *14*, 1971. <https://doi.org/10.3390/f14101971>

Academic Editor: Anuj Kumar

Received: 5 September 2023

Revised: 17 September 2023

Accepted: 25 September 2023

Published: 28 September 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Compared with traditional wood, bamboo resources have a shorter cycle to become timber. They can be regenerated after cutting and possess excellent physical and mechanical properties. The utilization of bamboo resources can effectively alleviate the supply-demand contradiction of wood in engineering structures and promote the rapid development of bamboo structure buildings [1–3]. Bamboo scrimber is a novel type of bamboo-based composite material composed of bamboo bundle fibers. Bamboo materials are assembled according to the grain, glued, and pressed to form an ideal green high-strength structural material [4–8]. Among all types of bamboo engineering materials, bamboo scrimber exhibits excellent comprehensive performance and is particularly suitable as a load-bearing component of the structure. However, bamboo scrimber is a viscoelastic material, and its mechanical properties may change over time. The creep characterization of bamboo scrimber is an important index that affects its widespread application. Therefore, it is of great significance to deeply study the creep characterizations of bamboo scrimber for its application in the structure field.

Currently, numerous preliminary studies on the creep characteristics of bamboo materials have been conducted by scholars. In the study of raw bamboo creep, Gottron et al. explored the influence of different loading directions on the creep properties of green bamboo materials [9]. Kanzawa et al. discovered that the effect of bamboo density on initial deflection is greater than that of long-term creep [10]. TuDaowu et al. used the Burgers model to analyze the transverse compression creep behavior of mao bamboo under

different moisture content, temperature, and stress levels [11]. The results have indicated that the creep characteristics were influenced by its own structure and environmental factors, with various factors exhibiting interaction.

In terms of bamboo material creep research, LiNing carried out a long-term creep test of bamboo skidding beams [12]. To analyze this data, the Burgers model is employed for linear regression analysis, leading to the development of a creep model. Finite element software is utilized to analyze and predict the long-term deformation of engineering bamboo bridges. Dong Chunlei et al. analyzed the fast creep property and 90-day creep property of an I-beam made from bamboo wood composite according to American standards ASTM D5055-04 and ASTM D6815-02a [13]. Xiao Yan et al. investigated the axial tension compression creep properties of glued bamboo, fitting the creep constitutive equation using the Burgers model [14,15]. Zhang explored the effects of different loading conditions, moisture content, and thickness on three-point bending creep characteristics of bamboo scrimber boards [16].

On the research of bamboo scrimber, Yang investigated the creep resistance of bamboo fiber-reinforced recycled PLA composites (BFRPCs). They established the master curve of the short-term creep test of BFRPCs at different temperatures using the principle of time-temperature superposition [17]. Ma conducted creep tests on bamboo scrimber and bamboo laminated timber under different temperature and humidity conditions respectively [18,19]. They analyzed these two materials using the principle of time temperature equivalence and mechanical adsorption creep model, and discussed the influence of temperature and humidity changes on bending creep properties. Additionally, they established creep deflection models for bending of two kinds of boards by using the Burgers model. Chen Si studied the creep strain, creep strain growth rate, and creep compliance of bamboo scrimber in parallel-to-grain compression, and established creep strain models at different load levels using the Burgers model. Furthermore, they studied the change rule of Burgers model parameters with the stress level [20]. Wu Peizeng conducted tensile and compressive creep tests on bamboo scrimber under different stress levels in an indoor environment and used the Burgers model and Findley model to fit and analyze the long-term creep strain of bamboo scrimber under different stress levels [21].

In conclusion, researchers have extensively explored the creep behavior of bamboo materials and established empirical and mechanical models for specimen creep deformation based on experimental data. However, these models were only applicable to bamboo specimens under experimental stress level conditions and could not be extrapolated to the full stress level of bamboo. Therefore, this paper focused on the study of tensile bamboo scrimber, utilized the self-developed multi-functional creep testing equipment to carry out the long-term tension creep tests of bamboo scrimber in parallel-to-grain in an indoor environment, aiming to investigate the failure mode, creep strain, and creep compliance of the long-term creep behavior of bamboo scrimber. A novel method for predicting the creep life of bamboo scrimber is proposed, followed by the establishment of a creep constitutive model and life prediction model for the full stress level under longitudinal tensile load. This paper provides theoretical guidance for the creep design of bamboo scrimber in engineering structures.

2. Materials and Methods

2.1. Test Materials

The bamboo scrimber was produced by Yiyang Taohuajiang Bamboo Industry Co., Ltd, Yiyang, Hunan, China. It is an advanced bamboo material composed of bamboo bundle or fibrotic bamboo veneer, which are assembled along the grain and pressed by bonding. The raw material for the bamboo bundle was moso bamboo, which originated from Jiangxi Province, with a growth age of 3–5 years. To determine the mechanical properties of the bamboo scrimber, uniaxial tensile tests were conducted using ASTM D143-09 test standard method [22]. Five specimens with dimensions of 15 mm × 15 mm × 200 mm (standard section) were tested. The results of the mechanical properties measurements of bamboo scrimber are presented in Table 1. The average values of ultimate tensile strain, ultimate

tensile strength, and tensile modulus of elasticity were determined to be 0.0092, 118 MPa, and 12.71 GPa, respectively.

Table 1. Mechanical properties of bamboo scrimber.

Property	Mean	Standard Deviation Coefficient
Ultimate tensile strain	0.0092	0.00012
Ultimate tensile strength	118 MPa	16.8
Tensile modulus of elasticity	12.71 GPa	0.37

2.2. Test Equipments

This study employed a self-designed multi-function creep test equipment, dial indicator, and thermo-hygrometer. The multi-function creep test equipment is illustrated in Figure 1. The test loading was conducted using the lever principle, which involved supporting each loading beam with a middle pin, connecting one end to the tensile specimen, and placing a weight on the other end that amplifies the load by 2 times through a pulley system. The distance between the pulley center and the pin center remained fixed, while the distance between the center of the tensile specimen and the pin center could be adjusted. This allowed for a flexible modification of the lever load amplification factor by adjusting the position of the test piece center.

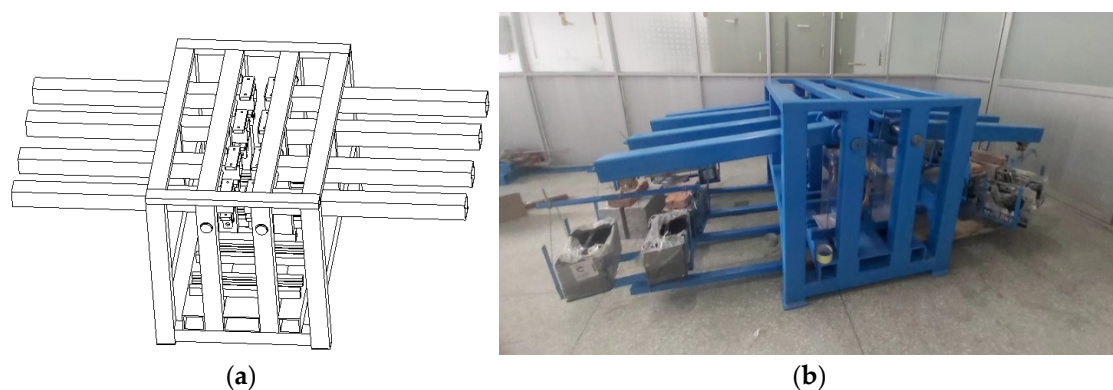


Figure 1. Multi-function creep test equipment: (a) model, (b) prototype.

2.3. Creep Test Methods

According to ASTM D143-94 (2000) Test Methods for Small Flawless Wood Specimens and GB/T 1927.14-2021 (2021) Test Methods for Physical and Mechanical Properties of Small Flawless Specimens of Wood, the tensile creep test specimen is shown in Figure 2. The specimen is dumbbell type; with the standard section size was 20 mm × 10 mm × 180 mm. Here, the dimension of 180 mm was in parallel-to-grain, and its density was 1.1 g/cm³. Its water content (mass fraction) was approximately 9%.

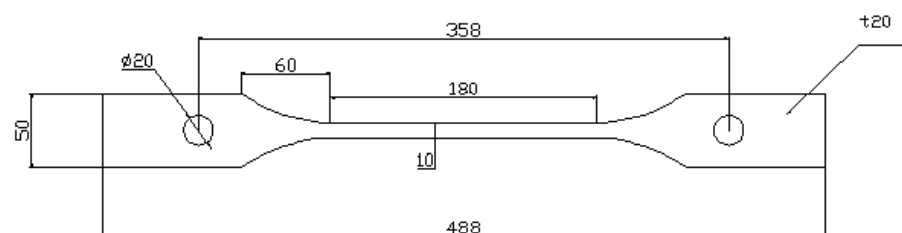


Figure 2. Tensile creep specimen.

The details of specimens are presented in Table 2. The stress levels were determined to be 0.3, 0.4, 0.5, and 0.7 times the ultimate load, recorded as L1, L2, L3, and L4, respectively.

Each group consisted of two specimens, which were replicated for testing. According to the tensile strength of the bamboo scrimber in parallel-to-grain, which was 118 MPa, the theoretical stress of four test pieces can be calculated.

Table 2. Details of specimens.

No.	Stress Ratio	Theoretical Stress of Specimen (MPa)	Load Weight (kg)	Specimen Size (Thickness × Width, mm)	Load Stress of Specimen (MPa)	Load Stress/Theoretical Stress
L1-1	0.3	35.4	25	19.6 × 10.2	35.1	99.1%
L1-2				19.6 × 10.1	35.4	100%
L2-1	0.4	47.2	35	19.6 × 10.1	45.9	97.3%
L2-2				19.6 × 10.1	45.9	97.3%
L3-1	0.5	59	51/47	19.6 × 9.6	58.8	99.6%
L3-2				19.6 × 9.9	57.7	96.7%
L4-1	0.7	82.6	70.6	19.6 × 10.0	83.7	101.3%
L4-2				19.6 × 10.1	83.0	100.3%

The test was conducted in an indoor setting. During the experiment, the room windows were kept closed and the specimen were shielded from direct sunlight exposure. The long-term tensile creep test was initiated on 25 July 2022, with a test period of 80 days. Prior to specimen loading, readings from each meter were documented every five hours between 9:00 a.m. and 7:00 p.m. for three consecutive days, followed by daily recordings for the remainder of the month. Finally, readings were taken from each meter every three days until the conclusion of the creep test.

2.4. Creep Life Prediction Method

Regarding the prediction of creep life in bamboo wood, several scholars have established empirical and mechanical models based on experimental data. Currently, there is no unified creep constitutive model for the tensile load condition of the bamboo scrimber at full stress level. Moreover, there is a lack of research on the prediction of creep life for the tensile structure of the bamboo scrimber. Therefore, this paper proposes a novel method for predicting the creep life at full stress level in bamboo scrimber. Firstly, the theoretical creep compliance model of the bamboo scrimber in parallel-to-grain was obtained by fitting the multi-branch Kelvin–Voigt phenomenological mechanical model based on the creep compliance data measured during experiments. Secondly, since common finite element software did not support the theoretical creep compliance model, but only supported the Prony series shear relaxation model, the Laplace transform, and inverse Laplace transform of the creep compliance theoretical model were used to obtain the shear relaxation modulus in the time domain. A Prony series shear relaxation model was then obtained by fitting the shear relaxation modulus with a multi-branch generalized Maxwell model. Thirdly, using Prony series shear relaxation model as the creep constitutive model of bamboo scrimber, the finite element model of the creep of bamboo scrimber tensile specimens was established to predict the creep deformation of bamboo scrimber under arbitrary stress levels, which resolved the problem of the creep test during the service life of bamboo scrimber. Lastly, the creep life of the bamboo scrimber in parallel-to-grain at full tensile stress level was predicted according to the creep failure rule and the prediction of creep deformation. The detailed process was as follows.

Step 1: Establishing the creep compliance theoretical model. The multi-branch Kelvin–Voigt (KV) phenomenological mechanical model is shown in Figure 3. The KV model was utilized to fit the creep compliance measurements obtained from the experiment, resulting in an analytical expression for the creep compliance $J(t)$:

$$J(t) = \frac{1}{E_0} + \sum_{i=1}^n \frac{1}{E_i} (1 - e^{-t/\gamma_i}) \quad (1)$$

where E_0 represents the initial Young's modulus, and E_i and γ_i are two fitting parameters that correspond to Young's modulus and relaxation time in the i th Kelvin–Voigt (KV) model branch, respectively. γ_i can be calculated as η_i/E_i , where η_i is the viscosity in the i th KV model branch.

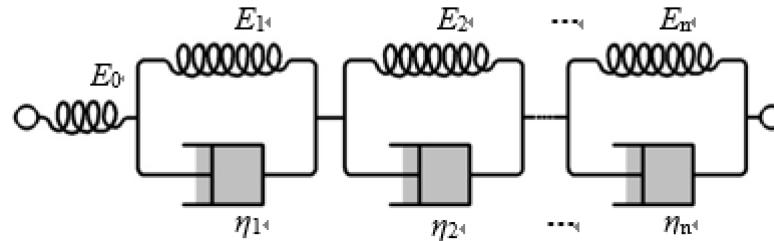


Figure 3. Multi branch Kelvin–Voigt phenomenological mechanical model.

Step 2: Establishing the shear relaxation model. By Laplace transformation of Equation (1) and the creep compliance in the complex number domain can be obtained as follows:

$$\bar{J}(s) = \frac{1}{sE_0} + \sum_{i=1}^n \frac{1}{s(1 + s\gamma_i)E_i} \quad (2)$$

Here, s represents a complex variable.

Also, the stress-strain relationship of bamboo scrimber tension can be simplified to a one-dimensional convolution equation:

$$\varepsilon(t) = \int_0^t J(t - \xi) \frac{d\sigma(\xi)}{d\xi} d\xi + J(t)\sigma(0) \quad (3)$$

$$\sigma(t) = \int_0^t E(t - \xi) \frac{d\varepsilon(\xi)}{d\xi} d\xi + E(t)\varepsilon(0) \quad (4)$$

Equations (3) and (4) represent creep and stress relaxation, respectively, while $J(t)$ and $E(t)$ represent uniaxial creep compliance and uniaxial relaxation modulus of bamboo scrimber, respectively.

The uniaxial elastic relaxation modulus in the complex number domain can be deduced by applying Laplace transformation to Equations (3) and (4), which are then combined with Equation (2) as below:

$$\bar{E}(s) = \frac{1}{s^2 \bar{J}(s)} = \left[\frac{s}{E_0} + \sum_{i=1}^n \frac{s}{(1 + s\gamma_i)E_i} \right]^{-1} \quad (5)$$

Due to the significantly lower volume relaxation rate of bamboo scrimber compared to its shear relaxation rate, the volume relaxation behavior of glass is usually neglected in engineering. The bulk modulus of bamboo scrimber can be expressed as $K(t) = K_0 = E_0/[3(1 - 2\nu)]$ [23]. By combining this expression with Equation (5), the shear relaxation modulus of bamboo scrimber in the complex number domain can be deduced as:

$$\bar{G}(s) = \frac{3\bar{K}(s)\bar{E}(s)}{9\bar{K}(s) - \bar{E}(s)} = \frac{1}{3s^2 \bar{J} - s(1 - 2\nu)/E_0} \quad (6)$$

The shear relaxation modulus $G(t)$ in the time domain can be obtained by the inverse Laplace transform of Equation (6). Since the shear relaxation modulus is usually represented by Prony series in commercial finite element software such as Marc, Abaqus, Ansys, Comsol, etc., this

paper uses the multi-branch generalized Maxwell model (as shown in Figure 4) to fit the shear relaxation modulus, and obtains it in the form of a Prony series as follows:

$$G(t) = G_0 \left(1 - \sum_{i=1}^n G_i \left(1 - e^{-t/\tau_i} \right) \right) \quad (7)$$

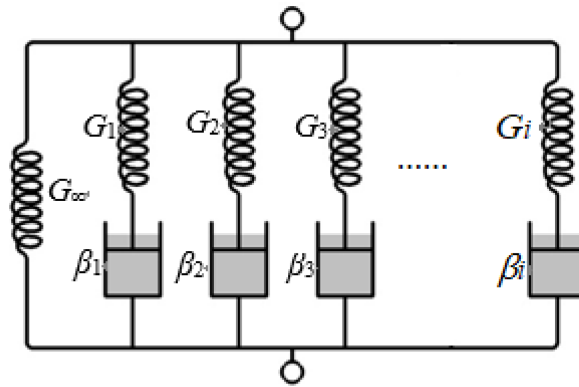


Figure 4. Multi branch generalized Maxwell model.

Here, G_0 represents the initial shear modulus of bamboo scrimber, and G_i and τ_i denotes the respective shear modulus and shear relaxation time of the i th Maxwell element. τ_i can be calculated as β_i/G_i , where β_i represents the shear viscosity of the i th Maxwell unit.

Step 3: Establishing the creep finite element model. Shear relaxation modulus Equation (7) is employed as the creep constitutive model of bamboo scrimber. A creep finite element model of the bamboo scrimber tensile specimen is developed, as shown in Figure 5. By utilizing the creep finite element model, the creep strain of the specimen at any given time can be calculated.

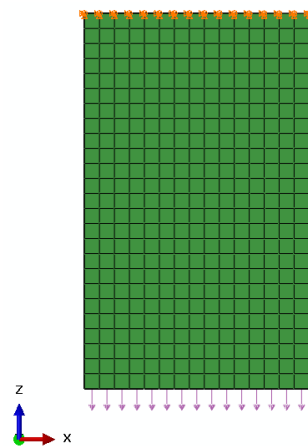


Figure 5. The finite element model of tensile creep of bamboo scrimber in parallel-to-grain.

Step4: Predicting creep life. The creep life is determined by the creep failure law, which takes into account two key factors. Firstly, Failure Criterion 1 is the minimum total failure deformation caused by the creep experiment of bamboo scrimber under tensile stress along the grain. Secondly, Failure Criterion 2 is based on the American Society for Testing and Materials (ASTM) D6815-02a guidelines for the creep of wood components, where the ratio of creep deformation to initial deformation should not exceed 1.0.

3. Results

3.1. Failure Mode

The failure mode of the specimens is illustrated in Figure 6. The fracture positions were uniformly distributed across the standard section of the specimens. The fracture shapes exhibited were either uniform or oblique, which was similar to the static tensile failure mode of bamboo scrimber reported by Wang et al. [24,25]. During the experiment, when the midline of the specimen basically coincided with the tension action line, the force applied to the standard section of the specimen remained relatively consistent. Due to the edge effect, the edges of the specimen were typically the first to break, followed by complete disintegration of the specimen. Consequently, the failure form exhibited a uniform fracture pattern. When the center line of the specimen deviated from the tensile action line, the edge stress near the tensile action line was high, which was likely to be destroyed first. Then, the specimen would undergo eccentric tension and fail in a manner of oblique fracture. Through video monitoring of the creep experiment, it was observed that the deformation of the specimen gradually changed slowly on the day before the fracture, reaching a maximum change of 0.005 mm in the last 10 s. Subsequently, the specimen failed instantaneously in the last second. Prior to the fracture, there were no visible cracks or other signs of damage, indicating that the creep failure mode of the bamboo scrimber under tensile load was an instantaneous failure.

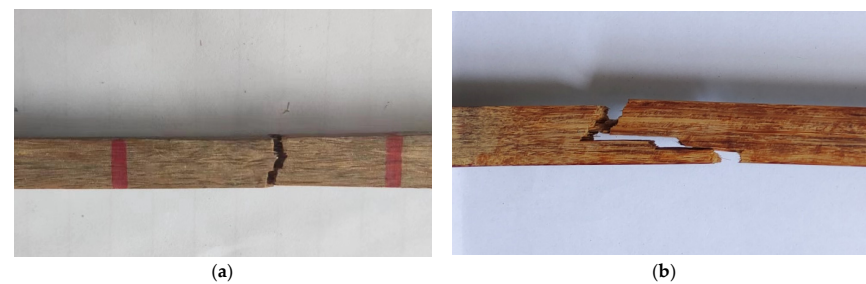


Figure 6. Failure mode of the specimen: (a) uniform fracture, (b) oblique fracture.

3.2. Creep Strain

Creep refers to the deformation over time that occurs in an object under constant stress. The typical creep curve, as proposed by the physicist Andrade, is illustrated in Figure 7. The static strain, denoted by ε_0 , can be divided into three stages: the unstable creep stage (AB stage), the stable creep stage (BC stage), and the accelerated creep stage (CD stage). During the unstable creep stage, the creep primarily arises due to the unstable flow of material with a gradually decreasing creep rate. Consequently, the material hardens. In the stable creep stage, the creep is mainly caused by the viscous flow of the material with a remaining approximately constant creep rate. The creep curve is approximately linear, and the duration of the stable creep time is typically longer, which constitutes the main stage of the creep phenomenon. In the accelerated creep stage, the creep rate increases rapidly until the creep failure.

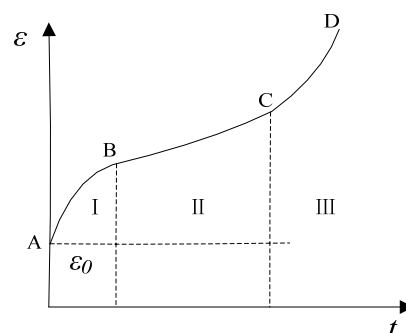


Figure 7. Typical creep curves.

The graph in Figure 8 illustrates the creep strain test results for bamboo scrimber specimens. The test strain is defined as $\varepsilon = \Delta L/L$, where ΔL is the deformation measured by a dial gauge, and L is the measuring distance of the dial gauge relative to the specimen. It could be observed that: (1) The creep strain trends of specimens with different stress levels were similar, and the total creep strain increased with the increase in stress level. However, the creep strain curves of specimens with the same stress level were not exactly the same. This may be attributed to the differences in raw material properties, bamboo bundle paving, and carbonization process among other factors. (2) All specimens exhibited an unstable creep stage followed by a stable creep stage, with no accelerated creep stage. This aligned with the creep phenomenon observed through video monitoring. The primary reason for this behavior is that bamboo scrimber does not experience significant cross-sectional area reduction or micro-cracks when subjected to long-term tensile loads. As a result, there is no acceleration in the creep deformation stage, which is related to its static tension in parallel-to-grain with linear elastic deformation and no plastic deformation. The unstable creep stage occurred from day 0 to day 5 when the creep strain changed greatly and the strain rate decreased continuously. The stable creep stage spanned from day 5 to day 80 when the creep strain changed slowly and experienced certain fluctuations. The main fluctuation periods were identified as days 34–41 and 74–76, and the causes of these fluctuations would be discussed in detail later. (3) Two specimens, L4-1 and L4-2, were damaged after 20 days and 43 days, respectively. The strain at the time of failure was 7.148×10^{-3} and 7.065×10^{-3} , respectively. The other specimens remained intact.

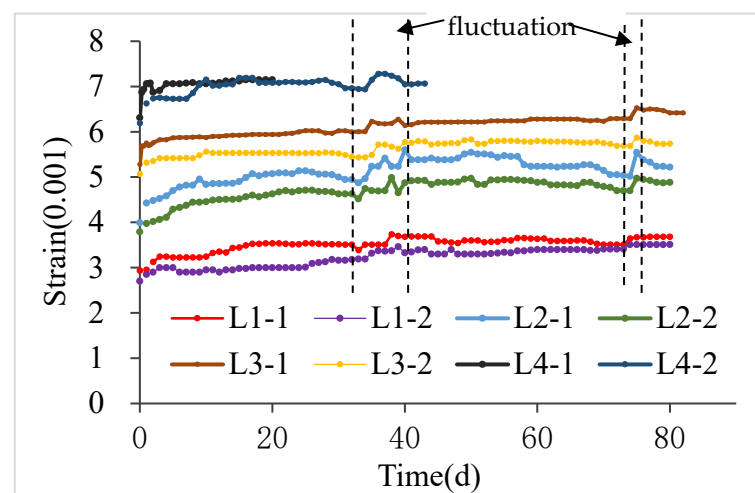


Figure 8. Creep strain test curve of bamboo scrimber specimens.

Figure 9 presents a comparison between the creep strain of specimen L2-1 and the ambient temperature and humidity. During the two main fluctuation periods of creep strain, the creep strain of specimen L2-1 increased by 0.727 and 0.364, respectively. Simultaneously, the ambient temperature decreased by 13.2 °C and 7.5 °C respectively, and the ambient humidity increased by 42% and 23%, respectively. This observation was consistent with the findings of Xu et al. who reported that the creep strain of bamboo increased with the increase in temperature and humidity, and decreased with the decrease in temperature and humidity [26,27]. In these two main fluctuation periods, the decrease in ambient temperature reduced the creep strain of the specimen, and the increase in ambient humidity increased the creep strain of the specimen. The combined effect of ambient temperature and humidity increased the creep strain of the specimen. Therefore, it can be concluded that ambient humidity is the main factor affecting the fluctuation in creep strain in this case.

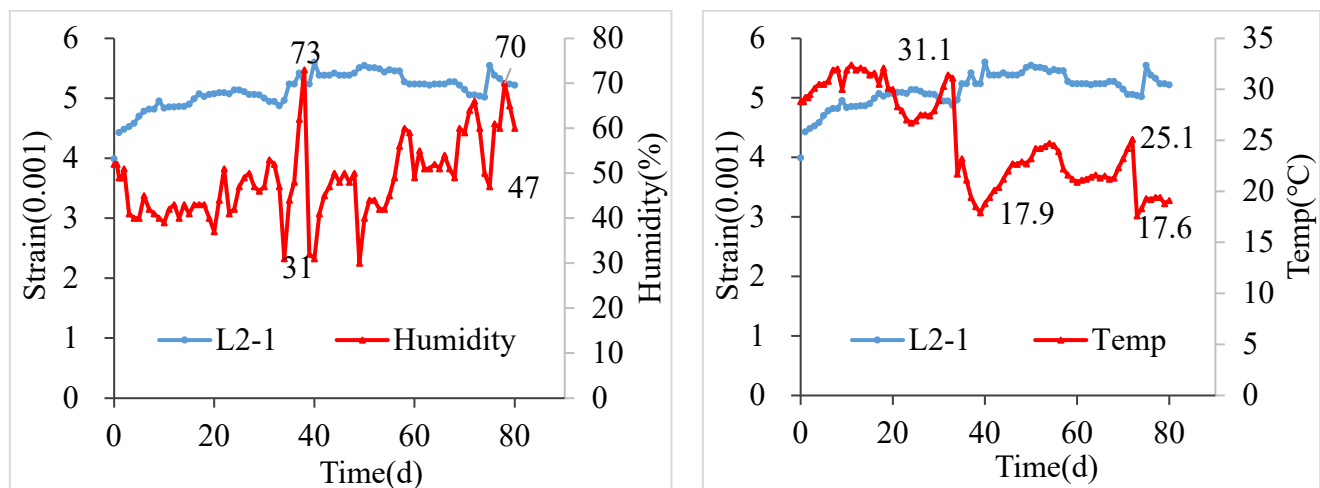


Figure 9. Comparison between the creep strain of specimen L2-1 and the ambient temperature and humidity.

Table 3 shows the creep test results of the specimen. ε_0 is the static strain, ε_1 is the total strain at the end of creep, ε_c is the total creep strain, $\varepsilon_c = \varepsilon_1 - \varepsilon_0$, and n is the creep coefficient, $n = \varepsilon_c / \varepsilon_0$, which represents the ratio of total creep strain to static strain. ε_{0a} is the average static strain, ε_{1a} is the average total strain at the end of creep, ε_{ca} is the average value of ε_c , and n_a is the average creep coefficient. The average static strains of these four groups of specimens were 2.818×10^{-3} , 3.891×10^{-3} , 5.177×10^{-3} , and 6.253×10^{-3} , respectively. This indicates that the static deformation of the specimen is proportional to the load applied to it. This was consistent with the linear section of the tensile deformation of the material at all selected load levels. The average total strains of the four groups of specimens were 3.596×10^{-3} , 4.964×10^{-3} , 5.050×10^{-3} , and 7.106×10^{-3} , respectively. The total strain of the specimens with load levels of 30%, 40%, and 50% is less than that of the specimens with a load level of 70%, indicating that the deformation of these specimens has not yet reached the creep failure state. Currently, there are no relevant regulations on the creep performance of bamboo components. Therefore, based on ASTM D6815-02a, which specifies the creep of wood components in the United States, the ratio of creep deformation to initial deformation of components should not be greater than 1.0. The minimum creep coefficient of all specimens was 0.135, while the maximum was 0.307, which meets the requirements of ASTM D6815-02a in the United States.

Table 3. Creep test results of specimens.

Specimen	ε_0 (10^{-3})	ε_{0a} (10^{-3})	t_c (d)	ε_1 (10^{-3})	ε_{1a} (10^{-3})	ε_c (10^{-3})	ε_{ca} (10^{-3})	n	n_a
L1-1	2.936	2.818	80	3.682	3.596	0.745	0.778	0.254	0.276
L1-2	2.700		80	3.510		0.810		0.300	
L2-1	3.991	3.891	80	5.218	4.964	1.227	1.159	0.307	0.298
L2-2	3.791		80	4.882		1.091		0.288	
L3-1	5.281	5.177	80	6.419	5.050	1.137	0.903	0.215	0.174
L3-2	5.073		80	5.742		0.669		0.132	
L4-1	6.312	6.253	20	7.148	7.106	0.873	0.855	0.138	0.137
L4-2	6.193		43	7.065		0.836		0.135	

3.3. Creep Compliance

Figure 10 shows the average creep compliance and average creep strain curve. The data reveal that the average creep strain of the specimen increases with an increase in the load level. The creep compliance, which represents the creep strain of the material under unit stress, is calculated as $J = \varepsilon / \sigma_0$. Prior to the failure of specimen L4, the average creep compliance curves of all four groups of specimens are very close, indicating that the creep

compliance is essentially independent of the load level. Tweedie studied that for ideal linear viscoelastic behavior, the creep compliance of the material is independent of the load level [28]. Therefore, at a maximum load level of 70%, bamboo scrimber exhibited linear viscoelasticity in tension parallel-to-grain structure.

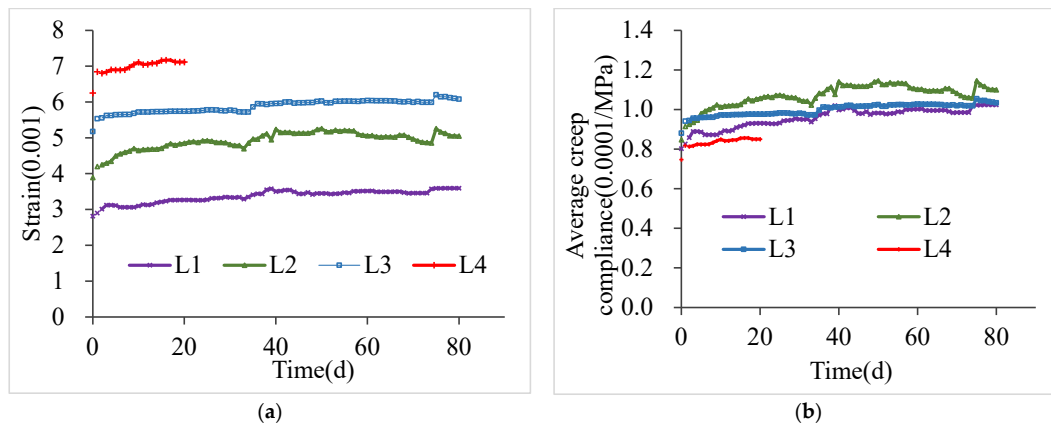


Figure 10. Average creep compliance and average creep strain curve: (a) average creep strain, (b) average creep compliance.

Since the tensile creep compliance of bamboo scrimber is independent of the load level, the test average creep compliance of four groups of specimens was calculated from Figure 10. The test average creep compliance was fitted by a 3-branch Kelvin–Voigt phenomenological mechanical model. The initial Young’s modulus E_0 was 12,700 MPa. The creep compliance fitting model is as follows:

$$J(t) = \frac{1}{12700} + \frac{1}{1.191e^5} (1 - e^{-t/0.3163}) + \frac{1}{2.338e^5} (1 - e^{-t/1605}) + \frac{1}{5.156e^4} (1 - e^{-t/26.63}) \quad (8)$$

The 4-branch Maxwell model (Maxwell 4) was utilized to fit the tensile shear relaxation modulus of bamboo scrimber. The initial shear modulus G_0 was determined to be 4810 MPa. The fitting process involved the following shear relaxation model:

$$G(t) = 4810 \left(1 - 0.1085(1 - e^{-t/0.2822}) - 0.1778(1 - e^{-t/21.31}) - 0.02991(1 - e^{-t/1538}) \right) \quad (9)$$

The fitting curve of the KV–3 model and the test average creep compliance of bamboo scrimber are presented in Figure 11. The fitting curve of the KV–3 model exhibited a good agreement with the test curve, as evidenced by the fitting coefficient R–square of 0.92. The test curve is significantly affected by environmental fluctuations, whereas the fitting curve remains relatively smooth. It can be observed from the fitting curve that the creep compliance increase rate of bamboo scrimber exhibited a relatively large fluctuation during the unstable creep stage. However, it tended to stabilize in the stable creep stage.

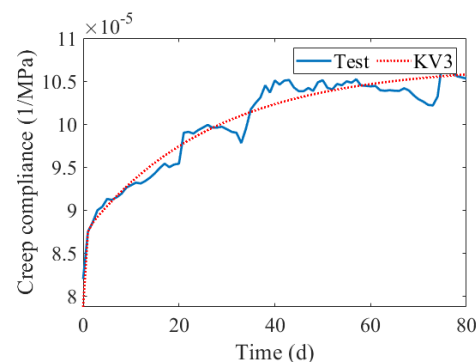


Figure 11. KV–3 model fitting curve and test average creep compliance of bamboo scrimber.

3.4. Residual Strength

Figure 12 illustrates the residual strength of the specimen. The residual strength is obtained by performing short-term tensile tests on the specimen after creep testing, and a stress ratio of 0 represents the specimen under short-term tensile testing. From the figure, it can be observed that the residual strength of all creep specimens is smaller than that of short-term tensile specimens. When the stress ratio was less than 0.3, the residual strength decreased slowly, and as the stress ratio increased, the residual strength decreased faster. At a stress ratio of 0.5, the average residual strength was 111.2 MPa, which was 30.2% lower than the short-term tensile strength.

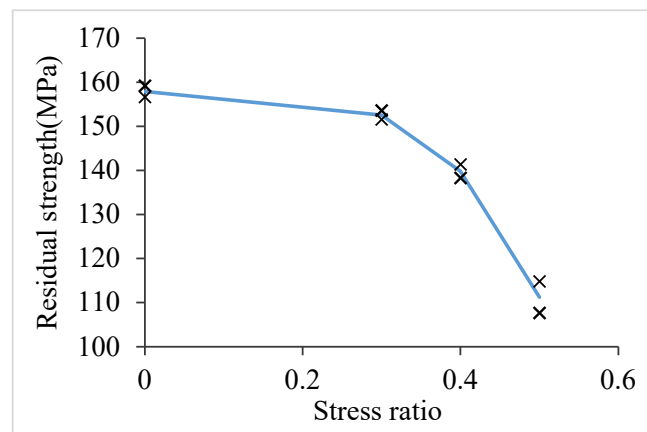


Figure 12. The residual strength of the specimen.

3.5. Creep Life Prediction

Equation (9) of Maxwell 4 model is utilized as the creep constitutive model of bamboo scrimber. The numerical simulation of a tensile creep specimen, L3, as shown in Figure 2 has been conducted. In Figure 13, the comparison between simulation and test creep strains of specimen L3 is presented. It can be observed that the simulation model remained unaffected by environmental fluctuations and exhibited a smoother creep strain curve compared to the test creep strain curve. During the initial stages of creep, the test creep strain increased rapidly, while the simulation creep strain increased at a relatively slower pace. Initially, there was a relatively large error between simulation creep and test creep at the beginning, but it gradually decreases over time. In summary, the simulated creep strain of the specimen was in excellent agreement with the experimental creep strain, demonstrating that the simulation model can accurately simulate the creep deformation of the specimen.

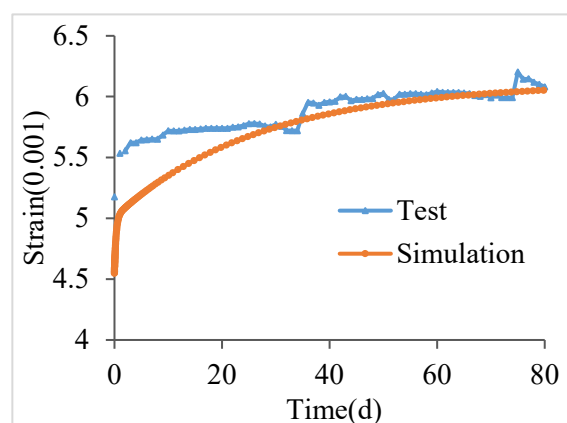


Figure 13. Comparison of simulation and test creep strain of specimen L3.

Based on GB 50068-2001 Unified Standard for Reliability Design of Building Structures, the design reference period is set at 50 years (18,263 days) [29]. The creep deformation of a bamboo scrimber tensile specimen was calculated using a finite element model as shown in Figure 14. The creep strain curves at all load levels exhibited similar characteristics. The creep strain growth rate was fast in the early stage but slowed down in the later stage. With an increase in load level, the creep strain also increased. In Figure 14c, ε_0 represents the static strain, ε_{5d} indicates the total creep strain at 5 days, ε_{80d} signifies the total creep strain at 80 days, and ε_{50y} depicts the total creep strain at 50 years. The creep strain histogram at all load levels was consistent. The ratio of creep strain at 80 days to static strain at all load levels was 34.4%, 33.6%, 34.8%, 33.8%, and 34.9%, respectively, which were similar. The ratio of creep strain in the first 5 days to 80 days to a 50-year design reference period was 37.9% and 84.5%, respectively, indicating that the creep strain during the early period accounts for the majority of the total design reference period.

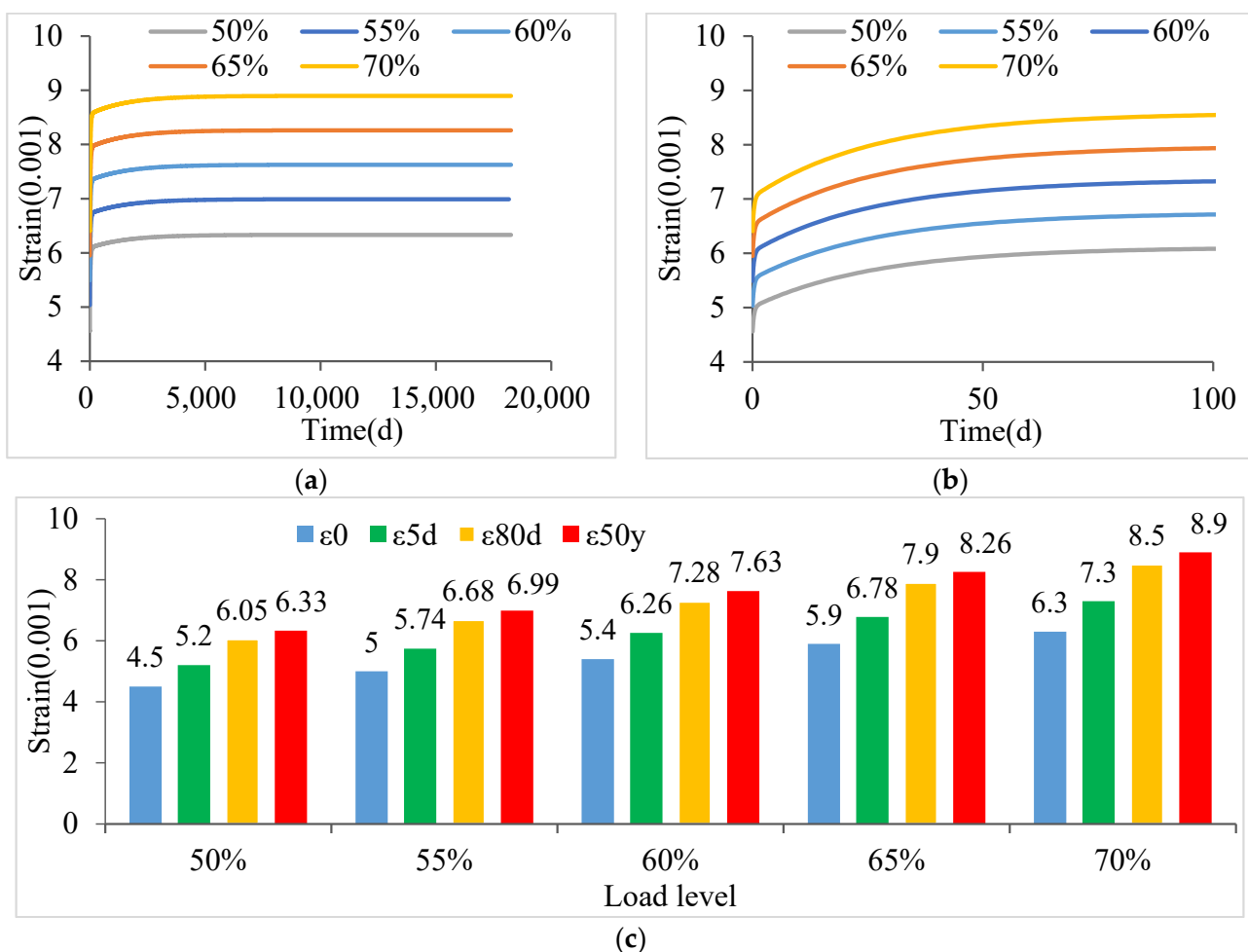


Figure 14. Simulated creep strain of bamboo scrimber tensile specimen: (a) global creep strain curve, (b) local creep strain curve, (c) histogram of creep strain at different time.

Based on the creep failure criteria, the creep failure strain of bamboo scrimber was determined as follows:

Firstly, according to Criterion 1 and Figure 8, the total strain of bamboo scrimber under a load level of 70% was taken as the creep failure strain at the low load level of the specimen. That is, when the total creep deformation reaches the total deformation under a load level of 70%, the specimen would fail to exhibit creep failure. Considering safety concerns, the minimum total deformation under a load level of 70% in Figure 8 was selected for life estimation. Specifically, the strain value 7.065×10^{-3} of L4-2 was chosen.

Secondly, in accordance with Criterion 2 and Figure 14, the ratio of creep strain in the 50-year period to initial strain was less than 1, which meets the requirement of Criterion 2. Therefore, the creep failure strain of bamboo scrimber was determined to be 7.065×10^{-3} .

Based on the creep failure strain value, the predicted creep lives of 50%, 55%, 60%, 65%, and 70% load levels were 50 years, 50 years, 40.8 days, 11.8 days, and 1 day, respectively. With these predicted creep lives as the original data, a prediction model of bamboo scrimber creep life under any load level was established. The prediction model is presented in Equation (10), and the fitting coefficient R-square was 1, which indicates that the model could accurately predict the tensile creep life of bamboo scrimber in parallel-to-grain conditions.

$$\begin{cases} T = 1.132e^{-14}L^{-70.13} & L \geq 0.55 \\ T = 18263 & L < 0.55 \end{cases} \quad (10)$$

As illustrated in Figure 15, the creep life prediction curve is plotted using Equation (10). The figure indicated that the creep life satisfied the design requirements of 50 years when the load level was below 55%; however, when the load level exceeded 60%, the creep life reduced to almost 0 within a few days. In contrast, when the load level fluctuated between 55% and 60%, the creep life varied significantly at different load levels. Specifically, the creep life increased approximately 450 times from the 60% load level to the 55% load level.

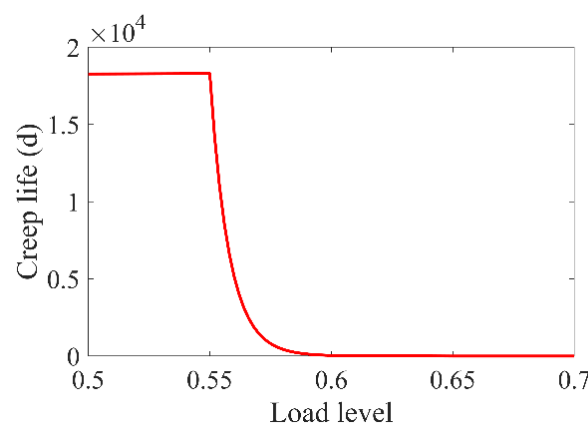


Figure 15. Creep Life Prediction Curve.

4. Discussion

In this paper, the creep failure mode, creep strain, creep compliance, and other creep properties of the bamboo scrimber under long-term tension in parallel-to-grain were investigated. A general creep life prediction method for the full stress level of the bamboo scrimber was proposed to provide a theoretical reference for the creep design of the bamboo scrimber in the field of engineering structures.

The study revealed that environmental humidity was the primary factor influencing the fluctuation of creep strain, which was primarily associated with mechano-sorptive creep in biomass materials. Mechano-sorptive creep refers to the gradual increase in creep strain of biomass materials as they absorb moisture. As the environmental humidity changed, so did the moisture content of bamboo scrimber, leading to a fluctuation in creep strain under the influence of mechano-sorptive creep. Zhang also demonstrated that the creep compliance of bamboo scrimber increased gradually with an increase in moisture content [16]. This could be attributed to the entry of water molecules into the bamboo cell wall, which resulted in a difference in internal stress between adjacent cell walls, weakening the glue adhesion, and thus reducing the stiffness of bamboo.

The results revealed that when the stress ratio was less than 0.3, the residual strength declined at a moderate pace. However, with an increase in the stress ratio, the rate of residual strength reduction accelerated. At a stress ratio of 0.5, the average residual strength was 111.2 MPa, which represented a decrease of 30.2% compared to the short-term tensile

strength. Luo has previously pointed out that when the stress ratio was less than 0.367, the tensile bamboo scrimber demonstrated a strength reduction coefficient close to 1.0 which is defined as the ratio of residual strength to short-term strength [30]. Furthermore, when the stress ratio was 0.45, the strength reduction coefficient was 0.75, consistent with the results presented in this paper. If we define the stress ratio threshold for tensile bamboo scrimber as 0.30, it falls below that of structural sawn timber (0.5) [31].

The bamboo scrimber was subjected to tensile and compressive creep tests under various stress levels in an indoor environment [21]. The long-term creep strain of the bamboo scrimber under different stress levels was fitted using the Burgers model and Findley model, resulting in an overall correlation coefficient R^2 of above 0.92. However, each stress level corresponded to a specific fitting model, with varying fitting coefficients, which made it difficult to generalize to all stress levels. To address this limitation, the paper proposed the use of a generalized Maxwell model to fit a unified shear relaxation model for the full stress range. We established a creep finite element model for the tensile specimen of the bamboo scrimber by taking the shear relaxation model as the constitutive model for creep. This approach allowed for the prediction of creep deformation at full stress levels of the bamboo scrimber, with a fitting correlation coefficient of 0.92. The main advantage of this method is its high fitting precision, uniform fitting model, and wide extension range. In summary, the paper presented an innovative approach to analyzing the creep behavior of bamboo scrimber under different stress levels, utilizing a unified shear relaxation model to improve the accuracy and applicability of future studies in this field.

5. Conclusions

As a viscoelastic material, the long-term creep property of bamboo scrimber is a critical factor in ensuring its safe usage. In this paper, we conducted a long-term tensile creep test of bamboo scrimber in parallel-to-grain in an indoor environment. The creep failure mode, creep strain, and creep compliance of bamboo scrimber were studied. A unified creep life prediction method at the full stress level was proposed, and the creep life prediction model of the bamboo scrimber in parallel-to-grain tension was established. In short, the following contributions were achieved in this paper.

The creep strain curve of bamboo scrimber included an unstable creep stage and a stable creep stage, but there was no accelerated creep stage. The specimen broke instantaneously in the last second, and the fracture shape was presented as a flush fracture and an oblique fracture.

Under 70% of the ultimate load level, the creep characteristics of the bamboo scrimber in parallel-to-grain tension were linear viscoelastic. The creep compliance was essentially independent of the load.

Based on the creep compliance test data, a theoretical model of bamboo scrimber creep compliance under parallel-to-grain tension was obtained by fitting the 3-branch Kelvin–Voigt model. Furthermore, a shear relaxation model in the form of Prony series was derived using the generalized Maxwell 4 model. The generalized Maxwell 4 model was then employed as the constitutive model for the creep of the bamboo scrimber, leading to the establishment of a finite element model for the tensile creep of the bamboo scrimber specimen. This model accurately calculates the creep deformation at full stress level for the bamboo scrimber specimen.

Based on the creep failure law and the creep deformation data calculated by the finite element model, a creep life prediction model for the tensile bamboo scrimber in the parallel-to-grain was developed. This model can accurately predict the creep life of bamboo scrimber at the full tensile stress level in parallel-to-grain. It can provide a theoretical reference for the creep design of bamboo scrimber in engineering structures.

Author Contributions: Methodology, C.L., X.W., X.L. (Xiubo Liu) and X.L. (Xianjun Li); software, X.W.; validation, X.L. (Xianjun Li); formal analysis, C.L. and X.W.; investigation, X.W. and X.L. (Xianjun Li); data curation, X.L. (Xiubo Liu); writing—original draft, C.L.; writing—review & editing, C.L., X.W., X.L. (Xiubo Liu) and X.L. (Xianjun Li); supervision, X.L. (Xiubo Liu) and X.L. (Xianjun Li); funding acquisition, X.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by China Postdoctoral Science Foundation, grant number 2021M690768 and Natural Science Foundation of Hunan Province, grant number 2020JJ5986.

Institutional Review Board Statement: The paper did not involve human or animal research, and did not require ethical review and approval.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author, upon reasonable request.

Acknowledgments: The authors would like to thank China Postdoctoral Science Foundation and Natural Science Foundation of Hunan Province for supporting this work.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Yu, W. Current situation and opportunities for the development of bamboo scrimber industry in China. *World Bamboo Ratt.* **2019**, *17*, 1–4. [\[CrossRef\]](#)
2. Fang, C.-H.; Jiang, Z.-H.; Sun, Z.-J.; Liu, H.-R.; Zhang, X.-B.; Zhang, R.; Fei, B.-H. An overview on bamboo culm flattening. *Constr. Build. Mater.* **2018**, *171*, 65–74. [\[CrossRef\]](#)
3. Li, H.; Wu, G.; Zhang, Q.; Deeks, A.J.; Su, J. Ultimate bending capacity evaluation of laminated bamboo lumber beams. *Constr. Build. Mater.* **2018**, *160*, 365–375. [\[CrossRef\]](#)
4. Liu, C.; Wu, X.; Li, X.; Wu, Y. Investigation into the effects of various processing treatments on the flexural performance of carbon fiber reinforced polymer-bamboo scrimber composites. *Aust. J. Struct. Eng.* **2022**, *23*, 370–386. [\[CrossRef\]](#)
5. Li, X.; Mou, Q.; Ji, S. Effect of elevated temperature on physical and mechanical properties of engineered bamboo composites. *Ind. Crops Prod.* **2022**, *189*, 115847. [\[CrossRef\]](#)
6. Huang, Z.; Chen, Z.; Huang, D.; Zhou, A. The ultimate load-carrying capacity and deformation of laminated bamboo hollow decks: Experimental investigation and inelastic analysis. *Constr. Build. Mater.* **2016**, *117*, 190–197. [\[CrossRef\]](#)
7. Wu, X.; Huang, X.; Li, X.; Wu, Y. Flexural performance of CFRP-bamboo scrimber composite beams. *J. Renew. Mater.* **2019**, *7*, 1295–1307. [\[CrossRef\]](#)
8. Raftery, G.; Kelly, F. Basalt FRP rods for reinforcement and repair of timber. *Compos. Part B* **2015**, *70*, 9–19. [\[CrossRef\]](#)
9. Gottron, J.; Harries, K.A.; Xu, Q. Creep behavior of bamboo. *Constr. Build. Mater.* **2014**, *66*, 79–88. [\[CrossRef\]](#)
10. Kanzawa, E.; Aoyagi, S.; Nakano, T. Vascular bundle shape in cross-section and relaxation properties of Moso bamboo (*Phyllostachys pubescens*). *Mater. Sci. Eng. C* **2011**, *31*, 1050–1054. [\[CrossRef\]](#)
11. Tu, D.; Shao, Z. Rheology model of bamboo under transverse heat-compression based on Burger-body. *J. Nanjing For. Univ. (Nat. Sci. Ed.)* **2008**, *32*, 67–70.
12. Li, N. Research on Long Term Deformation Behavior of Bamboo Based Component. Master's Thesis, Chongqing Jiaotong University, Chongqing, China, 2015.
13. Dong, C.; Zhang, H. Evaluation of the static bending creep of bamboo-wood composited I-beam. *J. Southwest For. Univ.* **2014**, *10*, 99–102.
14. Xiao, Y.; Li, L.; Yang, R.; Shang, B.; She, L. Experimental study on creep and loading property of laminated bamboo bridge. *Build. Struct.* **2013**, *43*, 86–91. [\[CrossRef\]](#)
15. Zhou, Q. Experimental Study and engineering Application of Glue Laminated Bamboo Beams. Ph.D. Thesis, Hunan University, Changsha, China, 2013.
16. Zhang, W.; Jiang, W.; Tang, R. Study on short-term bending creep behavior and microstructure of bamboo scrimber. *J. For. Eng.* **2017**, *2*, 33–37. [\[CrossRef\]](#)
17. Yang, T.; Wu, T.; Hung, K. Mechanical properties and extended creep behavior of bamboo fiber reinforced recycled poly(lactic acid) composites using the time-temperature superposition principle. *Constr. Build. Mater.* **2015**, *93*, 558–563. [\[CrossRef\]](#)
18. Ma, X.; Wang, G.; Jiang, Z.; Xian, Y.; Li, H. Comparison of bending creep behavior of bamboo-based composites manufactured by two types of stacking sequences. *Bioresources* **2014**, *9*, 5461–5472. [\[CrossRef\]](#)
19. Ma, X.; Jiang, Z.; Tong, L.; Wang, G.; Cheng, H. Development of creep models for glued laminated bamboo using the time-temperature superposition principle. *Wood Fiber Sci.* **2015**, *47*, 141–146.
20. Chen, S.; Wei, Y.; Zhao, K.; Hang, C.; Zhao, K. Creep performance and prediction model of bamboo scrimber under compression. *Acta Mater. Compos. Sin.* **2021**, *38*, 944–952. [\[CrossRef\]](#)

21. Wu, P. Experiment and Analysis on Creep Properties of Reconsolidated Bamboo. Master's Thesis, Northeast Forestry University, Harbin, China, 2015.
22. ASTM International. *ASTM D143-2009 Standard Test Methods for Small Clear Specimens of Timber*; ASTM International: West Conshohocken, PA, USA, 2009.
23. Arai, M.; Kato, Y.; Kadera, T. Characterization of the thermo-viscoelastic property of glass and numerical simulation of the press molding of glass lens. *J. Therm. Stress.* **2009**, *32*, 1235–1255. [[CrossRef](#)]
24. Wang, D.; Lin, L.; Fu, F. Fracture mechanisms of moso bamboo (*Phyllostachys pubescens*) under longitudinal tensile loading. *Ind. Crops Prod.* **2020**, *153*, 112574. [[CrossRef](#)]
25. Liu, H.; Wang, X.; Zhang, X.; Sun, Z.; Jiang, Z. In situ detection of the fracture behaviour of moso bamboo (*Phyllostachys pubescens*) by scanning electron microscopy. *Holzforschung* **2016**, *70*, 1183–1190. [[CrossRef](#)]
26. Xu, K. Research on Mechanics Performance of Steel-Bamboo Composite Fox Column under Long-Term Load. Master's Thesis, Ningbo University, Ningbo, China, 2015.
27. Zhang, F.; Chen, X.; Xu, Q.; Wang, Z.; Chen, L.; Gong, C. Experimental study on mechanical behavior of timber beam strengthened with steel plate during 1200-day sustained loading. *J. Build. Struct.* **2017**, *38*, 78–85. [[CrossRef](#)]
28. Tweedie, C.A.; Van, K.J. Contact creep compliance of viscoelastic materials via nanoindentation. *J. Mater Res.* **2006**, *21*, 1576–1589. [[CrossRef](#)]
29. *GB50068-2001*; Unified Standard for Reliability Design of Building Structures. China Architecture & Building Press: Beijing, China, 2001.
30. Luo, X.; Wang, X.; Ren, H.; Zhang, S.; Zhong, Y. Long-term mechanical properties of bamboo scrimber. *Constr. Build. Mater.* **2022**, *338*, 127659. [[CrossRef](#)]
31. Hoffmeyer, P.; Sørensen, J.D. Duration of load revisited. *Wood Sci. Technol.* **2007**, *41*, 687–711. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.