

Research Article

Temperature and Stress Effects on the Compressive Creep Behavior of Parallel Strand Bamboo

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Parallel strand bamboo (PSB) is an engineered bamboo product fabricated using crushed bamboo fiber bundles. Recently, this product finds applications in the civil engineering field. It is expected that the use of this composite will continue to grow because of its excellent mechanical performance, relatively low variability in material properties, and shape standardization. Modern bamboo structures made from PSB composites may be subjected to temperature variations during service. So far, however, there has been little discussion about the temperature-dependent creep. In this study, an investigation was carried out on the short-term behavior of the compressive property of PSB. A stress range of 8 to 64 MPa over a temperature range of 25°C to 75°C was considered in the 24-hour creep tests. In addition, Burgers model was adopted to describe the short-term creep behavior of PSB. Temperature and stress effects on the creep compliance of the Burgers model were also discussed.

1. Introduction

Parallel strand bamboo (PSB), a kind of engineered bamboo product, is made from raw bamboo strands which are compressed along the grain direction under high pressure. It has been proved that PSB has excellent mechanical properties and is an important alternative to traditional constructional materials [1–4]. This engineered bamboo product is considered to have great potential to be used as structural columns, beams, and flooring materials in the construction industry [5–8]. Biomaterials, such as wood and bamboo, are classified as viscoelastic materials at normal operating load, temperature, and moisture content. The viscoelastic behavior-induced microvoids and microcracking may lead to stiffness degradation and consequently develop macrocracks resulting in the premature failure of structures, of which the stress is significantly lower than expected. To avoid the creep rupture of a structural member, design codes require reductions in static strength to account for long-term performance. Therefore, it is necessary to evaluate the creep and

relaxation of biomaterials since this property may affect their long-term performance.

More recently, a considerable amount of literature has been published, including mechanical properties of PSB, fracture toughness, fire resistance, and performance of PSB columns/beams [7–14]. However, few writers have been able to draw on any systematic research into the viscoelastic properties of PSB. To the authors' knowledge, no single study exists which discusses the variation of tensile/compressive properties of PSB during a wider temperature range and a time duration. Modern bamboo structures made from PSB may be subjected to temperature variations during service. For instance, on winter nights, the temperature on the surface of some structural members can reach below 0°C. In a hot climate under direct sun, however, the temperature can even rise to over 50°C [15]. Hence, characterization of PSB creep behavior under a wide temperature range is important to ensure confidence in structure design and to assess potential failure due to excessive deformation or rupture.

Over the past few decades, there have been several investigations into the creep behavior of wood and wood-based composites. 10-hour creep tests of SPF under constant temperature and humidity were performed by Kuwamura [16]. He states that when the stress level exceeds 80% of the static strength, the creep strain transitions from the secondary stage to the tertiary stage and terminates in fracture. Kobbe et al. [17–21] conducted short- and long-term creep tests on wood-based composites to evaluate the creep behavior and concluded that they are very sensitive to the magnitude of the applied load, temperature, and relative humidity changes. The overall effect of temperature was an acceleration of creep with increasing temperature. In recent times, several investigations were devoted to creep behavior of raw bamboo material [22–24]. The effects of the environmental condition and the specimen part (outer or inner culm of the bamboo stem) have been clarified. Wu [25] conducted tensile and compressive creep tests of PSB at a stress range between 10% and 40% of tensile/compressive strength under constant temperature and relative humidity. The material exhibited linear viscoelastic behavior within the applied stress levels.

The time-dependent behavior of PSB, however, is not well understood at elevated temperatures, and very little information is available. The present study sets out to assess the temperature effect on the creep behavior of PSB composites. The creep tests over a stress range of 8 MPa to 32 MPa and a temperature range of 25° to 75°C were conducted in a temperature-controlled environmental chamber. The relative humidity was set at 50%. The results and analysis from creep tests were reported in detail. Moreover, the Burgers model was adopted to evaluate the creep behavior, and the creep compliance of the Burgers model was discussed.

2. Experimental

2.1. Material and Manufacturing. The experimental material used in this study was manufactured using 5-year-old Moso bamboo from the Jiangxi province of China. Firstly, bamboo culms were split into strips which are 2 m long with a section of 15 mm in width and 3 mm in thickness. The bamboo strips were carbonized for 140 min. The temperature and pressure were 130°C and 0.3 MPa, respectively. Carbonation treatment can improve the weatherability and dimensional stability of the PSB product and reduce shrinkage and swelling deformation. The bamboo strips were then dried at 80°C temperature until they reached a moisture content of approximately 11%. After carbonizing and drying treatment, the strips were crushed into rough bamboo strands. The strands were then impregnated with water-soluble phenolic resin. The solid content of resin and the impregnation time were 25% and 14 min, respectively. Then, the strands were compressed under a pressure of 4 MPa at 160°C to make PSB panels. The curing time is related to the thickness of the PSB panel, generally 1 min/mm.

2.2. Creep Test Procedure. All the specimens used in this study were designed per ASTM D2990-17 [26]. As shown in

Figure 1, the manufactured PSB panels were cut into specimens of 100 mm length with a section of 25 mm × 25 mm.

Creep tests are very sensitive. Thus, applying constant load and no shock during the creep test are expected. The creep tests were conducted in a temperature-controlled environmental chamber controlled to 50% relative humidity. Three temperature levels of 25°C, 50°C, and 75°C and three stress levels of 8 MPa, 16 MPa, and 32 MPa were selected. Initially, the stress level of 64 MPa was also selected. However, the specimens at the stress level of 64 MPa and the temperature of 50°C and 75°C failed prematurely. Only at 25°C, strain data under the stress of 64 MPa were recorded during the whole creep test. Thus, we also reported the results of 64 MPa in Section 3.1. Specimen temperatures during the creep tests were maintained within a tolerance of $\pm 1^\circ\text{C}$ to the target temperature. The average value of the ultimate static strength of PSB is 106.7 MPa at 25°C and drops to 42.7 MPa at 75°C. Hence, the lowest stress level 8 MPa was about 7.5% of the compressive strength at 25°C and 18.7% of that at 75°C. The highest stress level 32 MPa was about 30% of the compressive strength at 25°C and 74.9% of that at 75°C. All the specimens were preconditioned for the target temperature. Each creep test lasted 24 hours. The load, deformation, and time were recorded immediately following loading and at an interval of 15 s in the first hour and then at an interval of 75 s for the next 23 hours. The test setup and environmental chamber arrangement are shown in Figure 2(a), whereas the schematic representation is shown in Figure 2(b).

Since scatter in the properties is unavoidable in PSB, creep tests set at each test condition were repeated three times to improve the confidence of the test results. These specimens were named “Temperature-stress-No.” For example, the specimens tested at 25°C and 8 MPa were named “25°C-8 MPa-1/2/3.” The average results using three separate specimens were adopted for discussion.

3. Results and Discussion

3.1. Creep Behavior at Room Temperature. The time-dependent behavior of PSB specimens at 25°C and different stress levels is displayed in Figure 3. All the specimens showed similar behavior, and no creep rupture was observed.

The specimens first suffered an instantaneous strain upon loading. The instantaneous strain was expected to be more pronounced for greater loading. Such behavior can be seen in Figure 3. The strain then increased over time. This time-dependent response is creep strain. Creep behavior of wood composites is generally considered to have three stages [27, 28]. As shown in Figure 4, they are primary, secondary, and tertiary stages. Generally, primary creep occurs in a relatively short period of time. During the primary stage, the strain usually increases with a continuously decreasing strain rate. Then, the secondary creep stage with a constant strain rate is usually reached. The duration of the secondary stage is related to material properties, the level of sustained loading, and the loading condition. The tertiary stage usually indicates progressive failure of the material. It is clear that, at the

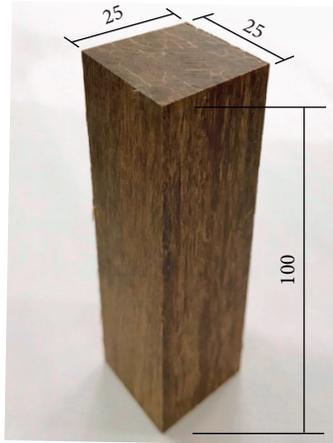


FIGURE 1: PSB specimen for the compressive creep test (unit: mm).

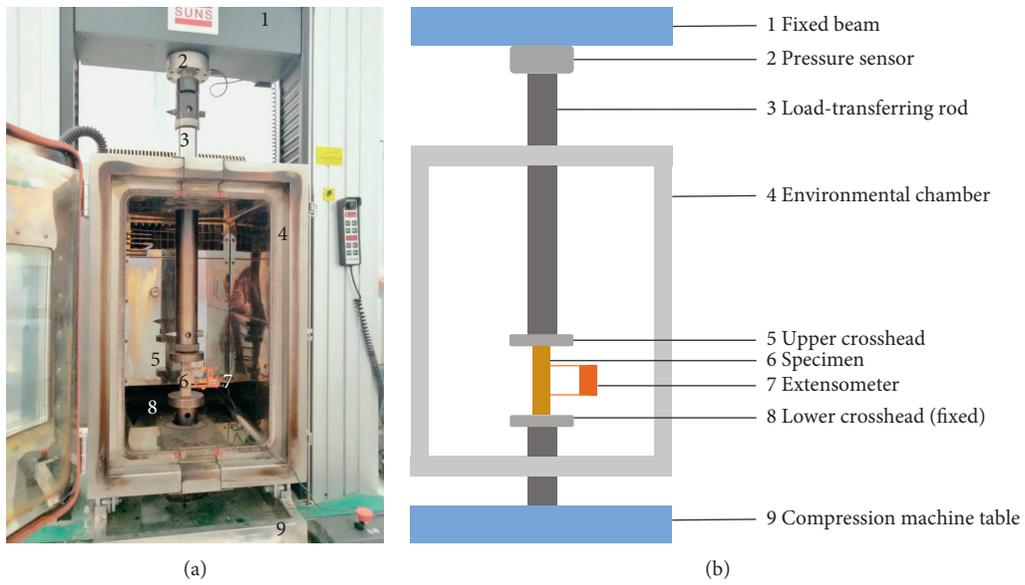


FIGURE 2: Experimental setup used in this study. (a) Test setup for loading. (b) Schematic of the test setup.

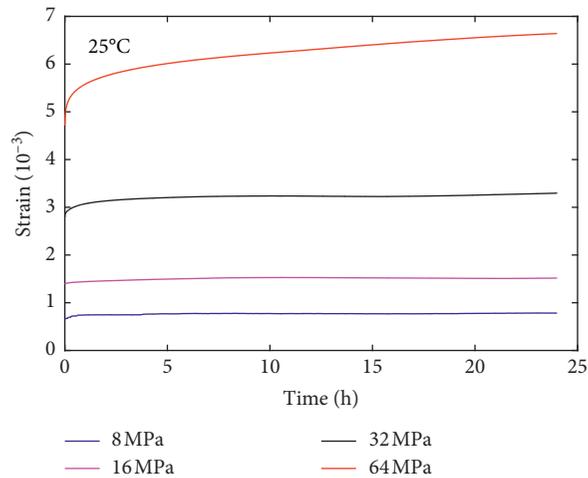


FIGURE 3: Creep behavior of PSB at 25°C and different stress levels.

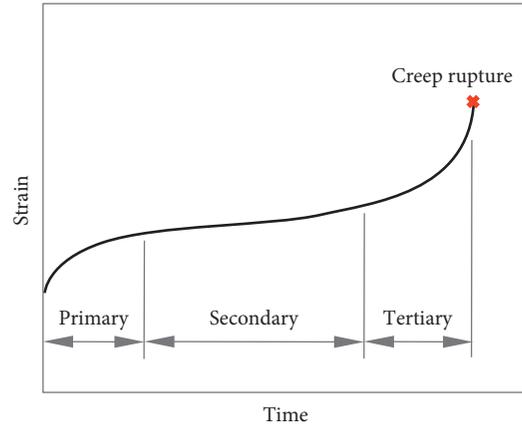


FIGURE 4: Three stages of the creep curve.

end of the tests, all specimens stay in the secondary creep stage.

The creep responses in the range of 8–64 MPa at 25°C are similar such that creep strains increase over time. As shown in Figure 3, the stress levels had an influence on the amount of creep strain of PSB material. The higher the level of sustained loading, the larger the creep strain. From the figure, we can see that, at the end of the tests, the creep strain was 0.79×10^{-3} under the stress level of 8 MPa. The creep strain increased to 3.30×10^{-3} at the stress level of 32 MPa and further increased to 6.64×10^{-3} at the stress level of 64 MPa. These results suggest that, at the temperature of 25°C, the increase in creep strain was proportional to the increase in stress within the range of this study.

When observing the creep curves plotted in Figure 3, note that the strain rate at 64 MPa is higher than the lower stress level. The observed difference may indicate the existence of a change in the creep mechanism at the high stress level. At lower stress levels, the creep is mainly induced by the molecular motions, while at higher stress levels, the creep may be dominated by the damage that occurred in the material.

3.2. Creep Behavior at Elevated Temperature. Considering the variation of seasonal temperatures in the south area of China, temperature variations at the surface of structural members are estimated to range from 25°C to 75°C.

Figure 5 may help us understand the temperature effect on creep behavior. At a constant stress level, the creep strain increased with the temperature. A possible explanation for this might be that exposure to high temperatures reduces the stiffness of PSB material [11]. At the stress levels of 8 MPa and 16 MPa, the creep strain at the end of the test was increased 2 times when the temperature was increased from 25 to 75°C. In the creep test under 75°C with the sustained load of 32 MPa, two specimens (75°C-32 MPa-1 and 75°C-32 MPa-3) failed within 24 hours. Therefore, the creep curve of 75°C in Figure 5(c) is not the average result, but the result of specimen 75°C-32 MPa-2.

It can be seen from Figures 3 and 5 that the temperature and stress level have a great influence on the amount of creep strain of PSB material. However, the strain rate appeared to be unaffected by the temperature and stress levels, except for the case with the stress of 32 MPa and temperature of 75°C.

Although this study was not intended to investigate the creep rupture of PSB material, specimen failure was recorded at the stress level of 32 MPa. As shown in Figure 6, the specimens enter the tertiary stage when the load is maintained for 17–18 hours. The creep deformation increases sharply, leading to creep rupture, indicating the likelihood of some material damage resulting from the increased temperature and sustained loading in this case. Such results suggest that although the bamboo-based structure is designed at low stress levels, high temperature and long time may still cause large creep deformation and even material failure.

4. Modeling of Creep

4.1. Burgers Model. To evaluate the time-dependent behavior of PSB material, a reliable and widely accepted model is needed. The generalized Kelvin model has been proven to apply to a variety of viscoelastic materials [29, 30]. Since this study focuses on the short-term creep behavior, the Burgers model which can be seen as a simple generalized Kelvin model consisting of one Kelvin unit is adopted here.

The Burgers model consisting of a Maxwell unit and a Kelvin unit in series is reasonably simple, as shown in Figure 7(a). Considering a creep test of a PSB specimen under compression, the behavior of the Burgers model can be understood as the combination of the element behavior connected in series in Figure 7(a). Thus, the total strain of the Burgers model at time t is decomposed into three parts:

$$\varepsilon(t) = \varepsilon_1(t) + \varepsilon_2(t) + \varepsilon_3(t), \quad (1)$$

where ε_1 , ε_2 , and ε_3 are the strain of the spring, Newton's dashpot, and the Kelvin unit, respectively. Given the stiffness and viscosity of the elements in the Burgers model, ε_1 , ε_2 , and ε_3 can be expressed as

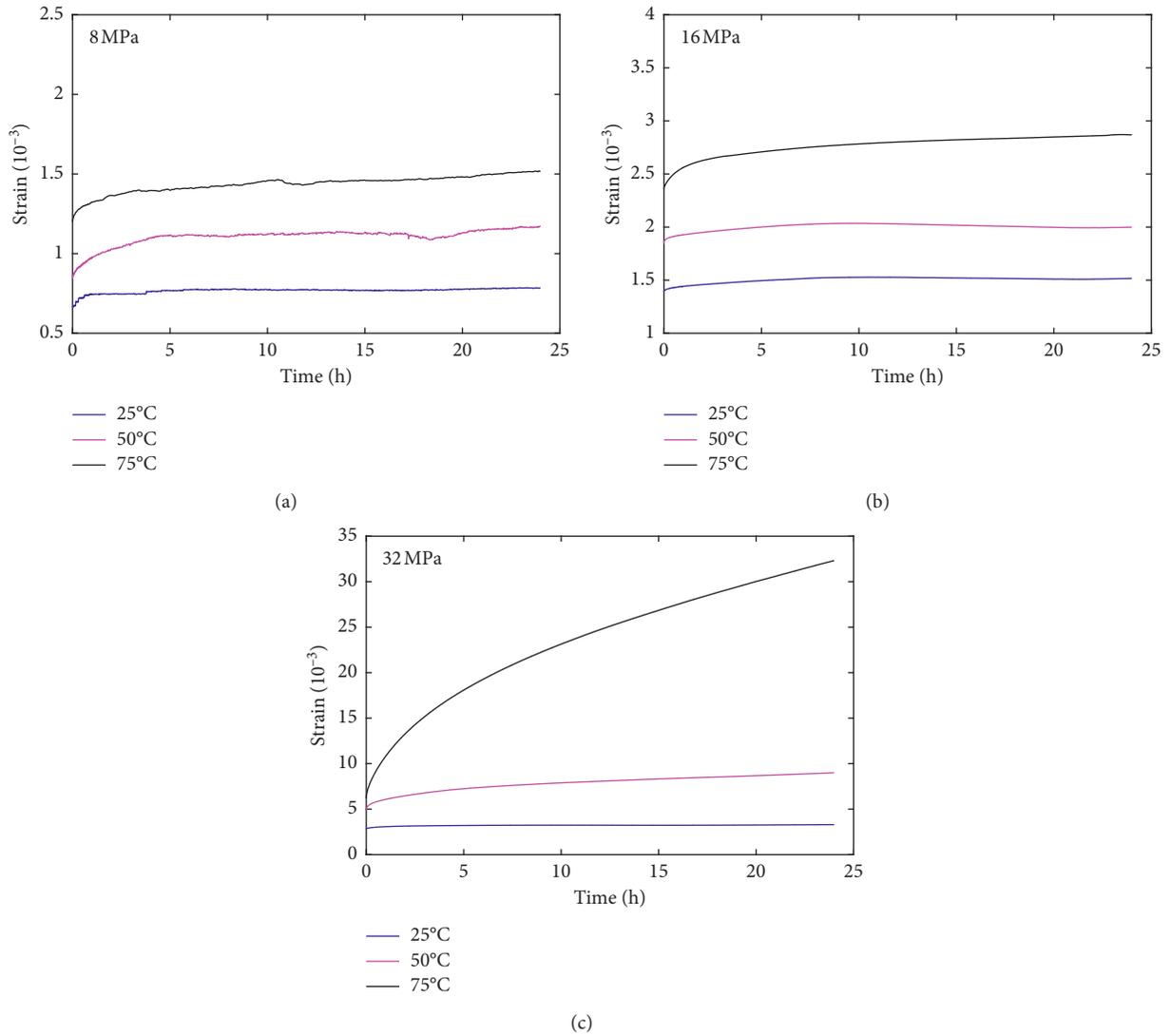


FIGURE 5: Creep behavior of PSB at temperatures between 25 and 75°C. (a) Creep test results at constant loading of 8 MPa. (b) Creep test results at constant loading of 16 MPa. (c) Creep test results at constant loading of 32 MPa.

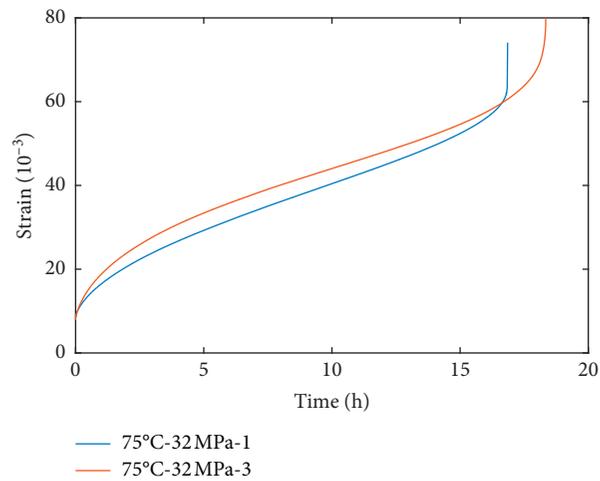


FIGURE 6: Creep rupture of specimens at 75°C and 32 MPa.

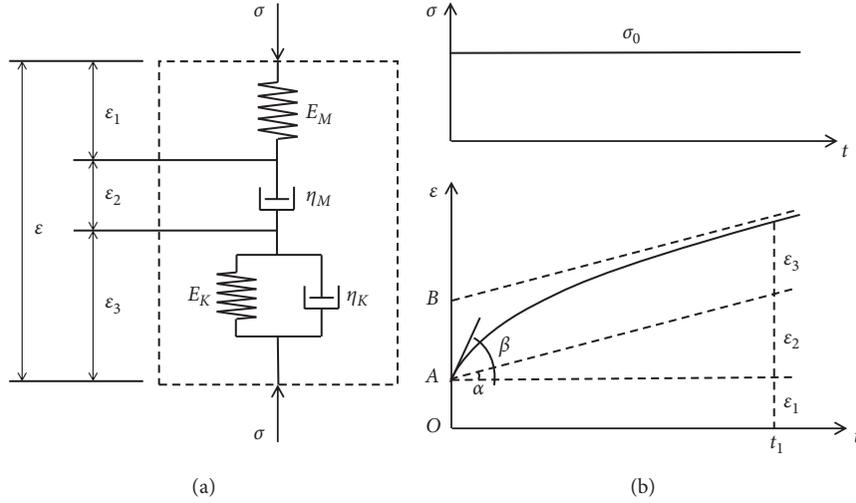


FIGURE 7: Burgers model. (a) Schematic illustration. (b) Creep response under a constant load.

$$\varepsilon_1 = \frac{\sigma}{E_M}, \quad (2)$$

$$\dot{\varepsilon}_2 = \frac{\sigma}{\eta_M}, \quad (3)$$

$$\dot{\varepsilon}_3 + \frac{E_K}{\eta_K} \varepsilon_3 = \frac{\sigma}{\eta_K}, \quad (4)$$

where E_M and η_M are the stiffness and viscosity of the Maxwell unit, respectively, and E_K and η_K are the stiffness and viscosity of the Kelvin unit, respectively.

The creep response of the Maxwell model is the sum of the spring and Newton's dashpot:

$$\varepsilon_1(t) + \varepsilon_2(t) = \frac{\sigma}{E_M} + \frac{\sigma}{\eta_M} t. \quad (5)$$

On the right-hand side of (5), the first term represents the instantaneous elastic strain since the spring will act immediately upon loading. The second term represents viscous flow because it takes time for the dashpot to build up the strain.

The creep behavior of the Kelvin model is expressed by solving first-order nonhomogeneous ordinary differential equation (4) with the initial condition $\varepsilon_3(0) = 0$. Thus,

$$\varepsilon_3(t) = \frac{\sigma}{E_K} \left(1 - e^{-(E_K/\eta_K)t} \right). \quad (6)$$

The right-hand term of (6) represents delayed elasticity of the Kelvin model. Then, the creep strain of the Burgers model can be expressed as follows:

$$\varepsilon(t) = \frac{\sigma}{E_M} + \frac{\sigma}{\eta_M} t + \frac{\sigma}{E_K} \left(1 - e^{-(E_K/\eta_K)t} \right). \quad (7)$$

Differentiating (7) yields the creep rate $\dot{\varepsilon}$:

$$\dot{\varepsilon}(t) = \frac{\sigma}{\eta_M} + \frac{\sigma}{\eta_K} e^{-(E_K/\eta_K)t}. \quad (8)$$

Based on the knowledge of the physical response of simple elements in the Burgers model, the material constants E_M , η_M , E_K , and η_K can be determined as follows:

$$\overline{OA} = \frac{\sigma}{E_M}, \quad (9a)$$

$$\tan \alpha = \frac{\sigma}{\eta_M}, \quad (9b)$$

$$\overline{AB} = \frac{\sigma}{E_K}, \quad (9c)$$

$$\tan \beta = \frac{\sigma}{\eta_M} + \frac{\sigma}{\eta_K}, \quad (9d)$$

where the four values \overline{OA} , \overline{AB} , α , and β illustrated in Figure 7(b) are obtained from the creep curve.

Figure 8 compares the Burgers model with the creep test results. Both primary and secondary creep stages can be well represented by the Burgers model. The comparison demonstrates the effectiveness of this model to evaluate the short-term creep behavior of this material.

4.2. Creep Compliance. The creep response of Burgers model (7) may also be written in the form

$$\varepsilon(t) = \sigma J(t) = \sigma \left(J_0 + J_\eta t + J_K \left(1 - e^{-(t/\tau)} \right) \right), \quad (10)$$

and $J(t)$ is defined as the creep strain resulting from unit stress, known as the compliance function. It is the visco-elastic material property used to describe behavior during creep loading. J_0 is the initial compliance. It is time independent and only related to the elastic modulus of the spring in the Maxwell unit. J_η is the delayed compliance due to the viscosity of the dashpot in the Maxwell unit. J_K and τ are the delayed compliance and retardation time due to the Kelvin unit in the Burgers model.

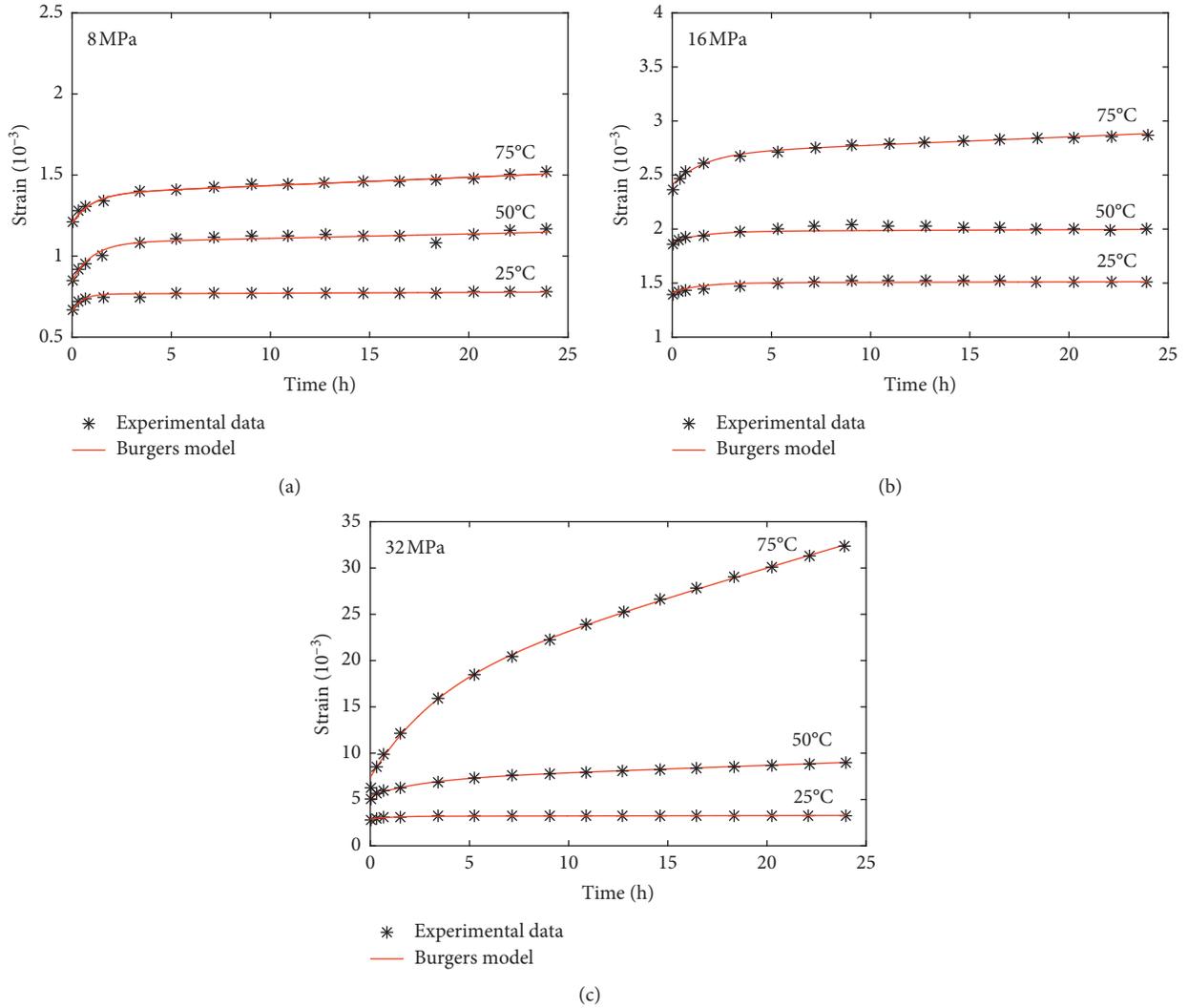


FIGURE 8: Measurements and Burgers model predictions for creep strain. (a) At constant loading of 8 MPa. (b) At constant loading of 16 MPa. (c) At constant loading of 32 MPa.

TABLE 1: Creep compliance and retardation time.

Condition	J_0	J_η	J_K	τ
25°C-8 MPa	823.3	0.6	134.3	0.5
50°C-8 MPa	1055	3.4	297.8	1.0
75°C-8 MPa	1495	6.4	224.9	1.2
25°C-16 MPa	881.4	0.3	57.1	1.3
50°C-16 MPa	1175	0.5	61.5	1.5
75°C-16 MPa	1566	4.8	181.2	1.6
25°C-32 MPa	902.3	1.3	91.6	1.0
50°C-32 MPa	1686	24.3	543.3	2.6
75°C-32 MPa	2307	198.2	3110	3.4

The compliance J_0 , J_η , J_K and the time quantity τ are key characteristic properties of the model. Indeed, no knowledge of each element in the Burgers model is necessary. The creep response of a material can be completely characterized provided the creep compliance is known. The compliance can be derived from the data collected in the creep tests, as summarized in Table 1.

Figure 9 compares creep compliance values determined using different stress levels at elevated temperatures. Evaluating the compliance shows that compliance is temperature dependent. There is an increasing trend with temperature, especially at higher stress level. At a temperature of 25°C, the compliance values are basically identical when the loads are no more than 32 MPa, 30% of the static strength. This

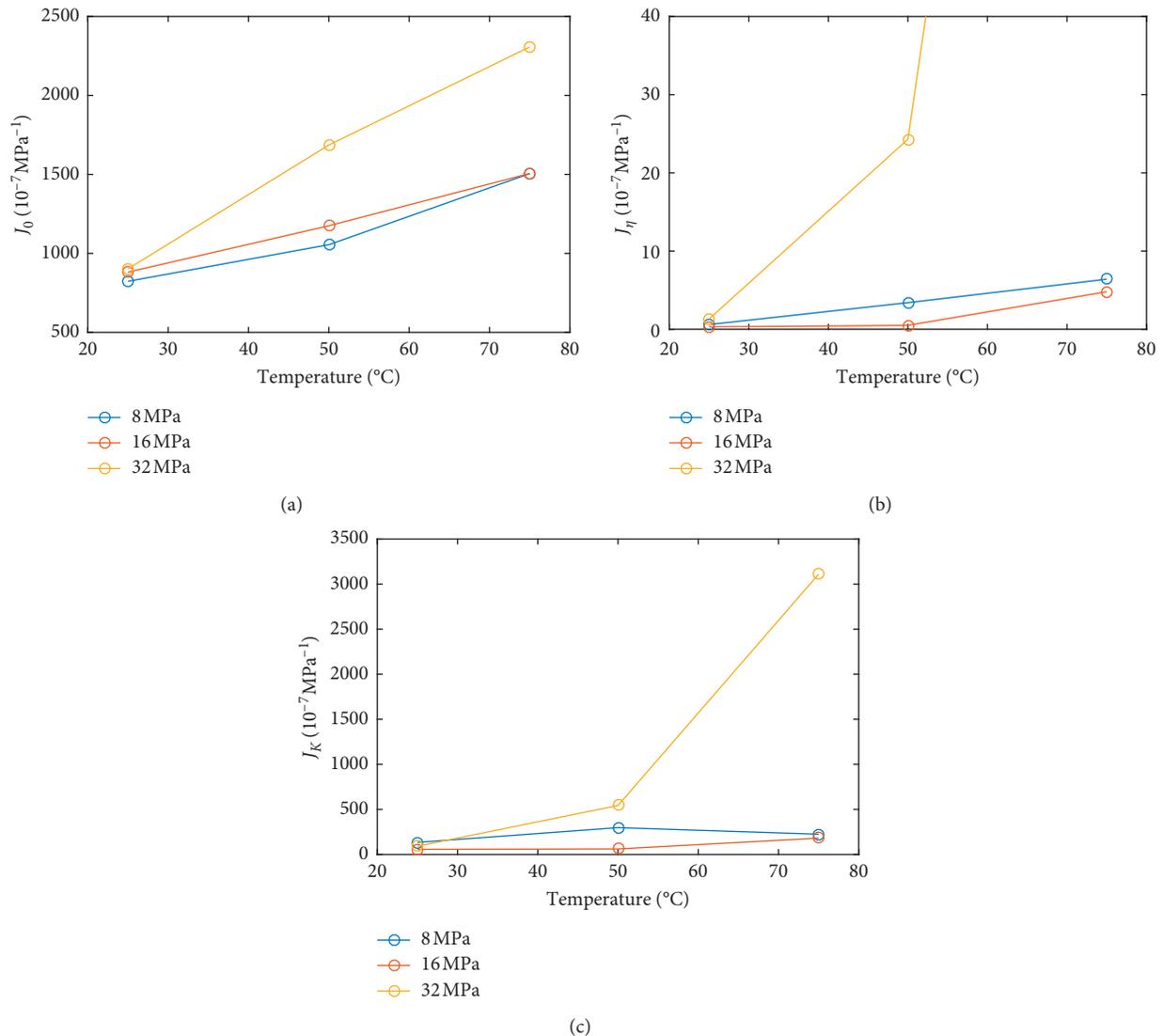


FIGURE 9: Evaluation of the creep compliance. (a) Initial compliance J_0 . (b) Delayed compliance J_{η} . (c) Delayed compliance J_K .

indicates the linear viscoelastic behavior of PSB at relatively low temperature and under relatively low stress. High temperature and stress level may increase the creep compliance, leading to larger creep deformation.

5. Conclusions

The present study was designed to investigate the temperature and stress effect on the compressive creep behavior of PSB. The creep tests over a stress range of 8 MPa–32 MPa and a temperature range of 25°C–75°C were conducted in a temperature-controlled environmental chamber. At a constant load, the creep strain showed an increasing trend with the temperature. Elevated stress and temperature levels resulted in a noticeable higher creep rate, possibly indicating the existence of a different creep mechanism compared with relatively low stress and temperature conditions. Creep

rupture observed in the creep test under 32 MPa and 75°C demonstrates that although the bamboo-based structure is designed at low stress levels, high temperature and a long time may still cause large creep deformation and even material failure.

Burgers model has proven to be an effective model for short-term creep behavior of PSB material. Using the Burgers model, the primary and secondary creep stage was predicted with accuracies at all stress and temperature levels. The creep compliance of the Burgers model is basically identical at 25°C when the load is no more than 32 MPa, indicating the linear viscoelastic creep behavior of PSB at relatively low temperature and stress. High temperature and stress levels may increase the creep compliance, leading to larger creep deformation. While the Burgers model can be helpful in interpreting observed creep behavior, the model is only valid for conditions within the range of this study. In

the future study, it is necessary to demonstrate the effectiveness of the model when used outside the conditions studied.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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