

Numerical and Experimental Study of the Transverse Creep-Recovery Behavior of Bamboo Culm (*Dendrocalamus hamiltonii*)

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Abstract

Hot compression creep-recovery behavior in the transverse direction of bamboo culm was studied. Creep-recovery tests were performed to investigate nonlinear viscoelastic strain. Long-term uniaxial creep-recovery laboratory tests were carried out at 5 different constant applied stress levels inside a boiling water bath. The Burgers model was used to characterize the observed creep data and the Weibull distribution equation was used to characterize the observed recovery data. The models successfully describe the main features for the investigated material and shows good agreement with the experimental creep-recovery data.

Keywords: Bamboo culm, Burgers model, constitutive behavior, creep and recovery, *Dendrocalamus hamiltonii*, Weibull distribution equation

Introduction

Bamboo is one of the oldest construction materials due to its versatile physical and mechanical properties. Bamboo is also anisotropic, viscoelastic, and heterogeneous possessing high strength and stiffness along the axial direction, but poor mechanical properties in the transverse direction (radial or tangential direction) [1]. This characteristic is generally due to the morphology that is composed of the lignin matrix reinforced with fibers aligned in an axial direction. Nonetheless, the bamboo culm is composed of thin-walled hollow cylinders without fiber reinforcement in the radial direction. In addition, bamboo is a hygroscopic material that can absorb moisture from its surroundings. Also, the dimension of the bamboo is likely to be dependent upon changing environmental conditions. Dimensional variation is a serious and complex behavior, since it can cause a damaging effect on other mechanical and physical properties [2]. Bamboo is favored for use in scaffolding, low-rise houses, footbridges, and construction platforms. Recently, there has been a considerable amount of interest in bamboo because of its environmental conservation and wood-based resource insufficiency [2]. In addition, to be an eco-friendly material, bamboo is appropriate to replace wood. One of the reasons is that bamboo can be harvested in 3 to 5 years. At this lifetime its mechanical strength and anatomical characteristics become immovable and grown-up [3].

Bamboo is also a polymeric material consisting of crystalline and amorphous phases. Amorphous bamboo phases, such as hemicelluloses and lignin, exhibit a viscoelastic behavior influenced by temperature and moisture content. At low temperature, amorphous bamboo constituents are in a glassy state exhibiting high strength and modulus. As the temperature increases, values of the strength and modulus decrease rapidly within a small temperature range called the "glass transition temperature, T_g ". Amorphous bamboo constituents obtain another softer state which is called a rubbery state [4]. The glass transition temperature in wood, ranging from 60 to 235 °C, depending on the moisture content, wood chemical composition and method of testing [5]. Various techniques of softening bamboo culms have

been reported by many researchers. Guisheng [6] dipped bamboo strips (*Phyllostachys pubesens*) into boiling water for several hours followed by paraffin at 130 °C for 10 min. Kyokong *et al.* [7] successfully softened black sweet-bamboo culm (*Dendrocalamus asper* Backer) by immersion of bamboo strips in boiling water for 18 h followed by dipping into boiling linseed oil for 45 s. Cherdchim *et al.* [4] found that thermal softening behavior of bamboo culm in linseed oil was divided into 2 temperature regimes with the glass transition temperature at 115 °C. Nakajima *et al.* [8] found that a steep decrease in the relative relaxation modulus due to thermal softening of lignin was found around 60 °C in the heating process for bamboo.

Bamboo is a viscoelastic material exhibiting properties that are common to both solid and liquid. This property shows that stress is proportional to strain, rate of strain, and possibly higher time derivatives of strain. A constitutive equation for such material must correctly represent the behavior under conditions of stress and strain. These conditions are creep, stress relaxation, recovery, constant rate stressing and constant rate straining [9]. Because bamboo is a viscoelastic material at normal operating stress, temperature and moisture content, it is inclined to creep and can lead to usability problems resulting from excessive deformations or lead to safety problems resulting from strength reduction [10].

Various numerical models have been used to predict the creep-recovery behavior such as the Schapery's nonlinear viscoelastic material model and the 4-element Burgers model. The Schapery's nonlinear viscoelastic material model derived from the thermodynamic principles, consistent with nonlinear viscoelastic behavior of the metals and polymer composite materials [11]. The details of using the Schapery's nonlinear viscoelastic material model can be found in [11-13]. However, we would like to simplify the problem. Then, we used a simple model as the 4-element Burgers model instead of the Schapery's nonlinear viscoelastic material model. The 4-element Burgers model as shown in **Figure 1** can model creep-recovery behavior. The Burgers model is a combination of Maxwell and Kelvin-Voigt models. It is commonly used for determining creep behavior.

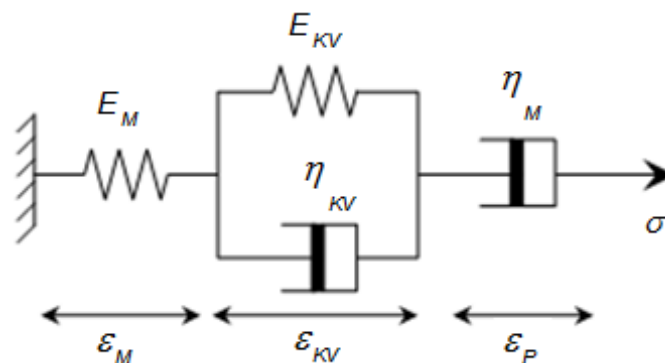


Figure 1 Schematic of the 4-element Burgers model [14].

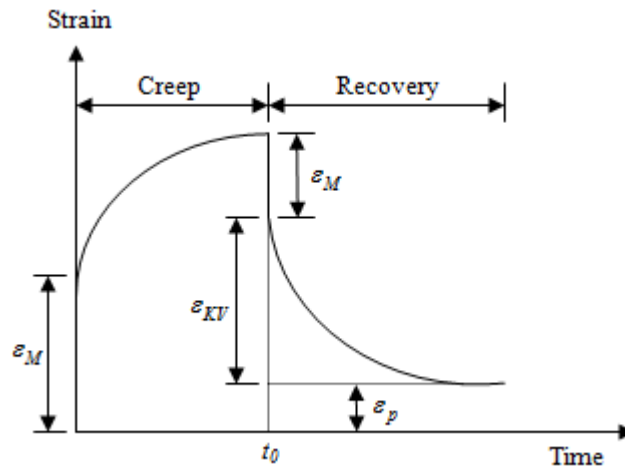


Figure 2 Typical creep and recovery curve in a viscoelastic material [14].

In general cases of a nonlinear viscoelastic solid, the total strain comprises 3 essentially separate strains [15] (as shown in **Figure 2**), that are the immediate elastic strain ε_M , the delayed elastic strain ε_{KV} , and the permanent strain ε_p . The total strain can be written as a function of time as follows [16];

$$\varepsilon(t) = \varepsilon_M + \varepsilon_{KV} + \varepsilon_p \quad (1)$$

$$\varepsilon(t) = \frac{\sigma}{E_M} + \frac{\sigma}{E_{KV}} \left[1 - \exp\left(-\frac{E_{KV}}{\eta_{KV}} t\right) \right] + \frac{\sigma}{\eta_M} t \quad (2)$$

where $\varepsilon(t)$ is the creep strain, σ is the applied stress, t is the time after loading, E_M is modulus of the Maxwell spring in the Burgers model, E_{KV} is modulus of the Kelvin-Voigt spring in the Burgers model, η_M is viscosity of the Maxwell dashpot in the Burgers model, η_{KV} is viscosity of the Kelvin-Voigt dashpot in the Burgers model.

Xu *et al.* [17] developed the Burgers model by introducing a stretching exponent n to the time t on the Kelvin-Voigt unit based on the 4-element Burgers model. The model is as follows;

$$\varepsilon(t) = \frac{\sigma}{E_M} + \frac{\sigma}{E_{KV}} \left[1 - \exp\left(-\frac{E_{KV}}{\eta_{KV}} t^n\right) \right] + \frac{\sigma}{\eta_M} t^n \quad (3)$$

when the applied stress σ is removed at the time $t = t_0$, the elastic component of deformation instantly decreases. The creep deformation also decreases with time and tends asymptotically to the value of σ / E_M .

The 4-element Burgers model was used to find the model parameters of recovery test data but the curve fitting process did not converge (not shown). Thus, a Weibull distribution equation that yielded a better fit was used. A Weibull distribution equation is often used to model the behavior of composite solids [18]. Fancey [19] show that the Weibull distribution equation can be used accurately to present the recovery behavior of polymeric materials. The Weibull distribution equation Eq. (4) [15] can be used to simulate the recovery part as represented in **Figure 2**. When the load is removed, some strain may be instantaneously recovered. The strain recovery can be written as;

$$\varepsilon_r(t) = \varepsilon_{KV} \left[\exp \left(- \left(\frac{t-t_0}{\eta_r} \right)^k \right) \right] + \varepsilon_p \quad (4)$$

where ε_r is the strain recovery, ε_{KV} is the delay elastic strain, η_r is the characteristic life, k is the shape parameter over recovery time t , t_0 is the time when stress is removed, and ε_p is the permanent strain from viscous flow effects.

The Burgers model and Weibull distribution equation of viscoelasticity have been applied to composite materials by many researchers. Ounjaijom and Rangsri [14] applied the model to construct the constitutive relation for describing the bending creep behavior of the bamboo culm. The result showed that the model successfully describes the main feature for the investigated material and showed good agreement with experimental creep-recovery data. The details of using the model for other materials such as composite materials can be found in [15,17,19,20]. Currently, the researchers found that no one has used this model to study the creep behavior of bamboo culm under thermal softening conditions.

In this paper, we present an experimental investigation of the transverse creep-recovery behavior of bamboo culm. The long-term uniaxial creep-recovery laboratory tests were carried out at 5 different constant stress levels inside a boiling water bath. The Burgers model was used to characterize the observed creep data and the Weibull distribution equation was used to characterize the observed recovery data respectively.

Materials and methods

Sample preparation

The dimensions of the bamboo specimen were 10 mm in the longitudinal direction, L, 10 mm in the radial direction, R, and 10 mm in the tangential direction, T, as shown in **Figure 3**. The bamboo culms (*Dendrocalamus hamiltonii*) approximately 3 to 4 years old were used in this study. They were taken from Mae Wang district, Chiang Mai province, Thailand. Specimens were taken from the bottom part, middle part and top part of each culm. After removing the outer and the inner surface of the culm, they were polished with Silicon Carbide (SiC) sandpaper to ensure a good finished surface. Then, the specimens were dried using an oven at 103 ± 2 °C for 24 h. After 24 h, the drying process was considered to be complete when the difference between the successive determinations of the mass did not exceed 0.01 g [21].

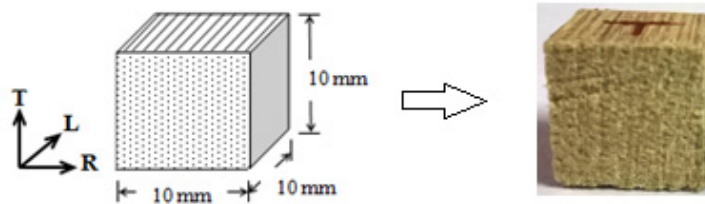


Figure 3 Dimensions of the bamboo culm specimen.

Creep characterization

The transverse creep-recovery tests were performed on a hot compression test system by applying a static load as shown in **Figures 4 and 5**.

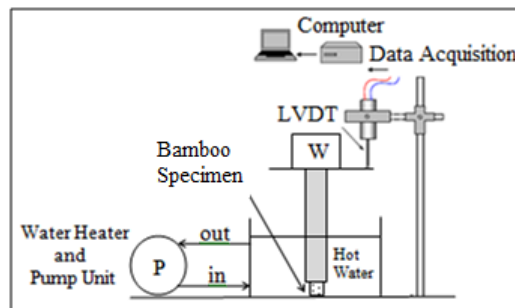


Figure 4 Schematic of the creep-recovery test rig.

The experiments were conducted using hot water at 90 ± 2 °C. This temperature is greater than the thermal softening of lignin [8]. Tissaoui [9] suggested a creep test duration of 4 h can be sufficient to account for the creep behavior of wood. In this study, the creep tests were performed according to the following schedule: 1, 2, 3 and 4 h, respectively, of uniaxial compression creep at constant applied stress σ with 5 different stress levels. The 5 levels were $\sigma = 10, 20, 30, 40$ and 50 % of the ultimate strength ($\% S_{ut}$), respectively. The ultimate strength of bamboo used in this study was 8.25 MPa obtained from the compressive test in hot water (90 ± 2 °C) of *Dendrocalamus hamiltonii* with the Hounsfield S-series H50KS / 06 universal testing machine. After the applied stress process, the stress was released and the sample was allowed to recover for 1, 2, 3 and 4 h, respectively. During these times, the recovery strain was monitored. The experiment was repeated 3 times for each stress level. Creep-recovery deformation of the specimens was measured using a LVDT transducer with a tolerance accuracy of ± 0.001 mm. Data was collected using the HBM MGCplus data acquisition system.

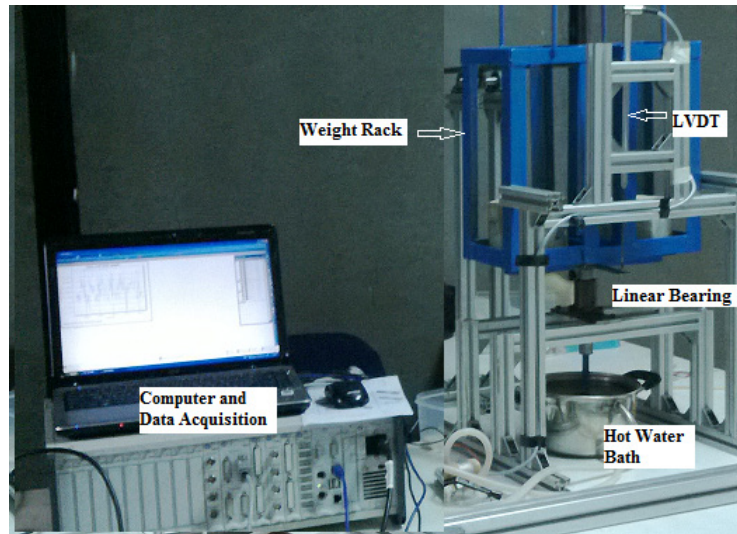


Figure 5 Creep-recovery test apparatus.

Parameters Identification

The schematic of the research methodology is shown in **Figure 6**.

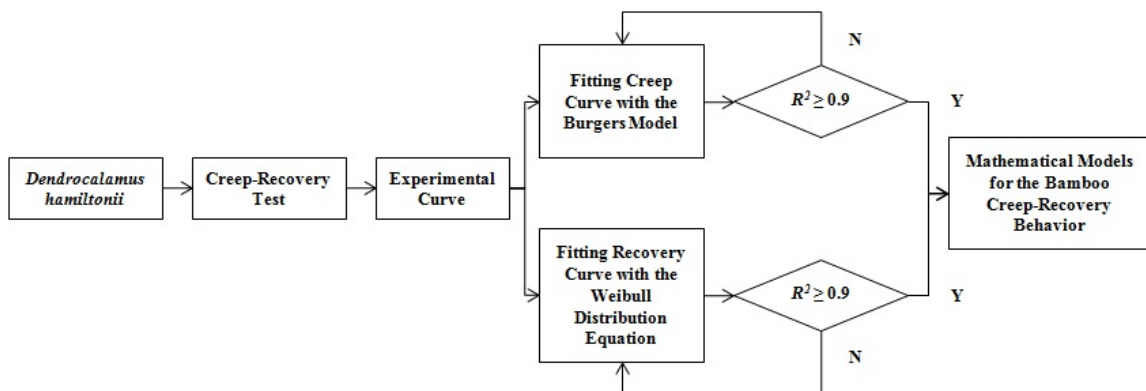


Figure 6 Schematic of the research methodology.

In order to describe the creep-recovery behavior of the tested specimens, the material parameters according to the Burgers model associated with the Weibull distribution equation as shown in Eqs. (3) and (4) were constructed. This was done using the Levenberg-Marquardt algorithm. It is a numerical optimization algorithm for solving nonlinear equalization problems with the method of least squares. The Levenberg-Marquardt algorithm is much more robust than the Gauss-Newton method, i.e. it converges with high probability, even with poor starting conditions [22]. Scilab code [23] was employed to estimate the material parameters by performing nonlinear regression on the creep-recovery data with the Levenberg-Marquardt algorithm.

Results and discussion

Relationship between strain and time at various applied load

Creep of the bamboo culm shows the typical viscoelastic behavior as follow: Creep strain gradually increases with time and the applied stress, and residual strains become noticeable under high loads, even after a period of active loading. Plots of the representative creep and recovery strain with the time at the various applied stress are shown in **Figure 7**.

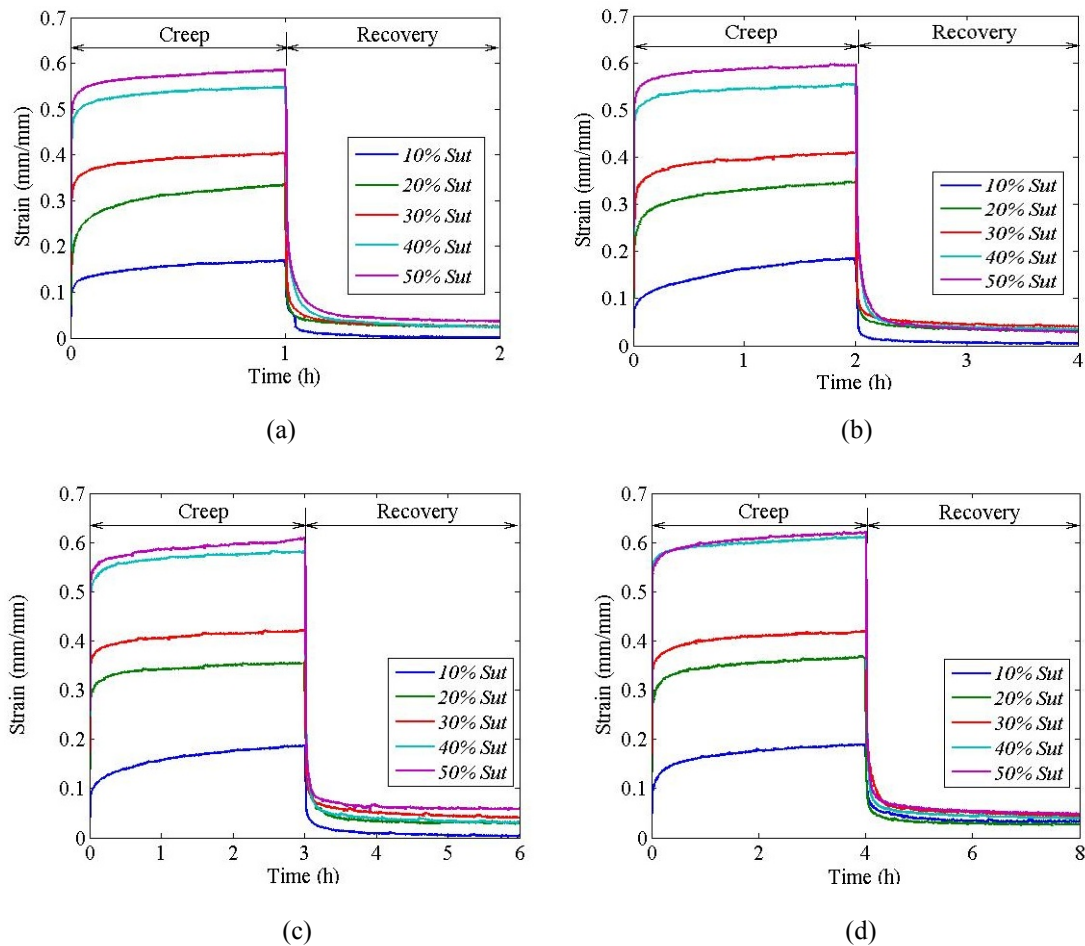


Figure 7 Creep and recovery tests data at different applied stress with the time. (a) 1 h applied stress, (b) 2 h applied stress, (c) 3 h applied stress, and (d) 4 h applied stress.

Consider the creep strain in **Figure 7**, the creep strain at applied stress 10 % S_{ut} are smaller compared to these obtained from other applied stress levels. The creep strain at applied stress 20 % S_{ut} and 30 % S_{ut} are similar to each other. Similarly, at the applied stress 40 % S_{ut} and 50 % S_{ut} , the strains are different to that of the applied stress less and will more precious when the applied stress increases. When the applied stress was released, the specimens were able to return to their original shape. But when the applied stress increases, the specimen was unable to return to the original shape due to permanent deformation.

The 4-element Burgers model and the Weibull distribution equation parameters identification

The compressive transverse creep-recovery data were compared with the constitutive material model. The readers should be reminded that the 4-element Burgers model and the Weibull distribution equation were used in this study. Using the Levenberg-Marquardt least squares method, the experimental data for each experiment was used to construct Eqs. (3) and (4) in order to obtain an appropriate value for each model parameters. The values of material model parameters for bamboo culm are summarized in **Table 1**.

Table 1 Summary of the material model parameters with different applied stress.

Applied load time	σ (MPa)	E_M (MPa)	E_{KV} (MPa)	η_{KV} (MPa·s)	η_M (MPa·s)	n	ε_{KV} (%)	η_r (s)	ε_P (%)	k
1h	0.825	126.866	3.523	5.646	0.931	0.214	0.193	0.014	0.002	0.663
	1.650	214.335	4.111	4.465	22.805	0.124	0.363	0.010	0.028	0.544
	2.475	278.376	3.563	3.563	32.430	0.082	0.465	0.010	0.029	0.482
	3.300	347.389	3.910	3.873	49.434	0.046	0.649	0.006	0.030	0.473
	4.125	392.812	3.134	3.195	62.089	0.043	0.701	0.004	0.041	0.450
2h	0.825	103.079	3.585	8.963	5.988	0.167	0.216	0.016	0.005	0.638
	1.650	183.376	4.465	4.524	25.386	0.123	0.402	0.012	0.031	0.507
	2.475	222.700	3.645	3.645	38.232	0.067	0.469	0.012	0.035	0.448
	3.300	300.018	4.257	3.910	62.742	0.043	0.662	0.006	0.039	0.410
	4.125	374.956	3.146	3.251	123.084	0.036	0.723	0.005	0.046	0.389
3h	0.825	91.626	4.632	10.295	7.304	0.156	0.233	0.018	0.007	0.499
	1.650	152.813	4.524	4.544	28.475	0.078	0.413	0.013	0.034	0.492
	2.475	186.637	3.651	3.896	40.691	0.065	0.519	0.013	0.035	0.418
	3.300	607.113	4.179	4.179	67.807	0.040	0.723	0.009	0.049	0.365
	4.125	332.623	3.251	0.914	148.846	0.035	0.747	0.005	0.055	0.314
4h	0.825	72.336	6.798	25.179	7.456	0.116	0.260	0.019	0.028	0.464
	1.650	134.178	4.695	5.134	41.116	0.059	0.454	0.014	0.034	0.464
	2.475	161.377	3.970	4.070	62.469	0.046	0.542	0.014	0.045	0.400
	3.300	234.056	4.270	4.340	93.121	0.036	0.803	0.012	0.050	0.337
	4.125	269.577	3.728	4.110	186.715	0.028	0.805	0.008	0.063	0.291

The parameters of the 4-element Burgers model and the Weibull distribution equation in Eqs. (3) and (4) are shown in **Figures 8** and **9**, respectively. The models of the creep strain and the recovery strain are plotted in comparison with the experimental results as shown **Figures 10** and **11**, respectively.

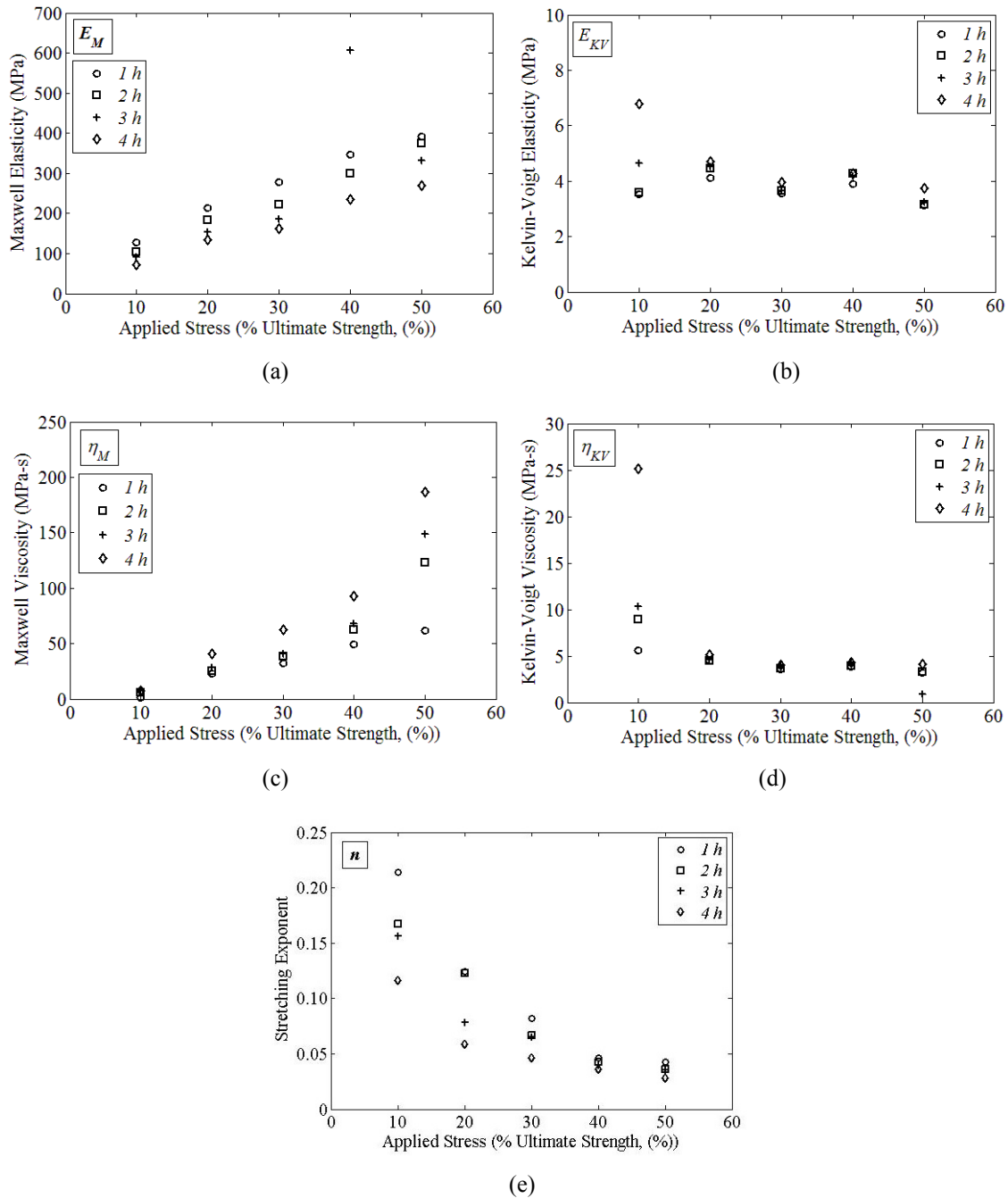


Figure 8 The parameters of the 4-element Burgers model Eq. (3) with different applied stress. (a) Maxwell elastic modulus, (b) Kelvin-Voigt elastic modulus, (c) Maxwell viscosity, (d) Kelvin-Voigt viscosity, and (e) Stretching exponent.

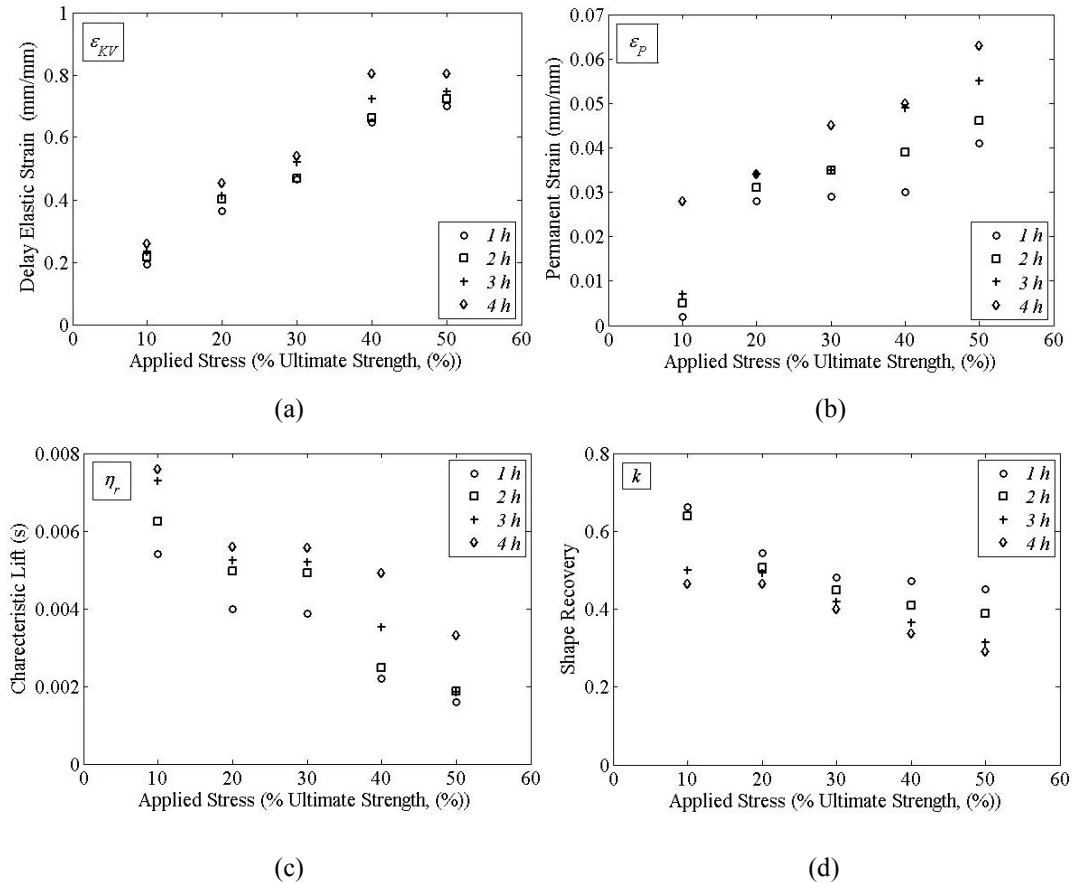


Figure 9 The parameters of the Weibull distribution equation in Eq. (4) with different applied stress. (a) Delay elastic strain, (b) Permanent strain, (c) Characteristic life, and (d) Shape parameters.

The influence of time on the creep-recovery behavior of the bamboo culm is clearly seen in **Figures 8 and 9**. With increasing time, the parameters E_{KV} , η_M , and η_{KV} in the creep part and the parameters ϵ_{KV} , ϵ_P , and η_r in the recovery part result in an increase in the creep strain and permanent strain of the bamboo culm.

The nonlinear curve fit function of the Levenberg-Marquardt algorithm was applied with 5 parameters: E_M , η_M , E_{KV} , η_{KV} , and n . In **Figure 8**, the parameters E_M and η_M show an increasing trend with the applied stress. The parameter E_M associates to the Maxwell spring instantaneous creep strain that can be recovered after stress elimination. The result shows that the applied stress has the ability to reduce the Kelvin-Voigt elastic modulus (E_{KV}) of the bamboo culm. The parameter η_{KV} indicates that the viscosity of the Kelvin-Voigt unit and shows a decreasing trend with the applied stress. One more important parameter is η_M which is also listed in **Table 1**. It represents the irrecoverable creep strain. It

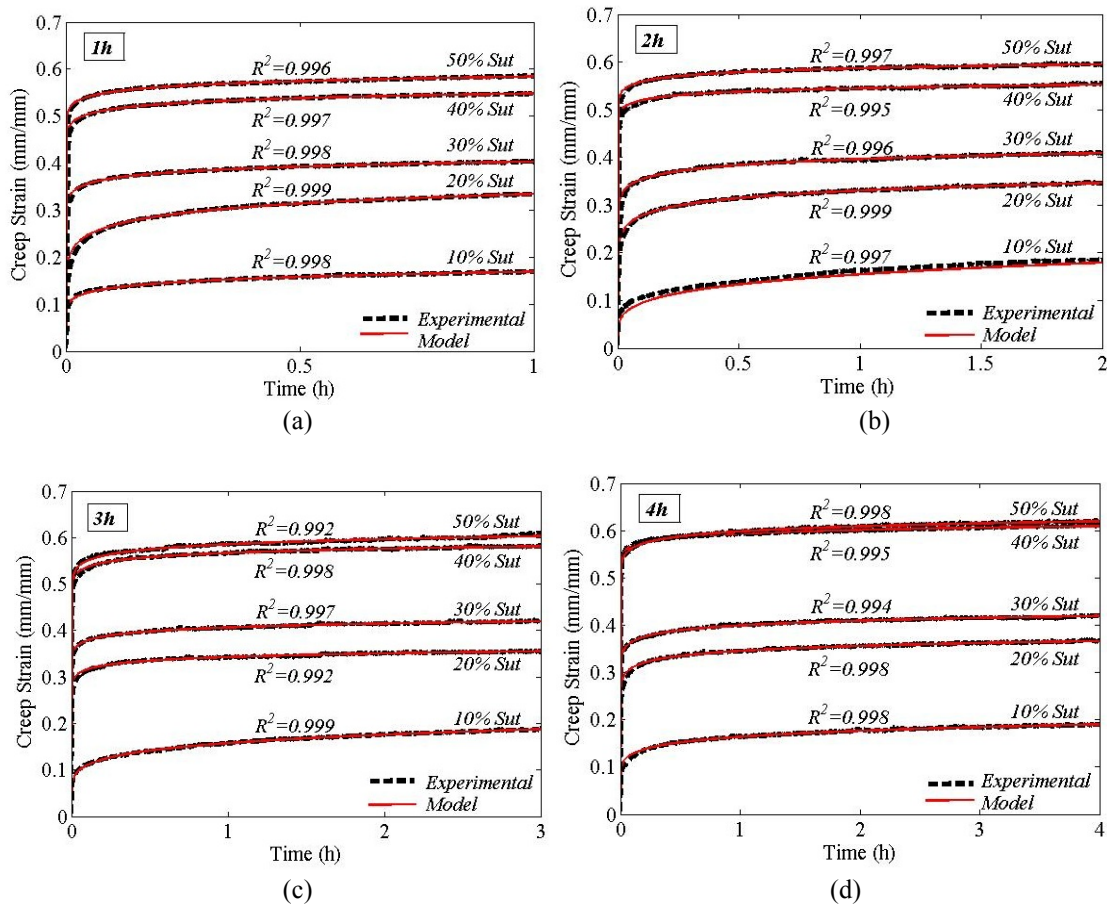
is noticed that the value of the parameter η_M is much higher than that of η_{KV} , and it is also sensitive to the applied stress. As seen from the fitting results, the parameter η_M increases with the applied stress and the permanent deformation. On the other hand, the parameter E_{KV} is related directly to the stiffness of the bamboo culm. It also decreases slightly to the applied stress. Consider the molecular bonds, when the stress is applied to the specimens, the strain will increase sharply because the molecular bonds stretch beyond the elastic limit. This adhesion molecular bonds are very strong and difficult to be broken, corresponding to the behavior of the dashpot element of the Maxwell model (η_M). Thus, the molecules shift from one position to another and form new secondary bonds. Finally, the molecules in the new position will keep this configuration due to the viscosity influence. This behavior can be described by the dashpot element of the Kelvin-Voigt model (η_{KV}) representing the behavior of the weak molecular bonds that make the creep strain constant when holding the applied stress.

The nonlinear curve fit function of the Levenberg-Marquardt algorithm was applied with 5 parameters of the Weibull distribution equation: ε_{KV} , ε_p , η_r , and k , as shown in **Figure 9**. The strain values of the delay elastic strain (ε_{KV}) and the permanent strain (ε_p) can be calculated. The results, obtained together with the parameters η_r and k , are shown in **Table 1**. It is apparent that the values of ε_{KV} and ε_p increase with the increasing applied stress. In addition, the values of η_r and k slightly decrease due to a reduced recovery performance. Results of the delay in the recovery make the permanent deformation increase depending on the level of applied stress. This permanent deformation occurs after the molecular bonds change to the new configuration.

Combining the analysis of the 2 parts indicates that increasing applied stress may lead to viscosity increasing in the creep part, and it may lead to viscosity decreasing in the recovery part. These behaviors are influenced by the parameters η_M and η_r , respectively. As a result, the permanent strain increases, and that reflects by the parameter ε_p . It is noticed that the permanent creep strain (ε_p) is the important parameter and is directly related to the recovery property of the materials. That is the effect of viscosity increases towards the permanent strain and recovery strain.

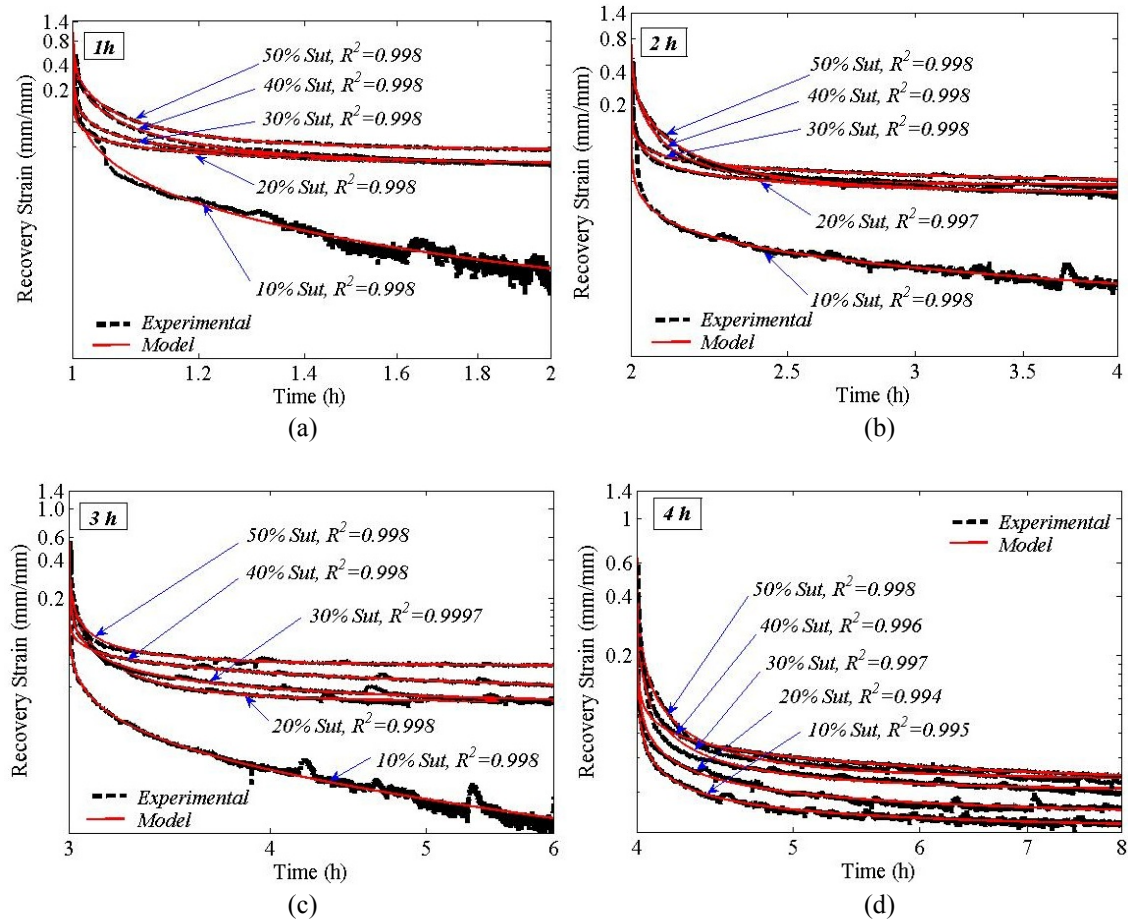
The experimental curves of creep phase and recovery phase were fitted by means of the 4-element Burgers model and the Weibull distribution equation as shown in **Figures 10** and **11**, respectively. The model shows a satisfactory agreement with the experimental data.

A good agreement between experimental and predicted curves shows that the assumption of viscoelastic behavior used in this study is practicable. This can be verified using the values of R -squares. Therefore, it can be confirmed that the 4-element Burgers model associated with the Weibull distribution equation in Eqs. (3) and (4) and Levenberg-Marguardt algorithm is suitable to solve the material model parameters of hot compression creep-recovery behavior in the transverse direction of bamboo culm. The model used in this study also shows good agreement with the models of other viscoelastic materials. For example, the analytical study for the polypropylene/multi-walled carbon nanotube composites by Jia *et al.* [15], bamboo fiber high-density polyethylene (BF/HDPE) composite materials by Xu *et al.* [17], polymeric materials by Fancey [19], and white spruce (*Piceaglauca* (Moench.) Voss.) wood by Moutee [20].



The 4-element Burgers model:
$$\varepsilon(t) = \frac{\sigma}{E_M} + \frac{\sigma}{E_{KV}} \left[1 - \exp\left(-\frac{E_{KV}}{\eta_{KV}} t^n\right) \right] + \frac{\sigma}{\eta_M} t^n$$

Figure 10 The 4-element Burgers model prediction and experimental data for creep strain responses at different applied stress with the time. (a) 1 h applied stress, (b) 2 h applied stress, (c) 3 h applied stress, and (d) 4 h applied stress.



The Weibull distribution equation:
$$\varepsilon_r(t) = \varepsilon_{KV} \left[\exp \left(- \left(\frac{t-t_0}{\eta_r} \right)^k \right) \right] + \varepsilon_p$$

Figure 11 The Weibull distribution equation prediction and experimental data for recovery strain responses at different applied stress with the time. (a) 1 h recovery time, (b) 2 h recovery time, (c) 3 h recovery time, and (d) 4 h recovery time.

Conclusions

In this present work, investigation of the transverse creep-recovery behavior of the bamboo culm in a hot compression test at different applied stress was the main aim. Experimental results were used to construct the constitutive relationship of the bamboo culm. The 4-element Burgers model and the Weibull distribution equation were used to characterize the observed creep-recovery data. The result showed that the constitutive model described fairly well the variation of transverse creep-recovery deformation. It can be shown in this study that the Levenberg-Margardt algorithm is suitable to solve these material model parameters of the bamboo culm. This algorithm is good in predicting the nonlinear viscoelastic behavior under compression load conditions in the transverse direction of bamboo. Both the 4-element Burgers

model associated with the Weibull distribution and Levenberg-Marquardt algorithm were used to predict the transverse creep behavior of the bamboo wood under thermal softening conditions.

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