

DEVELOPMENT OF CREEP MODELS FOR GLUED LAMINATED BAMBOO USING THE TIME-TEMPERATURE SUPERPOSITION PRINCIPLE

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(Received August 2014)

Abstract. This paper describes the development of creep models for glued laminated bamboo (GLB) using the time-temperature superposition principle (TTSP). Creep (15 min) and recovery (45 min) data were obtained at constant temperature levels ranging from 25 to 65°C. The moisture contents of specimens for testing were dry, 7% and 12%. The individual curve at each temperature was plotted against the log-time axis to obtain a master curve. A nonlinear regression analysis was used to estimate the model parameters. Then the individual temperature master curves were shifted again to a reference MC to construct an overall master curve using time-temperature-moisture principle. The relation of temperature and moisture shift factors $\log_a(T, M)$ to temperature (T) and MC (M) was analyzed. The results show that the TTSP was successfully applied to GLB tested at different moisture contents.

Keywords: Glued laminated bamboo, time-temperature superposition, dynamic mechanical analyzer, creep.

INTRODUCTION

Glued laminated bamboo (GLB) are being increasingly used in different engineering fields due to their inherently high specific mechanical properties, however, widespread use has been

limited due to an insufficient understanding of time-dependent behaviors, attributing to their viscoelastic nature. Creep, in particular, represents the long-term physical properties critical to product acceptance in many engineering applications.

To determine the long-term behavior of GLB, one can either conduct experiments for an

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extended period of time or use the principle of time-temperature superposition principle (TTSP) to construct a master curve from a number of short-term creep tests at different temperatures (Williams et al 1955). The basis of the principle is that temperature accelerates the time-dependent response of the material. The time-dependent material properties are determined at different temperature levels and shifted horizontally along the log-time axis through a time multiplier (shift factor), until a smooth curve is created. It is called “master curve”, which describes the time dependence of the investigated property at a reference temperature. Many studies have adopted this method for wood and wooden composites (Salmén 1984; Samarasinghe et al 1994; Sun and Frazier 2007; Engelund and Salmén 2011).

A theoretical basis has been developed based on free volume theory for TTSP (Ferry 1980). The temperature shift factors can be calculated based on the free volume concept. When the glass transition temperature of the polymer is chosen as the reference temperature, the temperature shift factor can be determined below T_g by an Arrhenius-type equation (Aklonis and MacKnight 1983; Tissaoui 1996):

$$\log a_T = -\frac{\Delta E}{2.303R} \left(\frac{1}{T} - \frac{1}{T_0} \right) \quad (1)$$

where $\log a_T$ is the horizontal displacement of each curve; a_T is the shift factor; ΔE is the activation energy (kcal/mole); R is universal gas constant (1.987 cal/mole/K); T_0 is the reference temperature and T is the temperature (K) at which the shift factor is desired.

It is known that the relationship between the plateau modulus and temperature is linear:

$$\frac{E_\infty(T_0)}{E_\infty(T)} = \frac{\rho_0 T_0}{\rho T} \quad (2)$$

Using TTSP, the plateau modulus can be expressed as

$$E_\infty \left(T_0, \lg \frac{t}{a_T} \right) = \frac{\rho_0 T_0}{\rho T} E_\infty(T, \lg t) \quad (3)$$

Then, the vertical shift factor (a_v) can be defined as

$$a_v = \rho_0 T_0 / \rho T \quad (4)$$

Unlike rubber, modulus of elasticity of wood, bamboo, and other engineering materials decreased with the temperature increased (Wang 2005). So the modulus should be changed:

$$E_\infty \left(T_0, \lg \frac{t}{a_T} \right) = \frac{\rho T}{\rho_0 T_0} E_\infty(T, \lg t) \quad (5)$$

The density changes little with temperature when the range of experimental temperature is not so wide, so the vertical shift factor (a_v) can be defined as (Zhang 2010)

$$a_v = T/T_0 \quad (6)$$

Ferry (1980) summarized several criteria in the application of TTSP:

1. The shapes of the adjacent curves at different temperatures must match over a substantial range of frequencies/time.
2. The same values of shift factors must superpose all the viscoelastic functions.
3. The temperature dependence of the shift factor must have a reasonable form consistent with experience.

Consequently, the objective of this study is to evaluate the feasibility of this accelerated method and to verify the Arrhenius equation by conducting a series of creep tests under various temperatures and moistures to construct master curves.

MATERIALS AND METHODS

GLB is made by gluing together strands of bamboo to form rectangular cross sections similar in shape and size to conventional lumber (Fig 1). Production of programs can be divided into four sections: dried, dipped, group billet, and pressure solidified. To apply, a commercial urea formaldehyde resin was used for the composite fabrication. The press temperature was 95°C. The lumber is 300 mm × 100 mm × 10 mm. Creep analysis was performed on a TA

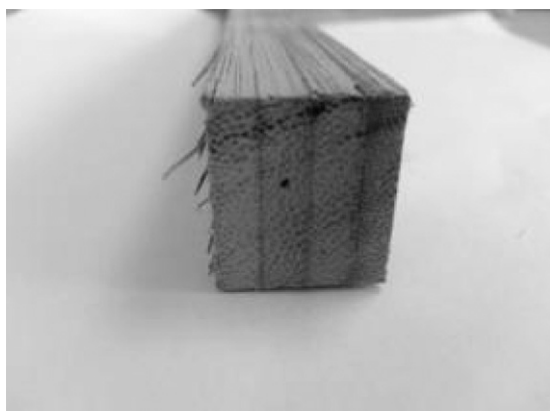


Figure 1. Cross section of glued laminated bamboo.

instrument DMA Q800 using a dry-air purge, and in dual cantilever bending (distance between clamping midpoints = 17.5 mm). Specimens were machined to: 60 mm × 10 mm × 3 mm. All specimens were placed with the veneers perpendicular to the load. They were conducted within the linear response region. Specimens were subjected to isothermal creep segments (15 min in creep; 45 min in recovery; stress = 3.5 MPa) at three MC levels (dry, 7%, 12%) in the temperature range from 25 to 65°C at 10°C intervals; 5 min equilibration periods were inserted between creep segments. Over-dried specimens were dried by oven, and then placed in the dryer for 7 da. The specimens of 7% were placed in the constant temperature and humidity equipment for 7 da. It is hard to reach the MC of 12% through the constant humidity equipment for GLB. Therefore, the specimens were soaked in the water for 2 da at first, and then equilibrated for 1 da.

The separate curves measured at different temperatures, but at common MC, were shifted on the log-time axis to a reference temperature of 25°C. The individual temperature master curves were shifted again to a reference MC of 7% to construct an overall master curve. Six specimens (460 mm × 20 mm × 20 mm) were prepared for

testing modulus of elasticity and rupture (MOR) in three-point bending (GB/T 17657-2013). They are summarized in Table 1.

RESULTS AND DISCUSSION

Creep and recoverable compliances at each temperature were plotted against log-time (logarithm to the base 10) as shown in Fig 2a-b for a typical specimen. Figure 2a-b indicate that the rates of change of creep and recovery increase with temperature. The data for 35°C overlapped with the data for 25°C, which means the differences of effect between the two temperatures are very small.

Creep and recovery compliance master curves, applicable to 25°C, were formed for each

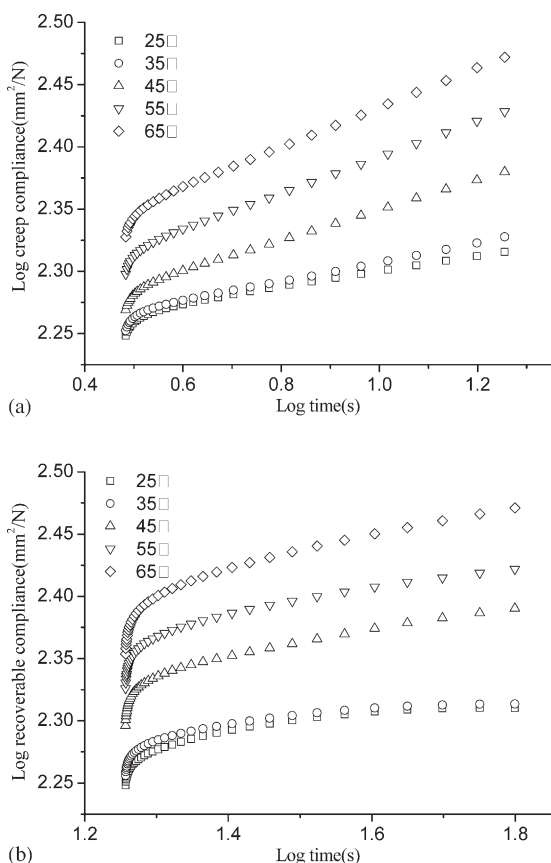


Figure 2. Creep test curves for a typical specimen at MC of 7%: (a) creep and (b) recovery.

Table 1. Material properties of accelerated test specimens.

Specimen	Specific gravity (g/cm ³)	Young's modulus (GPa)	MOR (MPa)
GLB	0.67	9.14	117.91

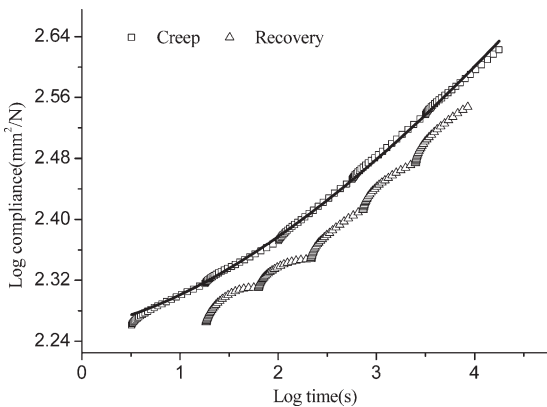
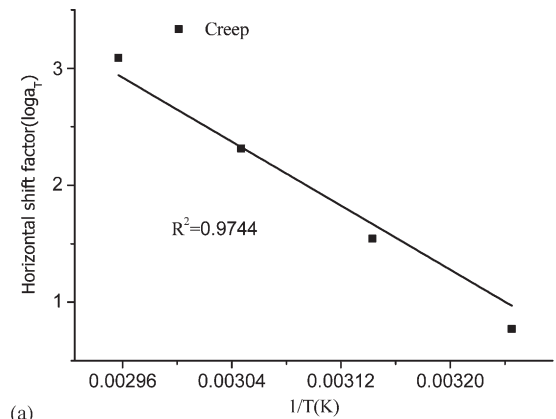


Figure 3. Master curves and power law fit of MC of 7%.

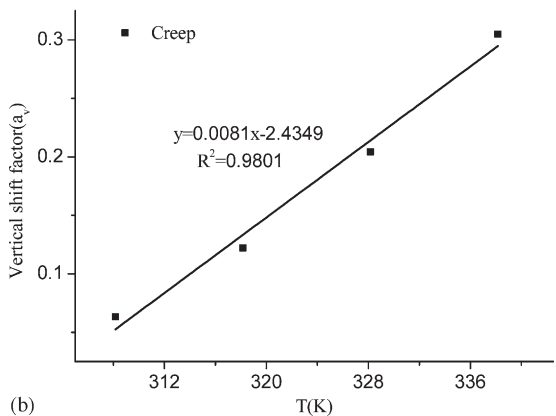
specimen with different MC levels. Creep and recovery master curves are shown in Fig 2. Master curves of Fig 3 were formed by successive joining of creep (or recovery) curves in regions where the slopes were equal by horizontal and vertical shifting. The master curves for a typical specimen indicate that the TTSP can be used to develop long-term creep curves, but not recovery curves. It should be noted that the recovery master curve is not smooth, and it does not meet the criteria for an application of the TTSP.

Since the predicted long-term response was within the glassy response region of wood, the horizontal shift factor should follow the Arrhenius formulation expressed by Eq (1), which states that the relationship between $\log a_T$ and $1/T$ is linear. Also, the vertical shift factor follow Eq (6), which shows that the relationship between a_v and T is linear. It can be seen in Fig 4 that the two linear regression analyses of MC of 7%. The coefficients of determination (R^2) for creep behavior of horizontal shift factor at three moisture contents are 0.97. The slope from this line can be used to obtain an estimate of activation energy ΔE . The values are presented in Table 2, and it can be seen that ΔE increased with the rise of humidity. These results indicate that the Arrhenius formulation was satisfied for creep behavior of GLB.

The creep and recovery master curves were fitted to the power law equation (Eq 7) using a non-



(a)



(b)

Figure 4. Temperature shift factors for 7% MC.

linear fitting procedure (OriginPro 8.5, American OriginLab Corporation) (Bond et al 1997):

$$D = D_0(1 + bt^k) \tag{7}$$

where D_0 is the initial compliance, b and k are estimated parameters, t is the time. The model parameters are presented in Table 2.

Then, the individual temperature master curves were shifted again to a reference MC of dry to

Table 2. Model parameters and activation energy for creep.

MC (%)	Creep master curve			
	D_0 (mm ² /N)	b	k	ΔH (kcal/mole)
Dry	135.05	0.31	1.11	30.57
7	160.69	0.08	1.92	31.33
12	158.21	0.23	1.69	37.06

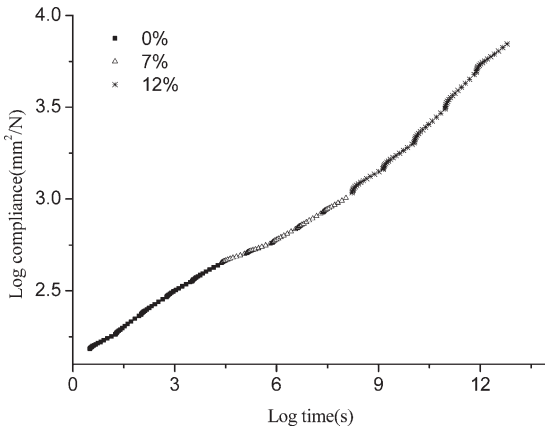


Figure 5. The master curve shifted to a reference temperature of 25°C and a MC of dry.

construct an overall master curve (Fig 5). It created by the time-temperature-moisture superposition allows the prediction of the creep compliance (Maksimov et al 1974; Wolcott 1989). Furthermore, with the experimentally derived temperature and moisture shift factors ($\log_a [T, M]$, Fig 6), the master curve can be shifted to different temperature and moisture levels with the reduced variable principle. The shifted master curve can predict the viscoelastic properties of the flakes at varying conditions. The fitted temperature and moisture shift factor surface is shown in Fig 6.

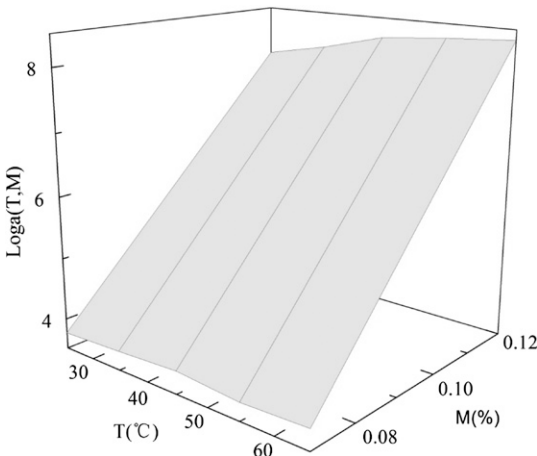


Figure 6. Dependence of $\log_a (T, M)$ on temperature and MC.

CONCLUSIONS

- (1) The TTSP can be used to develop creep master curves for predicting of GLB, but not recovery curves. The creep compliance curves were plotted against log-time. All compliance curves required vertical shifting in addition to the horizontal shifting. The selected master curves were represented by power functions using a nonlinear regression analysis technique.
- (2) The activation energy of creep of specimen within the temperature range of 25-65°C was 30.57 and 37.06. The values increase with the rise of humidity.
- (3) With temperature and moisture shift factors, an overall master curve can be shifted to different temperature and moisture levels. The time, temperature, and moisture effects on the GLB were included in this curve. The shifted master curve can predict the viscoelastic properties of the flakes at varying conditions.

ACKNOWLEDGMENTS

This project was supported by the China Department of Biomaterials, International Center for Bamboo and Rattan. The authors would like to express sincere thanks to State Forestry Administration Key Laboratory for Bamboo and Rattan Science and Technology. This research was funded by the National Scientific and Technical Supporting 12th Five-year Plan Project (2012BAD23B0203) and the National Forestry public Welfare Scientific Research Program (201204701).

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