MECHANO-SORPTIVE CREEP MECHANISM OF BAMBOO-BASED PRODUCTS IN BENDING

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(Received October 2016)

Abstract. The phenomenon of mechano-sorptive (MS) creep is critical to structural design. It can result in greater deformation and earlier failure under cyclical moisture conditions. This study focuses on the MS bending creep of bamboo laminated veneer lumber (BLVL) and glued laminated bamboo (GLB). All samples were found to exhibit a large creep increment during moisture cycling compared with samples under constant humidity conditions. Relative creep increased with adsorption and showed a slight increase with desorption. However, in the modified creep, subtracting the elastic and shrinkage-swelling components of the total creep, a substantial decrease in absorption for the BLVL was observed, whereas the adsorption increased for the GLB. The creep limit of BLVL was 1.293 mm, and GLB's limit was 3.363 mm.

Keywords: Mechano-sorptive creep, bamboo laminated veneer lumber, glued laminated bamboo.

INTRODUCTION

Creep can be divided into two categories, namely viscoelastic creep and mechano-sorptive (MS) creep. Viscoelastic creep is a deformation over time at a constant stress and constant environmental conditions. MS creep occurs at RH conditions, it is directly related to the change in moisture and mechanical stress in the material. It has been known since 1960 that the creep of

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Wood and Fiber Science, 49(3), 2017, pp. 1-8

wood depends primarily on the variation of MC and only slightly on loading time (Armstrong and Kingston 1960). MS creep contains two phenomena: shrinking and swelling, and a coupled effect of mechanical load and changing water content (Srpcic et al 2009). It results in greater deformation or earlier failure than that of viscoelastic creep under the same loading conditions. Due to the complex nature, variables, and effects of the phenomena related to mechano-sorption creep, much research has been focused on understanding what causes it to act the way it does (Grossman 1976; Hoffmeyer and Davidson 1989; Nielsen 2005).

The influence of annual ring width, slope of the grain, knots, compression wood, density and modulus on solid woods MS creep was monitored by Bengtsson (2001). The results showed that the relationship between relative creep and elastic modulus had a strong correlation. For timber, the influence of MC range, material size, and wood type has also been researched. The greater the moisture differential in each RH cycle, the higher the amount of creep produced (Armstrong and Christensen 1961). To investigate the effect of specimen size to creep behavior, two different sizes of beams were researched (Schniewind and Lyon 1973). The results showed that the size does determine the time to failure in cyclic variation conditions. Bodig and Jayne (1993) also stated that though the larger pieces of wood members are less sensitive to moisture cycling than smaller pieces of wood, it should be considered for design when structural wood members are exposed to cyclic moisture conditions. It has been shown that the relative creep of fiberboard was some five times that of the relative creep in solid wood. This means material type is a very important factor for MS behavior.

Engineered bamboo products, bamboo laminated veneer lumber (BLVL) and glued laminated bamboo (GLB) have been widely used in construction. In many situations, they are subjected to loads during variable RH. Bamboo possesses a similar chemical composition to wood in terms of cellulose and lignin content and crystallinity, which leads to similar creep mechanisms (Jennifer et al 2014). Therefore, the performance of bamboo relies heavily on its MC (Genevaux and Guitard 1988; Vaessen and Janssen 1997). It is necessary to avoid MC changes during long-term or short-term mechanical testing. In the present study, BLVL and GLB were stressed in bending to establish the relationship between relative creep and humidity during desorption. The MS creep behavior between BLVL and GLB were also compared under same conditions.

MATERIALS AND METHODS

Materials

The Bamboo species used was Cizhu (*Dendrocalamus farinosus*) and was grown in Sichuan Province, China. A commercial phenol formaldehyde resin obtained from the Taier Corporation (Beijing, China).

An untwining machine was used to broom and roll the bamboo strips into a laminated sheet. When the bamboo bundle sheets dried to 10 ± 2% MC, they were consolidated and then hot pressed into BLVL.

GLB was made by gluing together strands of bamboo to form rectangular cross sections similar in shape and size to conventional lumber. The press temperature was 95°C. The size of all specimens was 300 mm × 20 mm × 10 mm. Based on GBT 17657-2013, average density, bending MOR, and MOE of the two boards were determined (Table 1). The MC of specimens was 10 ± 2%. For each board, five specimens were tested in static bending load to obtain MOR and MOE.

Methods

Creep in variable humidity. There were two group bamboo products in this study. One group was BLVL, the other was GLB. Each group consisted of three boards (300 mm × 300 mm × 10 mm). Five creep test specimens (300 mm × 20 mm × 10 mm) were cut from

Table 1. Mechanical properties of two bamboo-based boards.

Material type	Density (g/cm^3)	MOE (GPa)	SD	MOR (MPa)	SD
BLVL	0.90	24.15	1.25	193.65	8.8
GLB	0.75	9.14	2.21	117.91	11.7

SD, standard deviation.

these boards. All specimens were selected from the middle of board. Three specimens were prepared to measure bending creep perpendicular to the adhesive layer; the other two specimens were used to measure pure swelling and shrinkage under changing RH. The same measurements were performed on the loaded specimens. The creep test based on ASTM D 6815. It was performed in an airtight chamber (Fig 1), in which RH was conditioned with supersaturated salt solutions, $MgCl_2$ and K_2SO_4, corresponding to 33% and 90% RH, respectively (Hong and Arima 1998; Zhou and Masami 1999). Two hygrometers were used to measure RH number inside and outside airtight chamber.

A three-point bending test where a 30% ultimate load was applied to the specimens. The ratio of span to depth was 18:1. The deflection of the bending test was recorded at 0.25, 0.5, 1, 2, 5, 10, 30, 60, 120 min, after which the test was performed at 5-h intervals. The total period was 768 h. Creep was measured by a dial gauge with an accuracy of 0.001 mm. The specimens were also placed on the frame to measure their swelling and shrinking. The creep tests were performed with a varying RH between 33% and 90% (±2%) in which one cycle length was 192 h (Fig 2). A total of four cycles were performed per.

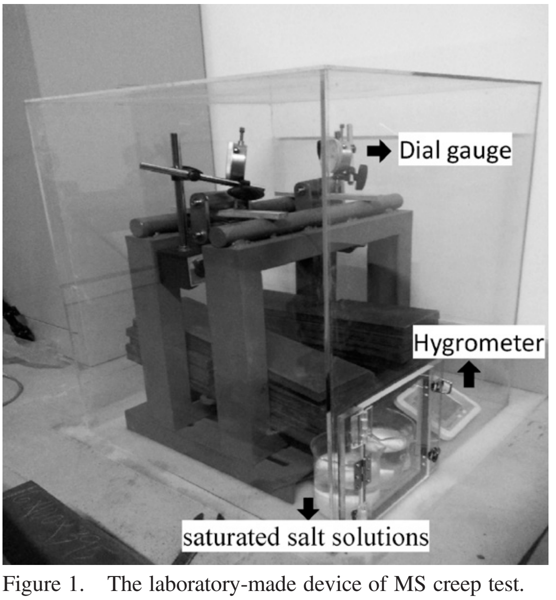

Figure 1. The laboratory-made device of MS creep test.

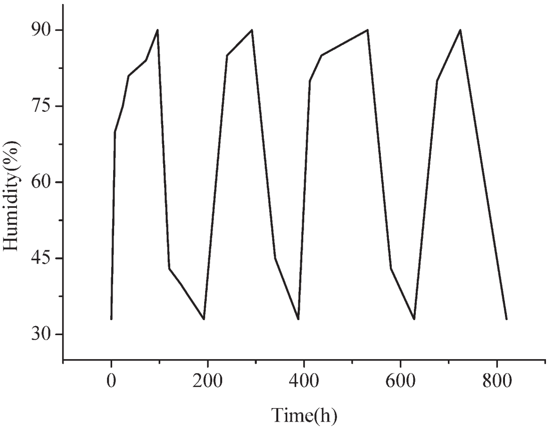

Figure 2. The humidity fluctuation of MS test.

Creep in constant humidity. For each species, three specimens were tested at 65% RH and 20°C environment in the same air-tight chamber. The experimental period was 33 da. The obtained data served as a control and were compared with the data from the variable humidity study.

RESULTS AND DISCUSSION

Comparison of Creep under Variable and Constant Conditions

When timber is loaded in variable humidity conditions, viscoelastic and MS creep both occur, which makes it difficult to separate to two forces. Therefore, we compare the creep between two different conditions at first. The first condition was a constant condition where deflection was measure over time resulting in a creep curve (Fig 3).

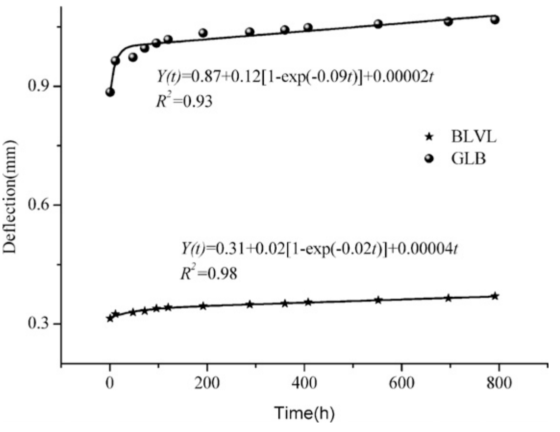

Figure 3. Creep deflection at constant RH of two bamboo-based boards.

Burgers model is commonly used to describe the primary and secondary creep and is capable of fitting a curve to the data. It can be written as (Pierce et al 1979):

$$Y(t) = \beta_1 + \beta_2[1 - \exp(-\beta_3 t)] + \beta_4 t \quad (1)$$

β_1 represents initial elastic deformation; β_2 and β_3 represent the delayed elastic or recoverable creep component; β_4 represents the flow component or irrecoverable creep.

The relative coefficient was 0.98 for BLVL and 0.93 for GLB. This indicated that Burgers model fit these two boards very well. β_1 of BLVL was smaller than that of GLB (Table 2), which meant that the elastic deformation of GLB was larger than that of BLVL. In addition, the creep deflection of GLB increased much more than BLVL. It was observed that the creep resistance of BLVL was more favorable than that of GLB. This result was similar to Nielsen (2000), who suggested that creep cracks prefer to propagate in regions of composites which were more flexible than other regions. Therefore, for engineered bamboo, less stiffness results in more creep.

Table 2. Creep coefficients of Burgers model.

Material type	β_1	β_2	β_3	β_4	Correlation coefficient
BLVL	0.31	0.02	0.02	0.0004	0.98
GLB	0.87	0.12	0.09	0.0002	0.93

The initial and final deflections were obtained (Table 3), as expected the deflection under varying humidity was greater than at constant humidity (Fig 4). For BLVL, creep growth rate at variable humidity conditions was 1.7 times greater (30.9/17.8) that at constant humidity. Similarly, for GLB, it was 3.3 times (67.7/20.68). The deflections fluctuation was caused primarily by variable swelling and shrinking of the specimens in response to the variation of the ambient RH. In some literature, researcher indicated that the creep in low MOE specimens was more affected by humidity variation than in the case of higher MOE specimens (Robert 1994). Therefore, MOE is an important variable to MS creep.

MS Creep

Creep is quantified by relative creep in this article, where relative creep is defined as the increase in deflection at time *t*, expressed in terms of the initial elastic deflection, as follows:

$$\phi(t) = \frac{\eta(t)}{\eta_0} - 1 \quad (2)$$

in which η_0 and $\eta(t)$ signify the initial deflection and the deflection of the board, respectively, after *t* days from loading.

For each board, the relative creep of four separate cycles was different (Fig 5a). During cyclic moisture sorption, the behavior of relative creep was closely related to the RH. The relative creep of the two board types substantially increased during the first adsorption and slightly during subsequent adsorptions. The relative creep of BLVL gradually increased during desorption; however, relative creep of GLB increased slowly during desorption and was unchanged in the fourth desorption cycle.

The total creep under changing RH is assumed to consist of four main components: 1) elastic component, 2) pure creep under constant RH conditions, 3) shrinkage-swelling behavior, and

Table 3. Creep deflection of two bamboo-based boards at constant and variable RH.

Material type	Environment humidity	Initial deflection (mm)	SD	Final deflection (mm)	SD	Deflection change (%)
BLVL	Variation	0.905	0.13	1.185	0.08	30.90
	Constant	0.314	0.02	0.370	0.01	17.83
GLB	Variation	1.805	0.17	3.027	0.12	67.70
	Constant	0.885	0.10	1.068	0.21	20.68

4) MS portion. The relationship can be modeled as,

$$\varepsilon = \varepsilon_e + \varepsilon_w + \varepsilon_v + \varepsilon_m \quad (3)$$

where ε = total creep; ε_e = instantaneous deflection; ε_w = deflection due to the shrinkage-swelling behavior; ε_v = pure creep; ε_m = MS deflection.

In this model, pure creep and MS creep are difficult to separate; therefore, pure creep and MS creep were considered a single component (Wang 2005), which can be referred to as modified creep. ε_e and ε_w were measured in testing. Therefore, the relationship known as modified creep can be described as:

$$\varepsilon_v + \varepsilon_m = \varepsilon - \varepsilon_e - \varepsilon_w \quad (4)$$

The modified creep during the first adsorption substantially increased (Fig 5b). There was a statistically significant difference between the first cycle and the other three cycles of the BLVL. In subsequent moisture changes, desorption of moisture caused further increases in deflection, whereas adsorption led to a progressive decrease. The overall trend follows that described by Armstrong and Kingston (1962) in tests on wood beams of hoop pine.

The relative deflection appreciably increased in adsorption while showing a slight increase in desorption for the GLB. These behaviors were consistent with observations of Douglas-fir (Wu and Milota 1995), cedar beams (Ozawa et al 1995), and so on. These results showed

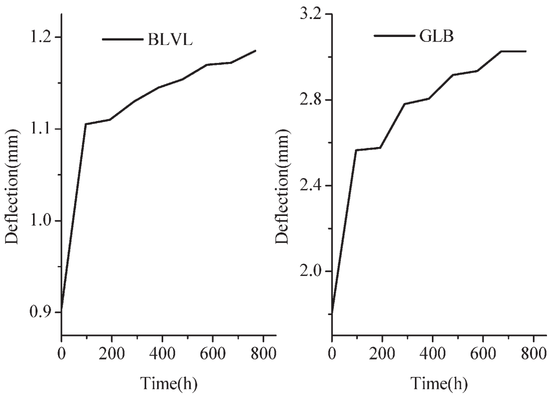

Figure 4. Creep deflection under cyclical RH conditions of two bamboo-based boards.

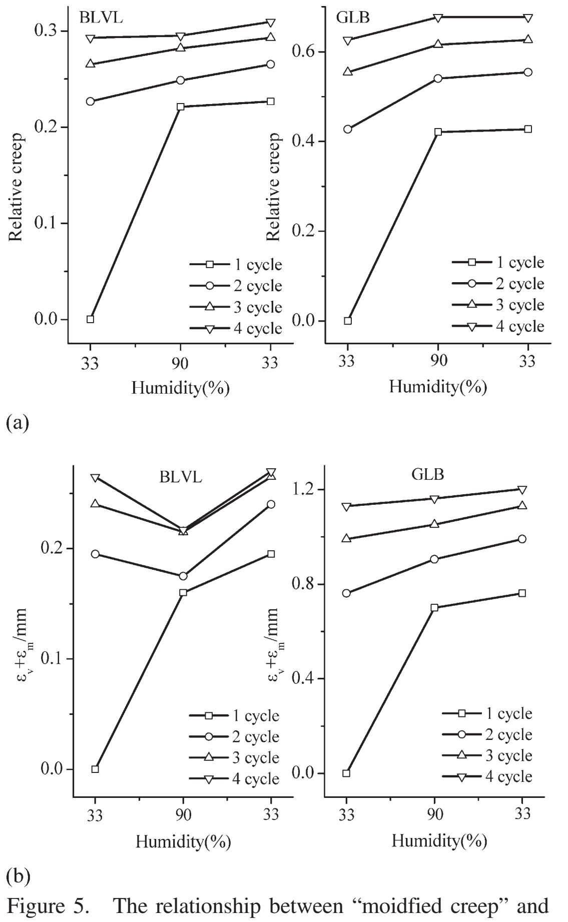

Figure 5. The relationship between "moidfied creep" and humidity of two boards.

that adsorption led to greater MS strain than did desorption at a given stress.

Due to molecular mobility theory, the hydrogen bonds between hydroxyl groups of adjacent cellulose chains and water molecules would be broken when MC changed. Under external stress, relative displacement between segments may arise, which result in an appreciable deformation (Zhou and Masami 2000). However, during subsequent adsorption, there is an obvious decrease in the relative creep in BLVL. This decrease can be regarded as a recovery. Some researchers discussed the recovery as a combination of molecular level with macromolecular level. They suggested that the recovery is related to the memory of initial shape of the cell wall. The microfibrillar framework keeps the memory and matrix softening to recover its initial shape. Therefore, in subsequent adsorption, there are two parts in deflection. One part is relative displacement for increasing deformation by mobility of molecules and the other part is the recovery to initial shape. If the MS compliance recovers completely, creep behavior shows a trend similar to BLVL, whereas if there is no complete recovery the creep behavior will have a trend similar to GLB.

The main reason for the different recover ability or creep trend is due to the structure, the two board types are clearly constructed differently. The glue is impregnated into the BLVL, but the surface is coated for GLB. In these two boards, the action of glue lines to impede moisture migration would be expected to restrain the development of creep, since internal moisture changes. In addition, different glue types result in different moisture migration and different restrain ability.

Creep Limit

Creep work is time consuming, which gives it an advantage when making a material model for predicting the effects of moisture variations. Many of such models can be found in literature (Grossman 1976; Hunt and Shelton 1987). Hunt showed evidence that a stable limiting state of creep could be obtained by a suitable load-humidity history.

The MS creep can be expressed in the form of an infinite series when the RH is cyclical.

$$\varepsilon = \sum_{n=1}^{\infty} f(\mathrm{d}W, n, \sigma) \qquad (5)$$

Where ε = strain; dW = moisture fluctuation; n = transformation frequency; σ = stress.

When the infinite power series is converging, creep will reach a limit. As a general rule, the material's strain response to stress is linear at lower stresses (less than 50% of the ultimate stress in bending) (Hunt and London 1989). This means that irreversible destruction in the material occurs at lower stresses and then the creep limit is obtained. The creep increment of two boards gradually decreases with time (Fig 6). Therefore, there will be a creep limit of the two board types as the number of cycles is increased.

The total deflection under constant pressure σ can be expressed as,

$$J = J_e + J_0 + \sum_{i=1}^{n} J_i \qquad (6)$$

where J = total deflection after n cycles; J_e = elastic deformation; J_0 = pure creep.

The analysis from Gibson and Ashby (1988) shows that there are many reasons for the creep

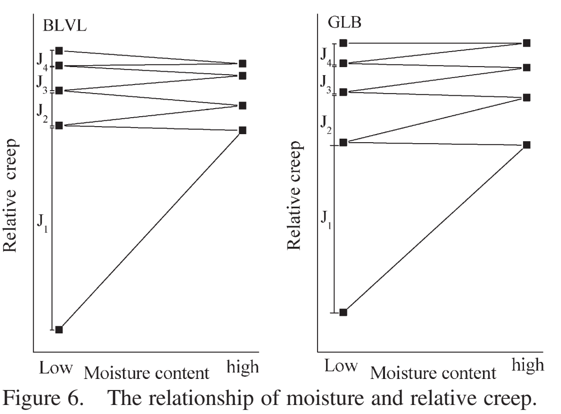

Figure 6. The relationship of moisture and relative creep.

Table 4. Creep limit and variables.

Variables	BLVL	GLB
J_e	0.900	1.800
J_0	0.022	0.055
J_1	0.187	0.906
J_2	0.184	0.602
N_1	979.601	621.775
N_2	20.112	20.420
J_∞	1.293	3.363

J1, J2: MS creep; N1, N2: cycling coefficient.

limit, one of the most common reasons is based on the recombination of molecular bonds by moisture variation. Therefore, the creep limit determined by exponential equations using a more accurate dual-exponential equation can be obtained (Hunt and Shelton 1988).

$$J = J_e + J_0 + J_1(1 - \exp(-n/N_1)) + J_2(1 - \exp(-n/N_2)) \quad (7)$$

where J_1, J_2 = MS creep; N_1, N_2 = cycling coefficient.

Therefore, creep limit can be expressed as:

$$J_\infty = J_e + J_0 + J_1 + J_2 \quad (8)$$

A computer program (OriginPro 8.5) was written to estimate the total deflection and variables of BLVL and GLB. As shown in Table 4, the creep limit of the two board types was 1.293 mm and 3.363 mm.

CONCLUSIONS

Bending creep behavior of BLVL and GLB under cyclical moisture changes was investigated in this study. The following conclusions can be drawn from the results.

1. The creep resistance of BLVL was more favorable than that of GLB.
2. The creep deflection under varying humidity was greater than at constant humidity of all specimens. For BLVL, creep growth rate at variable humidity conditions was 1.7 times greater than at constant humidity. For GLB, it was 3.3 times.
3. MS creep decreased in adsorption but increased in desorption for BLVL over three subsequent cycles. However, the creep of GLB showed an increase in adsorption.
4. A creep limit was obtained after moisture cycling. The creep limit of BLVL was 1.293 mm and GLB was 3.363 mm.

ACKNOWLEDGMENTS

This work was supported by The International Centre for Bamboo and Rattan, China, and was funded by China's "13th Five-Year Plan" to support science and technology project, Grant No. 2016YFD0600900

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