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Creep Behavior of Laminated Veneer Lumber from Poplar Under Cyclic Humidity Changes

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Many academic studies over the years have confirmed that mechano-sorptive (MS) creep is an inherent characteristic of wood. Unlike solid wood, bond lines are introduced into laminated veneer lumber (LVL), creating a laminated structure with different hygroscopicity. What are the effects of these differences on the MS creep of LVL? In this study, three groups of well-matched LVL samples were subjected to four-point bending loading within different relative humidity cycles. For each group, the applied load ranged from 15% to 35% of the short-term fracture load. The results showed that after the first hygroscopic process, LVL showed irreversible expansion (0.11 mm) and a relatively slow moisture adsorption rate. These made it difficult for LVL to show partial creep recovery during the first adsorption process no matter how low the load level was, while solid wood showed partial creep recovery when the load level was ≤ 25%. The following creep behavior of LVL was similar to that of solid wood: partial creep recovery started from the second adsorption stage when a moderate load level was applied.

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INTRODUCTION

Wood exhibits dramatic creep behavior during changes in relative humidity, and this phenomenon is called mechano-sorptive creep. The phenomenon was first discovered and reported by Armstrong and Christensen (1961). Grossman (1976) summarized the various phenomena of mechano-sorptive creep. Deflection increases during the first adsorption and for all of the desorption process, while there is partial deflection recovery during a subsequent adsorption phase. The mechano-sorptive creep is not directly dependent on time but on the change of the humidity. Since then, numerous investigations have been conducted on the topic (Nakanao 1999; Zhou *et al*. 1999; Navi and Stanzl-Tschegg 2009; Montero *et al*. 2012). A lot of theories and models have been proposed to explain its mechanism at various levels such as molecular level (Gibson 1965; Hunt 1984; Van der Put 1989), microfibril structure (Boyd 1982; Hoffmeyer and Davidson 1989), and swelling and shrinkage effects (Liu 1993; Srpčič *et al*. 2009). However, the cited models are insufficient to explain the various phenomena, especially the partial recovery.

Most of the related experimental work has been performed on solid wood specimens, and the results are therefore not completely comparable to wood-based panels that have more complex structures. Laminated veneer lumber (LVL), an engineered wood product assembled by multiple layers of thin wood along the grain direction using

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adhesives, has been widely applied to structural members for transient or long-term loading as an alternative of solid wood due to the lack of high quality of solid wood (Davies and Fragiacomo 2011). The structure and hygroscopicity of LVL are different from those of solid wood due to the presence of a bond line. What represents the difference between the mechano-sorptive creep behavior of LVL and solid wood? In the authors' previous study, the results showed that the solid wood presented a certain degree of recovery during the first adsorption process under a low level of loading (Huang 2016). Under the cyclic variation of relative humidity (RH), there was an amplified load effect in creep, which resulted in a rapid increase of the viscoelastic creep rate at the first adsorption process, thus veiling the pseudo-recovery. As for LVL, it is of interest to find out whether partial creep recovery can be observed in the first humidifying stage. Thus, in this study, the creep behavior of LVL from poplar under cyclic moisture changes was investigated. Then, a comparison was made between the hygroscopicity and mechano-sorptive creep of LVL and poplar wood.

EXPERIMENTAL

Materials

Poplar (*Populus* L.) veneers (500 mm × 500 mm × 1.5 mm) with an air-dry density of 0.394 g cm^{-3} and moisture content of 8.7% were sourced from Da Feng Yuan Quan Wood Industry Co., Ltd. (Xuzhou, China). Phenol formaldehyde (PF) resin was purchased from Yunnan Ding Tou Hong Co., Ltd. (Kunming, China). The mole ratio of phenol to formaldehyde was 0.8:1, and the resin content was 52%. To compare the creep of LVL with that of solid wood, the authors quoted data of poplar that was referred to as specimen "C-25%" in the authors' previous paper (Huang 2016).

LVL preparation

A total of 12 pieces of veneers with uniform thickness and without defects, such as knots and wormy parts, were selected from 50 pieces of veneers. Then, they were in half cut rectangle veneers with a length of 450 mm and width of 250 mm. After adding 20% flour fillers (Yunnan Ding Tou Hong Co., Ltd., Kunming, China) to the PF, the veneers were gummed, and the glue spread was 260 g m^{-2}. Four layers of veneers were assembled along the grain. After sizing and assembly, the veneers were displayed for a short time and then placed into the hot press (Hongyuan Jun Machinery Co., Ltd., Qingdao, China). The pressure was 1.2 MPa, the temperature was 130 °C, and the time was 10 min. The physical properties of six LVL plates prepared by the above hot-pressing process are listed in Table 1.

Table 1. Physical Properties of Six LVL Plates

Serial Number	Density (g cm^{-3})	Thickness (mm)	Compression Ratio (%)
1	0.493	5.1	15
2	0.507	5.09	14
3	0.503	5.14	16
4	0.52	5.17	16
5	0.503	5.11	15
6	0.505	5.13	15

Approximately 200 samples with dimensions of 110 mm (parallel to grain) ×10mm×5mm were cut from six LVL plates with dimensions of 450mm×250mm×5mm (length × width × thickness). These specimens were then conditioned for more than 1 week in a chamber at 20 °C and under 42% RH before utilization.

Before selecting specimens, the densities of all specimens were calculated by weighing and measuring their dimensions. At the same time, all the specimens were tested under four-point bending in their elastic range. The modulus of elasticity (MOE) was calculated by force-displacement curve. Thirty samples with similar size, density, and modulus of elasticity (MOE) were chosen. Six of them were tested under short-term fracture load in four-point bending tests. The bending test of MOE was implemented using a bench-top material tester (EZ Test; Shimadzu, Kyoto, Japan) (the span was 100 mm and the crosshead down-speed was 4 mm min^{-1}). The tester was enclosed in an air-controlled room to keep the RH constant during testing. The modulus of rupture (MOR) test lasted until the sample was broken. The average value of the six specimens was 255 N with a coefficient of variation of 4.7%. According to the different RH (Table 2), the rest of the 24 specimens were subdivided into 3 sets (A, B, and C). In each set, six samples were prepared for creep tests, and the detailed parameters of LVL are shown in Table 3. The other two samples were used for MC measurement during the creep tests.

Table 2. Designed RH Cycles for Specimens from Different Groups

Specimen group	RH[a] cycles
A	42-65-42%
B	42-80-42%
C	42-89-42%
[a] RH: relative humidity	

Table 3. Material Parameters of Each Group of Specimens (8 Specimens per Group)

Material Parameters	Group C			Group B			Group A		
	Min[a]	Max[b]	Mean[c] (± SD[d])	Min	Max	Mean (± SD)	Min	Max	Mean (± SD)
MOE[e] (MPa)	9933	10648	10186 (221)	10420	10742	10554 (102)	10226	10763	10534 (173)
Density (g cm^{-3})	0.50	0.52	0.51 (0.01)	0.50	0.51	0.51 (0.01)	0.49	0.52	0.51 (0.01)
[a] Min: minimum value; [b] Max: maximal value; [c] Mean: mean value; [d] SD: standard deviation; [e] MOE: modulus of elasticity									

Methods

Creep test

The creep tests were performed in a thermostatic-humidistat cultivating chamber (Binder KMF720; Binder, Tuttlingen, Germany) with a temperature of 20 °C and RH of 42% within an air-conditioned room (Fig. 1). The creep specimens from group A were placed on a frame with a span of 100 mm inside the chamber, and then every two specimens were loaded under four-point bending. Three levels of load were applied, which were equivalent to 15%, 25%, and 35% of the short-term fracture load, respectively (Fig. 2).
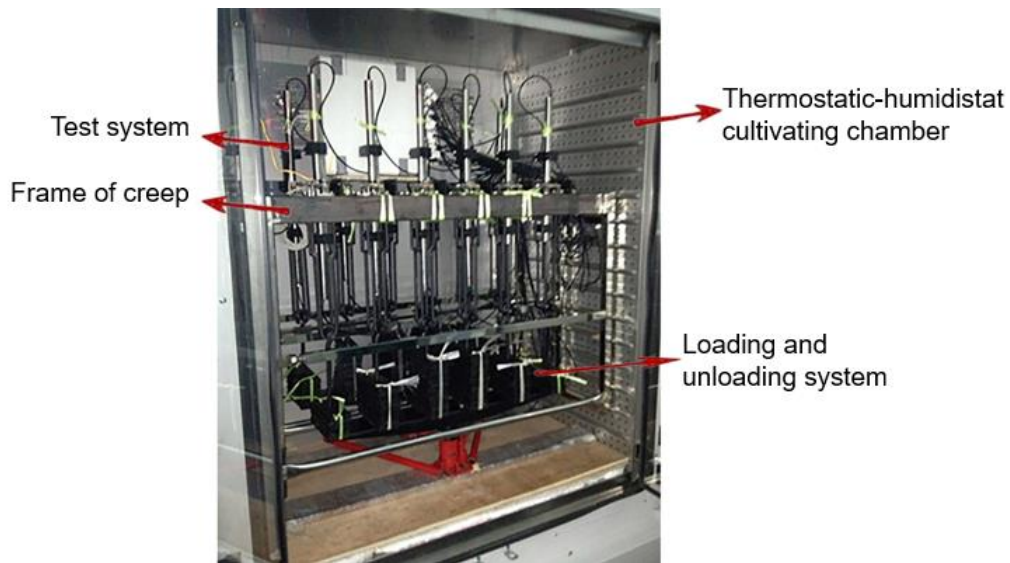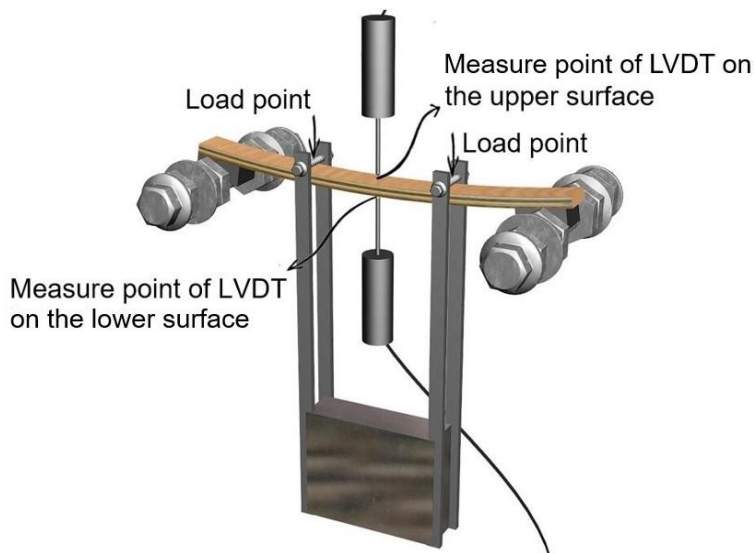
Fig. 1. Design of testing space

Fig. 2. Testing method for creep deflection; LVDT- linear variable differential transformer

The deflection of the LVL sample during the creep test was recorded by two linear variable differential transformers (LVDT). One was set on the upper surface of the specimen, while the other was on the lower face. The data recorded by the latter one was regarded as the actual deflection. The difference between the data of the two LVDT was regarded as the deformation of shrinkage and swelling. Specimens for MC measurement were also laid on the frame close to the creep specimens without loading. After adjusting the RH and temperature of the room to the match those of the chamber, the mass (m, g) of specimens used for MC measurement were weighed immediately using a digital balance (accuracy up to 0.001 g; Worner Lab Equipment, Shanxing, China) after removal from the conditioning chamber at each time interval (1h). After measurement, the LVL samples were placed back into the chamber. The specimens used for MC measurement were oven-

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dried at 103 ± 2 °C and weighed (m_0). Additionally, the MC value (w) was computed according to Eq. 1:

$$w = \frac{m - m_0}{m_0} \times 100 \qquad (1)$$

After the load was applied for 48 h, the RH inside the chamber was changed from 42% to 65%, and then an adsorption process was completed until the adsorption time reached 48 h. Next, the RH was adjusted back to 42%, followed by a desorption process for 48 h. The RH was set back to 42% for another subsequent 48-h desorption process. The aforementioned humidity cycle was repeated 1.5 times. Thus, in a creep test, a total of 2.5 humidity cycles were performed.

The creep tests were performed on the samples from group B and group C with the same procedure, where the RH cycle was 42%-80%-42% and 42%-89%-42%, respectively.

Microsoft Excel software (Microsoft Corporation, v. 2016, Redmond, WA, USA) was used to obtain the relationship between the shrinkage and swelling of LVL and its moisture content.

RESULTS AND DISCUSSION

Creep Behavior of LVL under Cyclic Humidity Changes

There were two specimens in the case of each load level, and one representative sample was selected to draw the deflection curve. Figure 3a presents the dynamic deflection of the samples from group C within the RH cycles from 42% to 89%. Different load levels led to different instantaneous deflection after the load was applied. The difference of their creep deflection after the first adsorption process was also obvious. For example, the deflection of the C-15% sample after the first adsorption reached 1.291 mm, which was 2.6 times the initial instantaneous deformation (0.505 mm). During the subsequent adsorption, its creep behavior was the same as solid wood reported in a previous study (Huang 2016). It first presented a deformation recovery for a while due to the mechano-sorptive effect (MSE), and then its deflection increased again. During the entirety of desorption, the deflection continuously increased. When the load level increased to 25%, C-25% exhibited similar creep behavior. However, when the load level was further raised to 35%, the creep deflection of specimen C-35% increased whether during the adsorption or desorption process. This means that at this load level, the load effect (LE) was much higher than the MSE. In the authors' previous study (Huang 2016), the load level that accounted for this phenomenon of poplar wood was 55%, indicating that the LE varies with materials. According to the experimental results in this paper, LVL is not suitable for an environment with high load and drastic humidity changes. Under the load level of 35%, the creep of LVL after several hygroscopic changes can reach more than 6 times the initial deformation, and further failure is likely to occur. Figure 3b displays the relationship between the MC and deflection of C-35%. According to the change of MC, the deflection could be divided into two stages. One was the stage of dramatic changes in MC in which the relationship between MC and deflection was mostly linear, suggesting that mechano-sorptive creep is closely linked with MC change. The other was the stage in which MC tended to be equilibrium. In this case, the creep deflection was mainly viscoelastic deformation and was no longer related to the MC change.
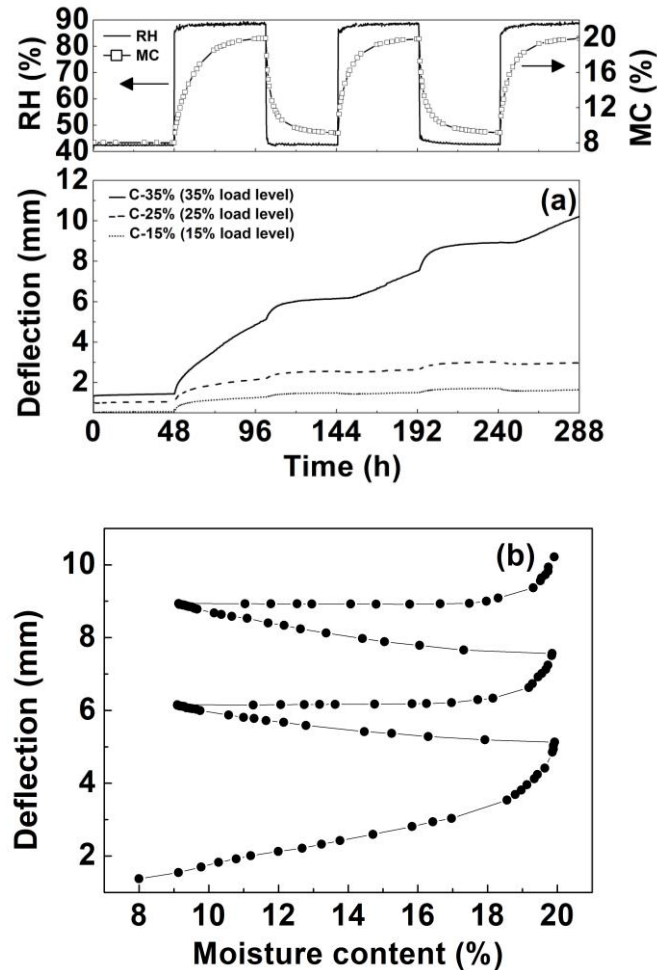
Fig. 3. Creep deflection of specimens from (a) group C in varying humidity from 42% RH to 89% RH and (b) the relationship between MC and deflection of C-35%

Figure 4a shows the defection of the samples from group B within the 2.5 RH cycles from 42% to 80% under different loads. When the load level was 35%, the LE amplified by the MC change far outweighed the MSE during all the sorption phases, leading to the continuous increase in creep deflection. As the load level was reduced to 25%, during the first two moistening phases, the LE of B-25% decreased compared with that of B-35% but was still greater than the MSE, so the deflection kept increasing. However, in the third moistening phase, the time-dependent LE was lower than the MSE. Thus, a partial recovery appeared. As the load level was further reduced to 15%, the LE correspondingly decreased. The MSE did not suppress the LE until the second moistening phase. Therefore, a partial recovery appeared during both the second and third adsorption processes.

A subtle distinction was found between B-25% and B-15% at the third humidifying stage through further comparison. The B-15% sample showed continuous decreased deflection, while the B-25% sample exhibited transitorily decreased deflection and then increased deflection most of the time. This was ascribed to the competition between the different LE and the MSE. As the RH cycles changed from 42% to 65%RH, the MSE that was closely related to MC change became weak. Meanwhile, the LE amplified by the MC change was also diminished.
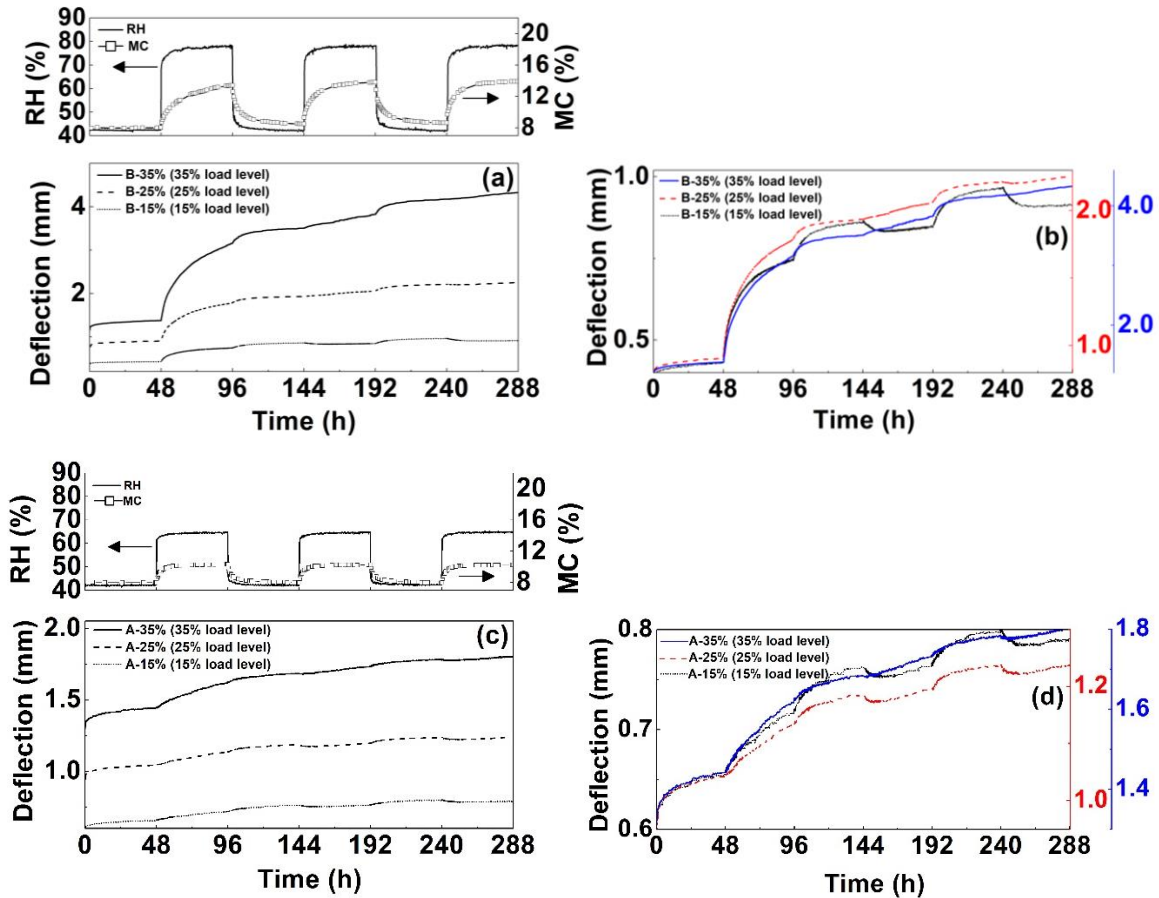
Fig. 4. Creep deflection of specimens from (a) (b) group B in varying humidity from 42% RH to 80% RH and (c) (d) group A in varying humidity from 42% RH to 65% RH

Compared with C-35% and B-35%, A-35% showed deflection recovery at the third adsorption stage. When a lower load level was applied, the LE was further weakened. Accordingly, A-25% and A-15% exhibited creep recovery from the second adsorption process. Additionally, at a 25% load level with RH cycles from 42% to 89%, a creep test was conducted to compare the long-term creep of solid wood and LVL (Fig. 5). Although the final deflection of LVL was different from that of solid wood, there was no essential difference between their creep behavior rules. Their behaviors were determined by the mutual competition, either the boosting or restraint of LE and MSE. At the early humidifying stage, the creep deflection kept increasing because the LE amplified by MC change was greater than MSE. At the later adsorption stage, the LE amplified by MC changes became weak while the MSE remained constant. Thus, the negative creep deflection became greater. The only difference was in the time of occurrence of partial recovery. The LVL showed obvious creep recovery at the third humidifying stage, while the solid wood showed that at the second stage. This indicated that under the same RH change and load level, the LE dominated longer for LVL compared with solid wood. After six cycles of adsorption/desorption processes, the creep deflection of solid wood reached 2.473 mm. Within the same load level and similar physical properties, the creep deflection of LVL was 4.344 mm, which was 1.76 times larger than that of solid wood. Because the decreased and increased deflection induced by MSE could be roughly offset after a

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complete adsorption/desorption cycle (Huang 2016), the great difference in creep deflection between solid wood and LVL comes from the time-dependent viscoelastic creep guided by the amplified LE caused by MC changes.
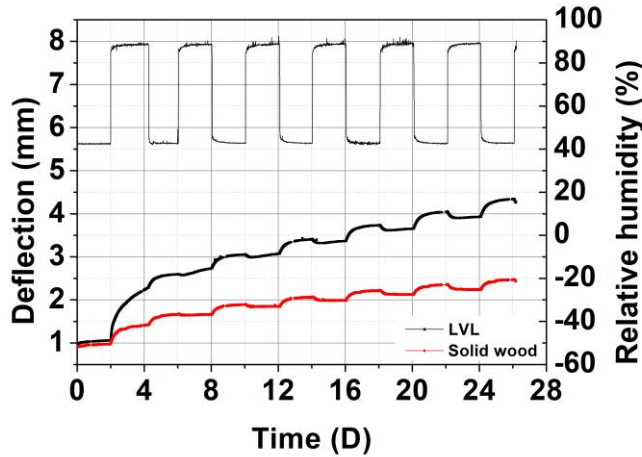

Fig. 5. The supplementary experiment where LVL and solid wood were loaded with a 25% load level in varying humidity from 42% RH to 89% RH (MC: moisture content; RH: relative humidity)
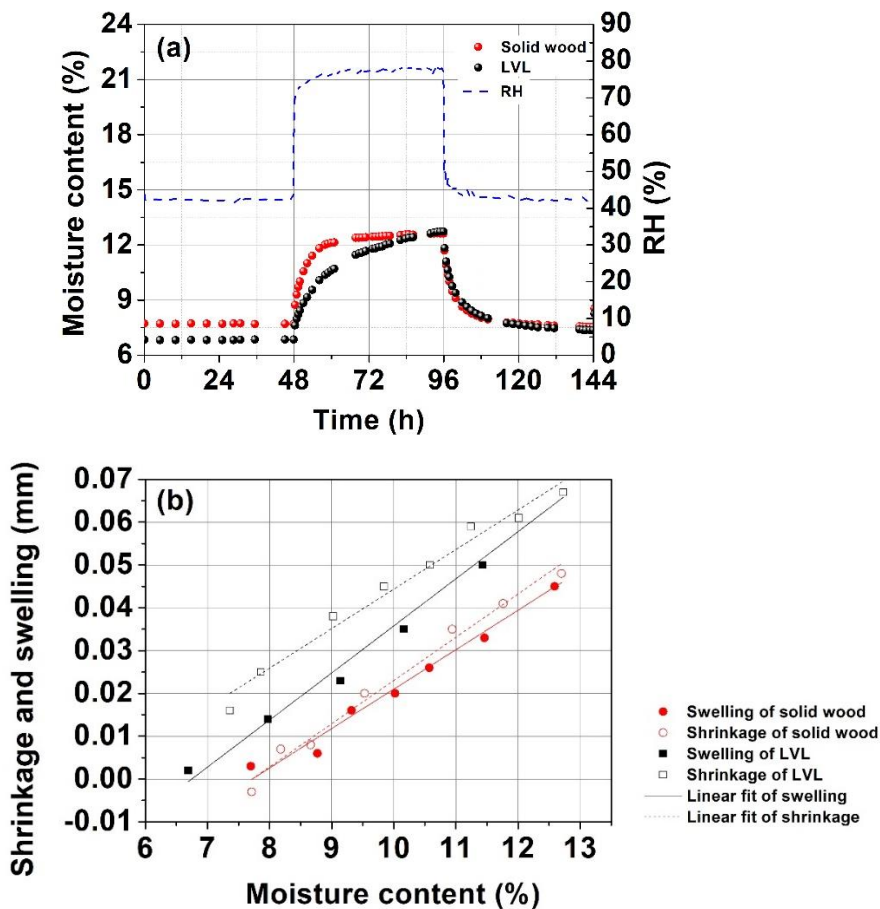

Fig. 6. The MC changes of solid wood and LVL during constant humidity, adsorption, and desorption processes (a) and relationship between the swelling, shrinkage, and moisture content of LVL and solid wood (b)

Comparison of the Hygroscopicity between LVL and Solid Wood

The MC changes of solid wood and LVL during the constant humidity, adsorption, and desorption processes are shown in Fig. 6a. The constant phase of MC was 0 h to 48 h, 48 h to 96 h was the adsorption phase, and 96 h to 144 h was the desorption phase. Under the same environmental conditions, the rate of moisture adsorption/desorption of solid wood was greater than that of LVL. Moreover, the time to reach the end of moisture adsorption/desorption for solid wood was shorter than that for LVL. The bond line of LVL had a certain blocking effect on the moisture migration. Thus, the average mass diffusivity of moisture in LVL was less than that in solid wood. Accordingly, the decreasing rate of the creep deflection induced by MSE for LVL was lower than that for solid wood. Furthermore, both MCs of LVL at the starting point and end point of the adsorption process were not the same as those of solid wood.

Under low humidity conditions, the initial MC of LVL was less than that of solid wood due to the bond line. When the humidity of the environment became higher, the irreversible recovery of LVL provided more space for the moisture absorption, leading to higher final MC compared with solid wood. In other words, under the same conditions, the deformation recovery of LVL caused by the MSE was greater than that of solid wood. This was confirmed by the deflection recovery of LVL and solid wood (0.149 and 0.104 mm, respectively) at the sixth adsorption stage where the time-dependent LE became negligible (Fig. 5).

There was a highly linear relationship between the swelling and shrinkage deformation of solid wood and LVL and their respective MCs (Fig. 6b). It was found that the swelling deformation of solid wood was $y_1 = 0.90 \times MC - 0.07$ ($R^2 = 0.98$), whereas the shrinkage deformation of solid wood was $y_2 = 1.06 \times MC - 0.08$ ($R^2 = 0.98$). In the case of LVL the swelling deformation was $y_3 = 1.09 \times MC - 0.08$ ($R^2 = 0.98$), whereas the shrinkage deformation of LVL was $y_4 = 0.98 \times MC - 0.05$ ($R^2 = 0.98$). Unlike solid wood, due to the existence of the irreversible recovery of hot-pressing compression deformation, the thickness of LVL after shrinkage was necessarily larger than its initial thickness. The swelling and shrinkage deformation of solid wood could almost offset each other. Nevertheless, the swelling deformation of LVL was 0.11 mm larger than its shrinkage deformation. In other words, the compression part of LVL produced a 0.11 mm dimensional recovery in the thickness direction during the first adsorption process. According to the formula for calculating elastic modulus, MOE is inversely proportional to the cube of the thickness. Thus, the thickness recovery sharply decreased the MOE, resulting in the enormous increase in deflection caused by LE. This explained why it was difficult for LVL to show partial recovery during the first adsorption while solid wood could show partial recovery under the same load level.

CONCLUSIONS

1. The law of mechano-sorptive creep of LVL was consistent with that of solid wood. Its creep behavior during varying humidity is still determined by the competition, promotion, or containment between the load effect (including the effect amplified by moisture change) and the mechano-sorptive effect.

2. At the desorption stage, the direction of load effect and mechano-sorptive effect was the same and the creep deflection kept increasing. In the case of adsorption, their direction was opposite. If the load effect outweighs the mechano-sorptive effect, LVL will exhibit increased deflection. Otherwise, there will be a decreased deflection.

3. In this study, even at a 15% load level, the load effect suppressed the mechano-sorptive effect, and the LVL did not exhibit any deflection recovery during the first adsorption process compared with solid wood.

ACKNOWLEDGMENTS

REFERENCES CITED

Armstrong, L. D., and Christensen, G. N. (1961). "Influence of moisture changes on deformation of wood under stress," *Nature* 191(4791), 869-870. DOI: 10.1038/191869a0

Boyd, J. D. (1982). "An anatomical explanation for visco-elastic and mechano-sorptive creep in wood, and effects of loading rate on strength," in: *New Perspectives in Wood Anatomy*, P. Bass (ed.), Nijhoff/Junk Publishers, The Hague, Netherlands, pp. 171-222. DOI: 10.1007/978-94-017-2418-0_8

Davies, M., and Fragiacomo, M. (2011). "Long-term behavior of prestressed LVL members. I: Experimental tests," *J. Struct. Eng.* 137(12), 1553-1561. DOI: 10.1061/(ASCE)ST.1943-541X.0000405

Gibson, E. J. (1965). "Creep of wood: Role of water and effect of a changing moisture content," *Nature* 206(4980), 213-215. DOI: 10.1038/206213a0

Grossman, P. U. A. (1976). "Requirements for a model that exhibits mechano-sorptive behavior," *Wood Sci. Technol.* 10(3), 163-168. DOI: 10.1007/BF00355737

Hoffmeyer, P., and Davidson, R. W. (1989). "Mechano-sorptive creep mechanism of wood in compression and bending," *Wood Sci. Technol.* 23(3), 215-227. DOI: 10.1007/BF00367735

Huang, Y. (2016). "Creep behavior of wood under cyclic moisture changes: Interaction between load effect and moisture effect," *J. Wood Sci.* 62(5), 392-399. DOI: 10.1007/s10086-016-1565-4

Hunt, D. G. (1984). "Creep trajectories for beech during moisture changes under load," *J. Mater. Sci.* 19(5), 1456-1467. DOI: 10.1007/BF00563040

Liu, T. (1993). "Creep of wood under a large span of loads in constant and varying environments," *Holz als Roh- und Werkstoff* 51(1), 63-70. DOI: 10.1007/BF02615022

Montero, C., Gril, J., Legeas, C., Hunt, D. G., and Clair, B. (2012). "Influence of hygromechanical history on the longitudinal mechanosorptive creep of wood," *Holzforschung* 66(6), 754-764. DOI: 10.1515/hf-2011-0174

Navi, P., and Stanzl-Tschegg, S. (2009). "Micromechanics of creep and relaxation of wood. A review COST Action E35 2004–2008: Wood machining – micromechanics and fracture," *Holzforschung* 63(2), 186-195. DOI: 10.1515/HF.2009.013

Srpčič, S., Srpčič, J., Saje, M., and Turk, G. (2009). "Mechanical analysis of glulam beams exposed to changing humidity," *Wood Sci. Technol.* 43(1-2), 9-22. DOI: 10.1007/s00226-008-0196-3

Van der Put, T. A. C. M. (1989). *Deformation and Damage Process in Wood*, Ph.D. Thesis, Delft University of Technology, Delft, Netherlands.

Zhou, Y., Fushitani, M., Kubo, T., and Ozawa, M. (1999). "Bending creep behavior of wood under cyclic moisture changes," *J. Wood Sci.* 45(2), 113-119. DOI: 10.1007/BF01192327