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An experimental study on the flexural performance of laminated glass

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Abstract. This paper reported an experimental study on creep behaviors of PVB and Ionoplast laminated glass (LG) under load duration of 30 days. The tests were carried out in room temperature (23℃). The study revealed that after sustaining loads for 30 days, the mid-span deflection of PVB LG increased by almost 102% compared with its short term deflection, while that of Ionoplast LG approximately increased by 14%; composite effects between two glass plies in PVB LG gradually reduced with time, but did not fully vanish at the 30th day; two glass plies in Ionoplast LG on the other hand was able to withstand loads as an effective composite section during the entire loading period; the creep behaviors of both LG were not finished yet at the 30th day. In addition to this, also studied was the varying of the bending stresses of PVB and Ionoplast LG under load duration of 2 hours. The tests were carried out in ambient temperatures of 30℃, 50℃ and 80℃ respectively. It was found that under a given load, although the bending stresses of both LG increased with increasing temperature, for PVB LG the increasing rate of the bending stress decreased with increasing temperature, while for Ionoplast LG the increasing rate of the bending stress increased with increasing temperature.

Keywords: PVB laminated glass; Ionoplast laminated glass; long duration load; temperature; creep; four-point bending

1. Introduction

Glass is commonly used in modern buildings thanks to its transparency and durability. The traditional role of architectural glass is as building envelopes (e.g., windows and curtain walls), so that glass is usually deemed as secondary structural elements in current codes of practice (such as JGJ 102-2003, prEN13474-1 and ASTM E1300-09a). Recently with the advance of the science and technology, the application of architectural glass has been gradually extended to load-carrying structural elements including plates, beams and columns (Ledbetter *et al.* 2006). The structural glass gains great popularity in customers due to the aesthetics. As a result, it attracts more and more attention from project developers and architects.

For safety's reason the structural glass normally employs laminated glass (LG) as explained by Callaghan (2012). LG consists of two or more plies of glass bonded together by soft elastic interlayer. Unlike monolithic glass, after breakage, the fragments of LG are retained to the

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interlayer, and thus the risk of injuries is reduced.

LG is a type of composite panel. Compared with ordinary monolithic glass of the same geometry, the flexural behavior of the LG is usually more complicated due to two main reasons, i.e., (1) large mismatch of elastic modulus between glass and interlayer and (2) visco-elasticity of interlayer (Callewaert *et al.* 2012, Rezaiee-Pajand *et al.* 2012, Allel *et al.* 2013). Therefore its structural performance is largely related to the material properties of its interlayer. A variety of materials have been used for the interlayer, among which polyvinyl butyral (PVB) interlayer and Ionoplast interlayer (such as SentryGlas® Plus manufactured by DuPont de Nemours) are two types commonly employed in practice (Bennison *et al.* 2001). These interlayer materials are normally visco-elastic, and these properties are highly dependent on load duration and ambient temperature (Ferry 1980). Therefore, the bending stress and deflection of LG will be varying when applied loads are continuously acted upon or the ambient temperatures are varied. This characteristic of LG is very different from monolithic glass.

A number of researches have been carried out regarding the influence of ambient temperature and load duration on the flexural performance of LG. Behr *et al.* (1986) experimentally studied the varying of stress of four-side simply supported PVB LG that continuously carried uniformly distributed loads for 1 hour, under the ambient temperatures of 22℃, 49℃ and 77℃ respectively. The study revealed that the stress at corners of the specimens increased with time, while the stress at the mid-span slightly decreased with time. By four-point bending tests Behr *et al.* (1993) studied the flexural performance of PVB LG and found that the flexural performance of PVB LG was close to the monolithic glass of equal thickness providing the ambient temperature was lower than 22℃ and the load duration was not greater than 3 seconds. Bati *et al.* (2010) studied the creep behaviors and varying of stresses of two-side simply supported PVB and Ionoplast LG that sustained loads for 2 weeks in room temperature. It was shown that the deflections and stresses at mid-span of the two types of LG increased monotonically. Yin *et al.* (2004) experimentally investigated the flexural behavior of four-point supported PVB LG that continuously carried loads for 180 days in room temperature. It was found that the deflection of the PVB LG increased with time, but the stress at the mid-point of each side only increased with time to a certain level after which the stress started to decease with time. The existing researches showed that the varying of stress and deflection of LG at a given load level was very complicated, which was not only affected by ambient temperature and load duration but also related to boundary conditions and loading patterns.

This paper reported a series of experimental study regarding the influence of load duration and ambient temperature on the flexural behaviors of PVB and Ionoplast LG under pure bending. The study adopted the four-point bending scheme and the tests were carried out in the ambient temperatures of 23℃, 30℃, 50℃ and 80℃ respectively. In the condition of 23℃ the LG specimens continuously carried loads for 30 days, while in the other temperature conditions the LG specimens sustained loads for 2 hours. The investigation was focused on the creep behaviors and varying of stresses of the two types of LG under pure bending. For comparison purpose, monolithic glass with thickness equivalent to the LG specimens was also tested under the same conditions. The detailed information of the study including test procedures, results and main findings were presented in this paper.

2. Test program

The tests were divided into two groups according to ambient temperature and load duration. In the first group the specimens continuously carried loads for 30 days under the ambient temperature of 23℃, while in the second group the specimens sustained loads for 2 hours under the ambient temperatures of 30℃, 50℃ and 80℃, respectively. Hereafter the two groups of the tests were referred to as 30-day room temperature tests and 2-hour elevated temperature tests, respectively.

2.1 Test specimens

The test specimens used in this study were all manufactured and supplied by DuPont de Nemours and were of three different types, i.e,. Ionoplast LG, PVB LG and monolithic annealed glass. The configuration of the LG specimens was 5mm annealed glass +0.76mm interlayer +5mm annealed glass. The dimensions of the specimens were all 1100×360mm. The nominal thickness of the monolithic glass was 10mm. To demonstrate the repeatability of test results, each type of glass had two nominally identical specimens. Presented in Table 1 were the ID symbols and measured overall thicknesses of the specimens.

2.2 Test set-up

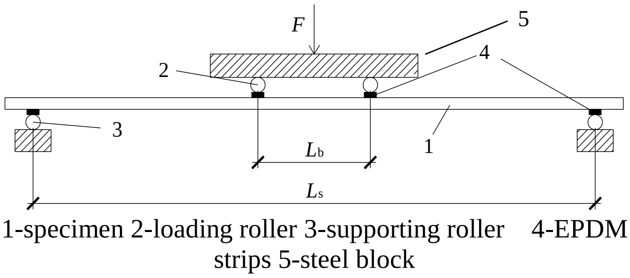
The test set-up for the 30-day room temperature tests was as shown in Fig. 1(a), in which the specimens were simply supported on two steel rollers along the short sides. Constant loads were applied onto the specimens through two additional steel rollers. The load pattern was schematically illustrated in Fig. 1(b), in which the distances between two loading rollers (L_b) and two supporting rollers (L_s) were approximately 200 mm and 1000 mm, respectively. To prevent any direct contact between the specimens and steel, EPDM strips were provided in between.

The main purpose of the 30-day room temperature tests was to investigate the creep behaviors of the specimens under long duration loads. Therefore dial gauges were placed in the mid-span and the supports of the specimens respectively. The mid-span dial gauge was positioned at the bottom

Table 1 ID numbers and measured thicknesses of the specimens

ID	Type	Measured overall thickness (mm)
(a) Specimens in the 30-day room temperature tests		
30d-Ionoplast-1	Ionoplast LG	10.3
30d-Ionoplast-2		10.3
30d-PVB-1	PVB LG	10.1
30d-PVB-2		10.2
30d-Monolithic-1	Monolithic glass	9.5
30d-Monolithic-2		9.3
(b) Specimens in the 2-hour elevated temperature tests		
2h-Ionoplast-1	Ionoplast LG	10.1
2h-Ionoplast-2		10.1
2h-PVB-1	PVB LG	10.1
2h-PVB-2		10.1
2h-Monolithic-1	Monolithic glass	9.9
2h-Monolithic-2		10.0

(a) Test devices



(b) Load scheme

(c) The position of the dial gauge in the mid-span

Fig. 1 Set-up for 30-day room temperature tests

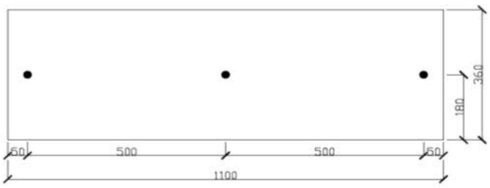


Fig. 2 Positions of dial gauges in 30-day room temperature tests (in mm)

side of the specimens to avoid conflict with the loading device. Fig. 1(c) demonstrated the relative location of the mid-span dial gauge with respect to the load device. The specific positions of the dial gauges were as shown in Fig. 2. The deflection data were collected manually at prescribed time.

In the 2-hour elevated temperature tests, the specimens were also simply supported along the short sides, and the distances between the loading rollers and the supporting rollers were 200 mm and 1000 mm as well. Fig. 3 showed the set-up of the tests. Applied loads were generated by a loading jack fixed on a steel frame. The loads were transferred from the jack and via a steel bar into the specimens. The tests were carried out in a bespoken thermal box. To facilitate setting up, the box was made up of two half parts (Fig. 3 demonstrated one of the parts.). A slot was preset on the top face of the box to accommodate the loading device and the steel frame. After fitted into position, the specimens were then enclosed by the two parts. The joints between the two parts were carefully sealed and the slot was covered by polystyrene boards to ensure thermal insulation. It was worth mentioning that the steel bar going through the thermal box was able to move up and down freely to allow for loading and unloading process during the tests without opening the thermal box. The temperature inside the thermal box was controlled by an electric thermostat.

Fig. 3 Set-up for 2-hour elevated temperature tests (only half of the thermal box was shown)

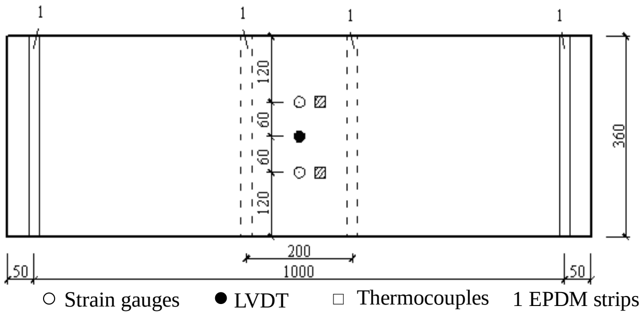


Fig. 4 Layout of measuring instruments for 2-hour elevated temperature tests

The 2-hour elevated temperature tests were carried out to investigate the varying of stresses of the specimens under the circumstance of long duration load (2h) and high temperatures. The acquiring data therefore were the stresses and temperatures of the specimens. These data were measured by strain gauges and thermocouples, respectively. Additionally, the mid-span deflection was also obtained by a LVDT during the tests. The layout of the instruments was as shown in Fig. 4. All the testing data were collected simultaneously by a computer data acquisition system.

2.3 Test procedure

In the 30-day room temperature tests, a steel block with self-weight of 16.8kg was applied onto the specimens. This load was approximately equal to the calculated strength of a 5+5mm double layered glass (or 50% of the strength of a 10mm monolithic glass) under load duration of 30 days (The calculation was based on prEN 16612 2013). The steel block was firstly lifted into a level that just touching the specimens (zero load was applied at this step), and then released gradually until its weight was completely carried by the specimens. The time used for the application of the load (from zero to 16.8kg) was kept around 2~3 seconds. The specimens then continuously carried the load for 30 days.

In the 2-hour elevated temperature tests, the test procedure was as follows: (1) set up the specimens and then close and seal the thermal box; (2) switch on the electric thermostat and heat the in-box temperature up to the specified level; (3) maintain the temperature for 1 hour; (4) zero

Table 2 Varying of deflections (in mm) at mid-span within 24 hours

ID	<3s	1min	5min	10min	1h	5h	10h	24h
30d-Ionoplast-1	1.70	1.72	1.72	1.75	1.75	1.75	1.76	1.77
30d-Ionoplast-2	1.74	1.75	1.78	1.77	1.77	1.81	1.77	1.77
30d-PVB-1	2.29	2.54	2.89	3.04	3.34	3.59	3.70	3.87
30d-PVB-2	2.30	2.66	2.87	3.00	3.39	3.53	3.64	3.90
30d-Monolithic-1	1.89	1.90	1.91	1.90	1.90	1.89	1.89	1.89
30d-Monolithic-2	1.95	1.97	1.99	1.99	1.99	1.99	1.99	1.99

the instruments; (5) apply a constant load of 100N at a rate of 2N/mm^{2}s to the specimens via the loading jack (it took 3~4s to complete the load application); (6) sustain the load for 2 hours, meanwhile the testing data was being collected by the computer data acquisition system at an interval of 5 minutes; (7) unload to 0; (8) keep the thermal box closed while elevate the temperature to the next level; (9) repeat the steps from (3) to (8).

3. Test results and discussions

3.1 The 30-day room temperature tests

The varying of mid-span deflections within the first 24 hours of each specimen was presented in Table 2.

Table 2 shows that the test results of two nominally identical specimens for each type of glass were in very good agreement.

It can be seen that the creep behavior of PVB LG was very significant. Sustaining loads for 1 minute, 1 hour, 5 hours and 24 hours, the mid-span deflections of PVB LG approximately increased by 13%, 46%, 57% and 69% respectively, compared with the short term deflection (<3s). In contrast, the creep behavior of Ionoplast LG within 24 hours was negligible. After 24 hours, the mid-span deflection of Ionoplast LG only increased by 3% compared with the short term deflection. The deflection of monolithic glass was generally independent to loading time as expected.

It can also be found from Table 2 that among three types of glass, at the same loading time the mid-span deflection of PVB LG was always the largest, while that of Ionoplast LG was constantly the smallest. It is well known that the flexural performance of LG is highly related to the properties of interlayer materials. Since the shear modulus of PVB interlayer is comparatively low, the shear force between two glass plies is unable to be transferred sufficiently and the composite action between the glass plies is unable to be fully developed. As a result, the flexural rigidity of the PVB LG is lower than that of monolithic glass with equivalent thickness. As opposed to PVB interlayer, Ionoplast interlayer has comparatively high shear modulus and enables the full composite action being developed between two glass plies, so that the flexural rigidity of the Ionoplast LG is close to monolithic glass with equivalent thickness. In this study, the flexural rigidity of the Ionoplast LG appeared to be slightly larger than that of the monolithic glass. This is mainly because the measured overall thicknesses of the former were slightly larger than that of the latter (see Table 1(a)).

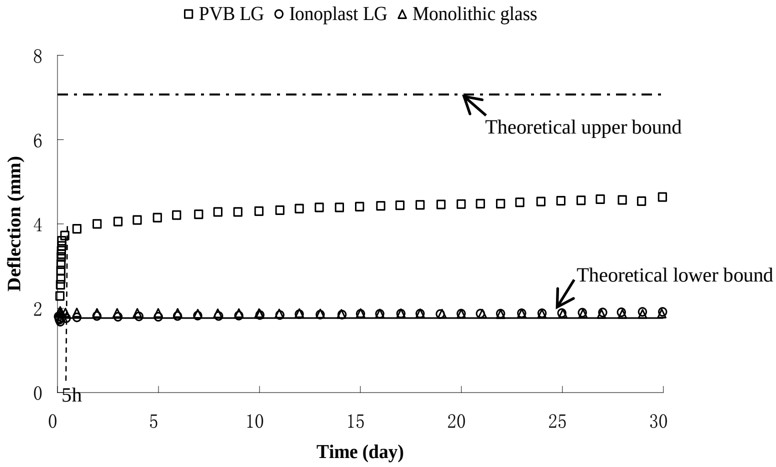


Fig. 5 Varying of deflections within 30 days

The varying of mid-span deflection within 30 days for each type of glass was presented in Fig. 5. As the test results of two nominally identical specimens were in very good agreement, the mean values were used to plot the deflection-time curves in Fig. 5. For comparison purpose, the deflections of a monolithic glass of 9.4mm thickness (equal to the mean value of the measured thicknesses of the monolithic glass specimens) and a double-layered glass of 4.7+4.7mm thickness undergoing the same loads were calculated and presented in Fig. 5, as the lower and upper bound values for the LG. Based on the elastic theory, the lower bound value was determined by the following equation

$$D = \frac{F(L_s - L_b)(1-\nu^2)}{8EBh^3}[3L_s^{\ 2} - (L_s - L_b)^2] \tag{1}$$

where, L_b and L_s are the distances between two loading rollers and two supporting rollers respectively (see Fig. 1(b)); B is the width and h is the thickness of the glass; E is the Young's modulus and ν is the Poison's ratio of the glass (E=70000MPa and ν=0.22 according to prEN 16612 2013); F and D are the applied load and corresponding mid-span deflection. In calculating the deflection of the double-layered glass (upper bound value), h in Eq. (1) was taken as the thickness of the single layer and F was halved.

From Fig. 5 it can be seen that within the loading time of 5 hours the creep rate of PVB LG was fast. During this period the deflection against time curve was roughly in a linear relationship and the increasing rate of the deflection was approximately 0.25mm/h. When the loading time exceeded 5 hours the creep rate of PVB LG gradually slowed down. During the loading period of 3s~30 days, the mid-span deflection of PVB LG increased approximately at a rate of 0.078mm/d and moved from the side of the theoretical lower bound toward the theoretical upper bound. This phenomenon was because the shear transfer capacity of PVB interlayer between two glass plies was deteriorative with time so that the coupling effect between two glass plies diminished with time. However, at the 30th day, the mid-span deflection of PVB LG was still 34% lower than the theoretical upper bound. This implied that at this time the composite effect between two glass plies had not been completely lost although the shear transfer capacity of PVB interlayer decreased a lot. At the 30th day, the mid-span deflection of PVB LG increased by 102% compared with the short term deflection and apparently the creep behavior was not finished yet.

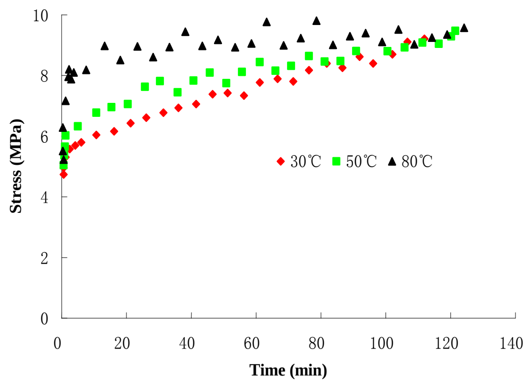
On the other hand, the creep of Ionoplast LG was comparatively limited and at the 30th day the mid-span deflection only increased by no more than 14% compared with the short term deflection. In the period of 3s~30 days, the mid-span deflection of Ionoplast LG was constantly close to the theoretical lower bound. This indicated that during the entire loading period Ionoplast interlayer can effectively transfer shear force so as to develop full composite action between two glass plies.

Monolithic glass did not have any creep behavior within 30 days and the mid-span deflection agreed well with the theoretical lower bound as expected.

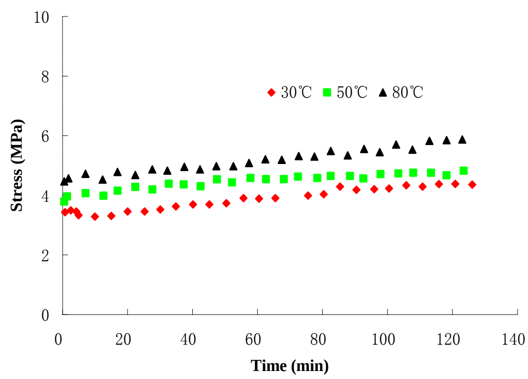
3.2 The 2-hour elevated temperature tests

For 2-hour elevated temperature tests, the stress-time curve and deflection-time curve of each type of glass were presented in Figs. 6 and 7, respectively. The mean values of the nominally identical specimens were used to plot the curves in Figs. 6 and 7. The stresses in Fig. 6 were referred to the bending normal stress at the mid-span and calculated by $E\varepsilon$. The Young's modulus E of the glass was taken as 70000N/mm^2 and the strain ε was measured by the strain gauges.

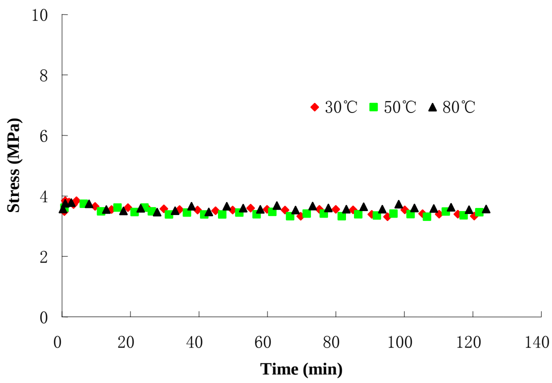
From Figs. 6(a) and 7(a) it can be seen that for PVB LG, at a given load level the bending stress and deflection considerably increased with the elevating temperature; meanwhile, at a given



(a) PVB LG



(b) Ionoplast LG



(c) Monolithic glass

Fig. 6 Load-stress curve of specimen in 2-hour elevated temperature tests

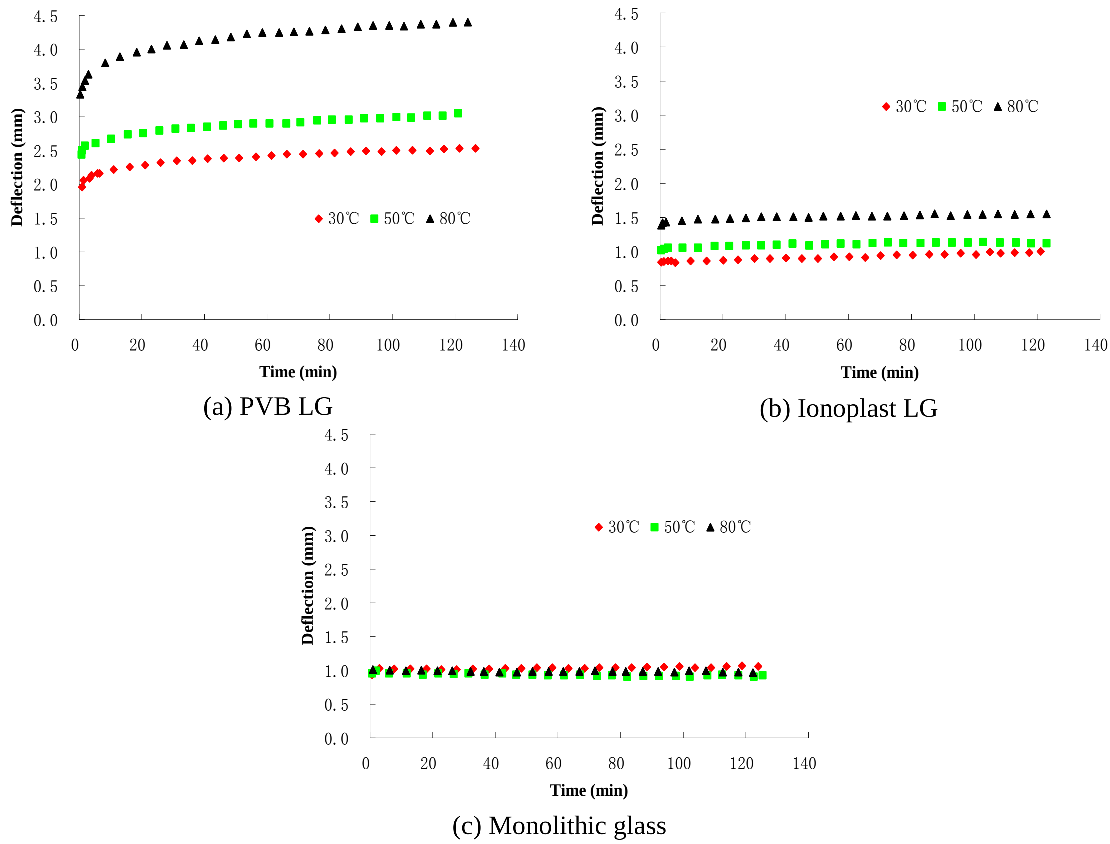


Fig. 7 Load-deflection curve of specimen in 2-hour elevated temperature tests

temperature the bending stress and deflection also substantially increased with increasing the loading time. The stress-time curve and deflection-time curve of PVB LG showed a non-linear characteristic, especially in the conditions of 50℃ and 80℃. It is worth noting that the increasing rate of the bending stress was slowed down as the temperature was elevated. For example, in the circumstance of 30℃ the bending stress of PVB LG nearly increased by 96% (from 4.7 MPa to 9.2 MPa) after 2 hours loading, while in the circumstance of 80℃ the bending stress only increased by 75% (from 5.5 MPa to 9.6 MPa). After 2 hours the bending stresses in various temperatures showed a tendency of convergence.

At a given load level the bending stress and deflection of Iononplast LG increased with elevating temperature as well as increasing loading time, but the increasing rate was much slower than that of PVB LG, as shown in Figs. 6(b) and 7(b). It is also worth noting that unlike PVB LG, the increasing rate of the bending stress of Ionoplast LG was raised as the temperature was elevated. For instance, in the circumstance of 30℃ the bending stress of Ionoplast LG was approximately increased by 13% (from 3.4 MPa to 4.4 MPa), while in the circumstance of 80℃ the bending stress increased by 31% (from 4.5 MPa to 5.9 MPa).

For monolithic glass, the bending stress and deflection at a given load level were basically unchanged and independent to temperature and load duration, as demonstrated in Figs. 6(c) and 7(c).

4. Conclusions

Through four-point bending tests, this paper investigated the creep behaviors of PVB LG and Ionoplast LG under load duration of 30 days at room temperature as well as the varying of the bending stresses and deflections of the two types of LG under load duration of 2 hours, at 30°C, 50°C and 80°C respectively. Based on the test results, the following main conclusions can be drawn:

For the 30-day room temperature tests:

• The creep behavior of PVB LG in room temperature was substantial. After sustaining loads for 5 hours, 24 hours and 30 days, the mid-span deflections of PVB LG increased by 57%, 69% and 102% respectively compared with the short term deflection. The creep rate was fastest in the first 5 hours and slowed down gradually after 24 hours, but the creep behavior had not been finished yet at the 30^{th} day.

• The creep behavior of Ionoplast LG in room temperature was fairly small. After sustaining loads for 24 hours and 30 days, the mid-span deflections of Ionoplast LG only increased by 3% and 14% respectively compared with the short term deflection. The creep behavior of Ionoplast LG had not been finished as well at the 30^{th} day.

• Although the shear transfer capacity of PVB interlayer decreased with time, the composite effect between two glass plies of PVB LG had not been completely lost after sustaining loads for 30 days.

• Coupling between two glass plies with Ionoplast interlayer can be maintained within 30 days.

For the 2-hour elevated temperature tests

• At a given load level, the bending stresses and deflections of Ionoplast and PVB LG increased with elevating temperature as well as increasing loading time.

• The bending stress and deflection of PVB LG were significantly influenced by the ambient temperature and load duration. The increasing rate of the bending stress of PVB LG however was slowed down as the ambient temperature was elevated.

• The influence of the ambient temperature and load duration on the bending stress and deflection of Ionoplast LG was comparatively limited. Whereas the increasing rate of the bending stress of Ionoplast LG was raised as the ambient temperature was elevated.

References

Allel, M., Mohamed, A. and Ahmed, B. (2013), "Stability condition for the evaluation of damage in three-point bending of a laminated composite", *Steel Compos. Struct.*, **15**(2), 203-220.

ASTM E1300-09a (2009), Standard practice for determining load resistance of glass in buildings, New York.

Bati, S.B., Ranocchiai, G., Reale, C. and Rovero, L. (2010), "Time-dependent behavior of laminated glass", *J. Mater. Civ. Eng.*, **22**(4), 389-396.

Behr, R.A., Minor, J.E. and Linden, M.P. (1986), "Load duration and interlayer thickness effects on laminated glass", *J. Struct. Eng.*, **112**(6), 1441-1453.

Behr, R.A., Minor, J.E. and Norville, H.S. (1993), "Structural behavior architectural LG", *J. Struct. Eng.*, **119**(1), 202-222.

Bennison, S.J., Davies, P.S., Van Duser, A. and Jagota, A. (2001), "Structural performance of laminated safety glass made with 'stiff' interlayers", *Proceedings of Glass Performance Days*, Tampere, Finland, June.

Callaghan, J.O. (2012), "Adventures with structural glass", *Proceedings of Glass Performance Days,* Sao

Paulo, Brazil, June.

Callewaert, D., Belis, J., Delincé, D. and Impe, R.V. (2012), "Experimental stiffness characterisation of glass/ionomer laminates for structural applications", *Constr. Build. Mater.*, **37**, 685-692.

Ferry, J.D. (1980), *Viscoelastic Properties of Polymers*, (3rd Edition), John Wiley & Sons, New York, USA.

JGJ 102-2003 (2003), Technical code for glass curtain wall engineering, Beijing.

Ledbetter, S.R., Walker, A.R. and Keiller, A.P. (2006), "Structural use of glass", *J. Archit. Eng.*, **12**(3), 137-149.

prEN 13474-1 (1999), Glass in building-design of glass panes-part1: General basis of design, London.

prEN 16612 (2013). Glass in building-determination of the load resistance of glass panes by calculation and testing, London.

Rezaiee-Pajand, M., Shahabian, F. and Tavakoli, F.H. (2012), "A new higher-order triangular plate bending element for the analysis of laminated composite and sandwich plates", *Struct. Eng. Mech.*, **43**(2), 253-271.

Yin, Y.W., Zhang, Q.L. and Huang, Q.W. (2004), "Experimental study on load bearing capacity of point-supported mid-hollow and laminated glasses", *J. Build. Struct.*, **25**(1), 93-98.