Structural Engineering and Mechanics, *Vol. 52, No. 3 (2014) 603-612*
DOI: http://dx.doi.org/10.12989/sem.2014.52.3.603

The flexural performance of laminated glass beams under elevated temperature

Xiaokun Huang[1], Gang Liu[1], Qiang Liu*[1] and Stephen J. Bennison[2]

[1]China Academy of Building Research, Beijing, China
[2]E.I. DuPont de Nemours & Co. Inc., USA

(Received March 25, 2014, Revised May 5, 2014, Accepted August 20, 2014)

Abstract. A series of experimental work is carried out with the aim to understand the flexural performance of laminated glass (LG) beams using polyvinyl butyral (PVB) and Ionoplast interlayers subjected to short term duration loads in the circumstance of elevated temperature. The study is based on a total of 42 laboratory tests conducted in ambient temperature ranging from 25℃ to 80℃. The load duration is kept within 20 seconds. Through the tests, load-stress and load-deflection curves of the LG are established; appropriate analytical models for the LG are indentified; the effective thicknesses as well as the shear transfer coefficients of the LG are semi-empirically determined. The test results show that within the studied temperature range the bending stresses and deflections at mid-span of the LG develop linearly with respect to the applied loads. From 25℃ to 80℃ the flexural behavior of the PVB LG is found constantly between that of monolithic glass and layered glass having the same nominal thickness; the flexural behavior of the Ionoplast LG is equivalent to monolithic glass of the same nominal thickness until the temperature elevates up to 50℃. The test results reveal that in calculating the effective thicknesses of the PVB and Ionoplast LG, neglecting the shear capacities of the interlayers is uneconomic even when the ambient temperature is as high as 80℃. In the particular case of this study, the shear transfer coefficient of the PVB interlayer is found in a range from 0.62 to 0.14 while that of the Ionoplast interlayer is found in a range from 1.00 to 0.56 when the ambient temperature varies from 25℃ to 80℃.

Keywords: polyvinyl butyral laminated glass; Ionoplast laminated glass; temperature; flexural performance; short duration load

1. Introduction

Laminated glass (LG) consists of two or more plies of glass bonded together by elastomeric interlayer and is commonly used in modern buildings thanks to its good safety and security performance. Unlike monolithic glass, in case of breakage the shards of LG are retained to the interlayer so that the risk of injuries can be minimized. As a result, LG is widely applied in buildings where safety issues are of concern.

Architectural LG often carries short term duration loads (<30 seconds) perpendicular to its plane. In this loading condition its flexural behavior is complicated because of two main reasons:

∗Corresponding author, Ph.D., E-mail: QXL393@gmail.com

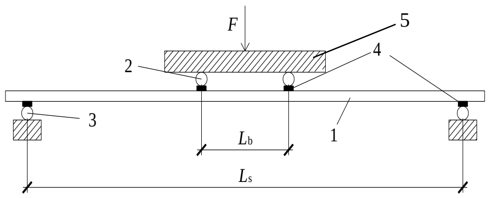
http://www.techno-press.org/?journal=sem&subpage=8 ISSN: 1225-4568 (Print), 1598-6217 (Online)

(1) large mismatch of elastic modulus between glass and interlayer; (2) temperature-dependent material properties of interlayer (Rezaiee-Pajand *et al.* 2012, Allel *et al.* 2013). It has been known that the flexural behavior of LG beams is highly related to the shear transfer capacity of the interlayer (Duser *et al*. 1999, Pankhardt and Balázs 2010). If the interlayer is unable to transfer shears between plies of LG, the plies will act independently as a layered section. Conversely, if the interlayer is able to effectively transfer the shears, the plies will carry loads integrally as a monolithic section. Since interlayer materials used in LG are normally visco-elastic, such as polyvinyl butyral (PVB) and Ionoplast SentryGlas® Plus (Bennison *et al*. 2001), the shear transfer capacities of these interlayers are always dependent on ambient temperature (Galuppi and Royer-Carfagni 2012). Wölfel (1987) has proposed an effective thickness method taking the shear transfer effect into account in structural design of LG. The principle of the method is to analytically transform the LG into a monolithic glass of the same bending properties in terms of strength and deflection, and thus the thickness of the monolithic glass is referred to as effective thickness of the LG. This design concept is being adopted in current codes of practice including the American design code ASTM E1300-09a (2009), the European design code prEN 16612 (2013) and the Chinese design code JGJ 102-2003 (2003). However, in spite of using the same concept, different codes sometimes can yield considerably different results. This is mainly because the analytical models employed in calculating the effective thickness are different in various codes. For example, JGJ 102-2003 (2003) suggests that the shear resistance of interlayer should not be considered at all so that LG is treated as a layered section under any circumstances; prEN 16612 (2013) allows to include the shear resistance and treat LG as a partially composite section only if the interlayer properties have been experimentally evaluated, otherwise the shear resistance of interlayer should not be considered; ASTM E1300-09a (2009) assumes LG to act as a partially composite section and provides an analytical expression to calculate the shear transfer capacity of interlayer, while a key parameter (shear modulus of interlayer) included in the expression has to be experimentally determined in advance. Existing researches (Behr *et al*. 1993, Callewaert *et al.* 2012, El-Shami *et al*. 2012, Serafinavičius 2013) have revealed that the flexural performance of both PVB and Ionoplast LG deteriorates with elevating temperature, while neglecting the shear resistance of interlayer can result in overly conservative results in case the LG is subjected to short term loads at and below room temperature. LG used in building envelopes often exposes to outdoors. Under the effect of solar radiation, surface temperatures of the LG are likely to be as high as 80℃ (Bennison and Stelzer 2011). For economic and safe design of LG, some basic information such as analytical models and effective thicknesses of LG and shear transfer capacities of interlayers in elevated temperature is therefore worth to be assessed.

This paper presents an experimental study on the flexural performance of LG beams using PVB and Ionoplast interlayers under the circumstance of elevated temperature. The tests are carried out in six temperature levels, i.e., 25℃, 40℃, 50℃, 60℃, 70℃ and 80℃, respectively. The study adopts the four-point bending scheme and the specimens are subjected to short term duration loads. The investigation is focused on the load-stress and load-deflection relationships with the objectives to indentify the appropriate analytical models and to determine the effective thicknesses of the LG beams, as well as to assess the shear transfer capacities of the PVB and Ionoplast interlayers in elevated temperature. For comparison purpose, monolithic glass and layered glass of the same nominal thickness as the LG specimens are also tested. The detailed information of the study including test procedures, results and main findings are presented in this paper.

Table 1 ID numbers and measured thicknesses of the specimens

ID	Type	Measured overall thickness (mm)
Ionoplast-1		10.20
Ionoplast-2	Ionoplast LG	10.12
Ionoplast-3		10.10
PVB-1		10.10
PVB-2	PVB LG	10.09
PVB-3		10.11
Monolithic-1		9.83
Monolithic-2	Monolithic glass	9.78
Monolithic-3		9.80
DL-1		9.46
DL-2	Double-layered glass	9.47
DL-3		9.47



1-specimen 2-loading roller 3-supporting roller 4-EPDM strips
5-steel block

(a) Load scheme

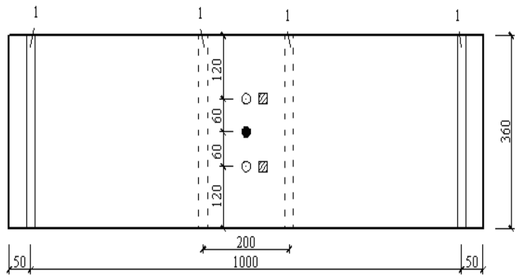
(b) Test devices (only half of the thermal box was shown)

Fig. 1 Test set-up

2. Test program

2.1 Test specimens

The test specimens used in this study are Ionoplast LG, PVB LG, monolithic glass and double-layered glass. The nominal thicknesses of these specimens are all 10 mm. The LG specimens are produced from two 5 mm thick Soda-Lime-Silica annealed glass with a 0.76 mm thick interlayer. The double-layered glass specimens consist of two 5 mm thick Soda-Lime-Silica annealed glass, between which lubricant is applied with the purpose to minimize friction. The thickness of the lubricant film is negligible. The monolithic glass specimens are 10 mm thick Soda-Lime-Silica annealed glass. The length and the width of the specimens are all 1100 mm and 360 mm. To demonstrate the repeatability of test results, each type of the specimens has three nominally identical samples. Presented in Table 1 are the ID symbols and measured overall thicknesses of the specimens. The actual overall thickness of every specimen is based on an average of four measurements, which are made respectively at the midpoints of four sides of the specimen.



○ Strain gauges ● LVDT □ Thermocouples 1 EPDM strips

Fig. 2 Layout of measuring instruments

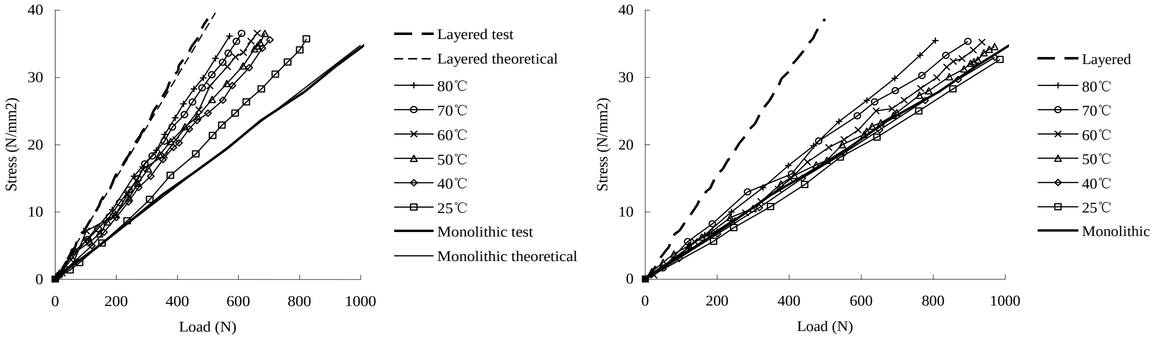
2.2 Test set-up

The specimens are under four-point bending according to prEN 16612 (2013). The load pattern is as shown in Fig. 1(a). The specimens are placed on two roller supports with a constant span (L_s) of 1000 mm. Loads are applied onto the specimens through two additional rollers at a spacing (L_b) of 200 mm. EPDM strips are provided between the specimens and rollers to reduce stress concentration. For the condition of high ambient temperatures (≥40℃), the tests are carried out in a custom-made thermal box (see Fig. 1(b)). The box is made of timber and attached with polystyrene boards in the inner surfaces to ensure thermal insulation. The temperature inside the thermal box is digitally controlled by an electric thermostat. The information about the test set-up in elevated temperature is described in more details in Huang *et al*. (2014).

The aim of the study is to understand the flexural behaviors of the specimens under elevated temperature. The acquiring data therefore are the temperatures, applied loads, tensile stresses and deflection at mid-span. These data are measured by thermocouples, load cell, strain gauges and LVDT, respectively. The layout of the instruments is as shown in Fig. 2. All the testing data are collected simultaneously by a computer data acquisition system.

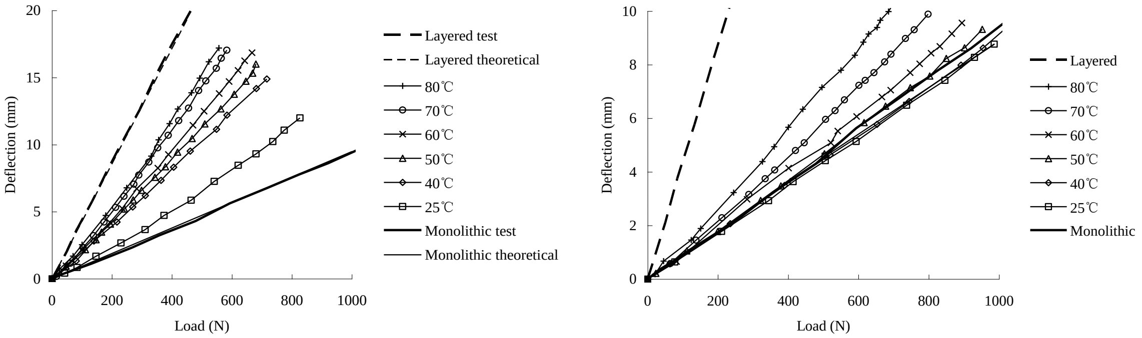
2.3 Test procedure

The LG specimens are tested in six temperature levels, i.e., 25℃, 40℃, 50℃, 60℃, 70℃ and 80℃. Since it is anticipated that the flexural behavior of Soda-Lime-Silica annealed glass will not be sensitive to temperature ranging from 25℃ to 80℃, the monolithic and double-layered glass specimens are only tested in room temperature of 25℃. For the tests carried out in room temperature, after set-up the specimens are monolithically loaded at a rate of 2N/mm^2/second until the tensile strain at the mid-span approximately reaches 350$\mu\varepsilon$. This value is about 50% of the ultimate tensile strain of annealed glass. The testing data are automatically collected through the computer data acquisition system. For the tests carried out in elevated temperature, the test procedure is 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 30 minutes; (4) zero the instruments; (5) apply loads and collect testing data in the similar way as the room temperature tests; (6) unload to 0; (7) keep the thermal box closed while elevate the temperature to the next level; (8) repeat the steps from (3) to (7). The load-carrying time (from the beginning to the end of load application) in any test is kept within 20 seconds.



(a) PVB LG (b) Ionoplast LG

Fig. 3 Load-stress curves of the specimens



(a) PVB LG (b) Ionoplast LG

Fig. 4 Load-deflection curves of the specimens

3. Test results

The load-stress and load-deflection curves of the LG specimens are graphed and presented in Figs. 3 and 4, respectively. As the test results of the nominally identical specimens are found in good agreement, mean values are used in plotting the curves. The stresses in Fig. 3 refer to the bending normal stress at the mid-span and are calculated by the expression of $E\varepsilon$, where the Young's modulus E of the glass is taken as 70000N/mm^2 and the strains ε are measured by the strain gauges. The corresponding curves of the monolithic glass and the double-layered glass are also presented in Figs. 3 and 4 for comparison.

The theoretical load-stress and load-deflection relationships of the monolithic glass as well as the double-layered glass are analytically derived to compare with the test results. Based on the classic beam theory (Timoshenko 1956), the maximum bending stress and deflection at mid-span (σ_{center} and D) of a simply supported beam under four-point bending can be respectively determined by the following equations

$$\sigma_{center} = 3F(L_s - L_b)/2Bh^2 \tag{1}$$

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

where, L_b and L_s are the distances between two loading and two supporting rollers respectively; B is the width and h is the thickness of the beam; E is the Young's modulus and υ is the Poison's ratio of the beam (E=70000 MPa and υ=0.22 for glass according to prEN 16612 2013); F is the applied load. In calculating the double-layered glass, h is taken as the thickness of the single layer and F is correspondingly halved. Through Eqs. (1) and (2) the theoretical load-stress and load-deflection relationships of the monolithic glass and double layered glass are calculated. The results were presented in Fig. 3(a) and Fig. 4(a) for comparison. Good agreement between the theoretical values and the test results demonstrate that the assumptions used in the classic beam theory are applicable to both monolithic glass and double-layered glass.

4. Discussions

4.1 Load-stress and load-deflection relationships of PVB LG and Ionoplast LG

It is interesting to note from Figs. 3-4 that the load-stress and load-deflection curves of the PVB and Ionoplast LG beams all show an approximate linear characteristic at any of the temperature levels no mater how large the deflections are. One reason for this observation is that the specimens are simply supported on the rollers and their lateral movement is unrestrained. Membrane stresses therefore are not developed and the effect of geometric nonlinearity is not activated even under large defection. In this study the applied loads are all short term duration (<20s). The approximate linear flexural behaviors of the PVB and Ionoplast LG beams also indicate that at a constant temperature level ranging from 25℃ to 80℃, the coupling effect (provided by either PVB interlayers or Ionoplast interlayers) between two plies of glass is not changed significantly under short term duration loads (otherwise nonlinear behaviors of the LG beams will be observed due to material nonlinearity).

As expected, the flexural performance of both the PVB and Ionoplast LG beams degrades with elevating temperature. The deterioration of the flexural performance of the PVB LG is significant particularly when the ambient temperature elevates from 25℃ to 40℃, while that of the Ionoplast LG is appreciable only when the ambient temperature is higher than 60℃. This is because the glass transition temperatures of the PVB and Ionoplast interlayers are on the order of 30℃ and 60℃ respectively. Above these temperatures the shear capacities of the polymers are highly reduced and as a result the flexural properties of the LG are highly deteriorated.

4.2 Analytical models for PVB and Ionoplast LG in elevated temperature

According to the classic theory for sandwich panels, the flexural performance of LG beams may be analyzed based on one of the three models, i.e., fully composite model, partially composite model or layered model. In the fully composite condition, plies of LG are considered to be contiguous with one another like a monolithic glass and no relative slippage when the LG is deformed. In the layered condition, plies of LG are assumed to act independently and each ply can slide freely relative to the adjacent ply. In the partially composite condition, each ply of LG is allowed to slip relative to the adjacent ply while certain amount of shear forces are transferred between the plies. Figs. 3-4 show that from 25℃ to 80℃ the load-stress and load-deflection curves of the PVB LG all locate between the curves of the layered and monolithic specimens. This indicates that in the temperature range the PVB LG behaves as the partially composite model. On

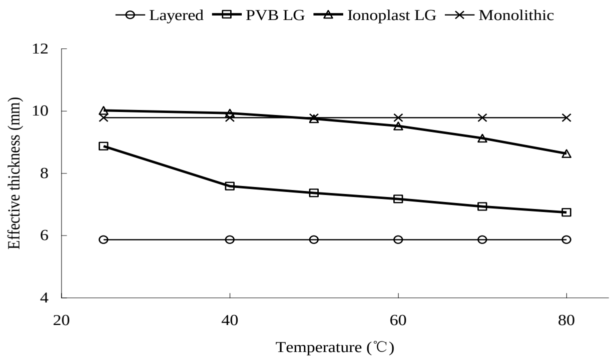


Fig. 5 Effective thicknesses for the PVB and Ionoplast LG in different ambient temperatures

the other hand, the flexural responses of the Ionoplast LG locate between the curves of the layered and monolithic specimens only when the ambient temperature elevates above 50℃. This means that the Ionoplast LG behaves as the fully composite model in the ambient temperature lower than 50℃ and acts as the partially composite model in the temperature range from 50℃ to 80℃.

4.3 Effective thicknesses of PVB and Ionoplast LG in elevated temperature

Since the deflections of the LG specimens are found developing in an approximate linear way with respect to the applied loads, the effective thicknesses (h_{ef}) of the PVB and the Ionopast LG beams in various temperatures are determined by a semi-empirical approach as follows: 1) conduct linear regression on the measured load-deflection curves using least square method; 2) determine the slope (φ) of the best fit line; 3) rearrange Eq. (2) into Eq. (3); 4) determine the effective thickness using Eq. (3).

$$h_{ef} = \sqrt[3]{\varphi(L_s - L_b)(1-\upsilon^2)[3L_s^{\ 2} - (L_s - L_b)^2]/8EB} \quad (3)$$

Using the same approach, the average effective thicknesses of the layered and the monolithic specimens are also determined, which are 5.9 mm and 9.8 mm, respectively. These semi-empirically obtained effective thicknesses are graphed with respect to temperature and presented in Fig. 5.

As shown in Fig. 5, the effective thickness of the PVB LG is approximately 90% of the monolithic glass having the same nominal thickness at 25℃, while drops rapidly to 75% as the ambient temperature elevates to 40℃; when the temperature further raises, the effective thickness constantly decreases but in a slower rate. It is worth noting that at 80℃ the effective thickness of the PVB LG is still approximately 15% higher than that of the layered glass having the same nominal thickness. This implies that at the temperature as high as 80℃ the coupling action between two plies of glass through PVB interlayer has not completely lost. For the Ionoplast LG, the effective thicknesses are slightly higher (1~2%) than that of the monolithic glass in the temperature range from 25℃ to 40℃ (This is because the average actual thicknesses of the Ionoplast LG and the monolithic glass in this study are 10.1 mm and 9.8 mm respectively. The presence of the Ionoplast interlayer increases section modulus of the Ionoplast LG and consequently results in higher effective thickness.); as the ambient temperature elevates to 50℃, the effective thickness becomes very close to that of the monolithic glass; when the temperature

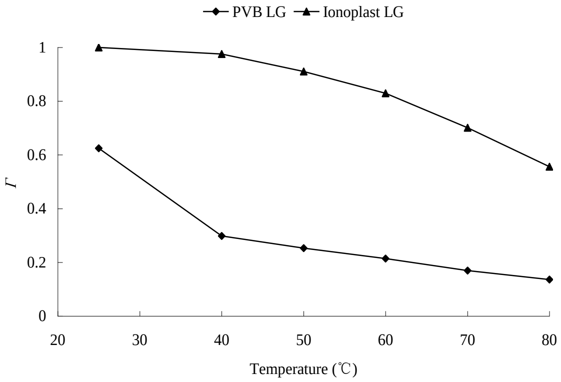


Fig. 6 Shear transfer coefficients of PVB and Ionoplast LG

further raises, the effective thickness turns lower than that of the monolithic glass; at 80℃ the effective thickness of the Ionoplast LG is about 88% of the monolithic glass.

4.4 Shear transfer coefficients of PVB and Ionoplast LG in elevated temperature

The shear transfer capacities of interlayer materials can be represented by a shear transfer coefficient (Γ) in accordance with ASTM E1300-09a (2009) and prEN 16612 (2013). This coefficient varies from 0 to 1. Zero value of Γ means that no shear stress can be transferred between glass plies, i.e., the LG is in the layered condition; Γ is equal to 1 representing that shear stress can be effectively transferred thus the LG is in the fully composite condition. An analytical relationship between the shear transfer coefficient and the effective thickness of LG is provided in the current American and European codes, in which the shear transfer coefficient can be expressed with respect to the effective thickness as:

$$\Gamma = \frac{(h_{ef}{}^3 - h_1^3 - h_2{}^3)(h_1 + h_2)}{12h_1h_2[0.5(h_1 + h_2) + h_v]^2} \tag{4}$$

where h_1, h_2 and h_v are the thicknesses of two glass plies and interlayer in LG respectively. By using the effective thicknesses obtained in the previous subsection together with Eq. (4), the values of Γ for the PVB and Ionoplast LG in various temperatures are semi-empirically determined and presented in Fig. 6. As shown in Fig. 6, for the PVB LG, the Γ value is approximately 0.62 at 25℃ and 0.14 at 80℃; for the Ionoplast LG, the Γ value is approximately 1.0 at 25℃ and 0.56 at 80℃. The reduction of the Γ value for the PVB is most significant in a temperature range from 25℃ to 40℃, while the reduction of the Γ value for the Ionoplast LG is appreciable when the temperature elevates above 60℃.

5. Conclusions

This paper investigates the flexural performance of PVB and Ionoplast LG beams subjected to short term duration loads in the circumstance of elevated temperature. The study is based on a total of 42 tests, in which a wide range of temperature is considered. The load-stress and load-deflection curves are recorded and examined. The effective thicknesses and shear transfer coefficients of the PVB and Ionoplast LG under various temperatures are semi-empirically determined. Based on the test results, the following main conclusions can be drawn:

• The bending stresses and deflections at mid-span of the PVB and Ionoplast LG beams are found in an approximate linear relationship with the applied loads. Since the geometric nonlinearity is not involved due to the simply supported boundary condition, the linear flexural behaviors of the PVB and Ionoplast LG beams indicate that at any temperatures from 25℃ to 80℃ and under short term duration loads, the changing of material properties is not significant for both the PVB and Ionoplast interlayers.

• Both the PVB and Ionoplast LG beams have a deteriorated flexural performance with elevating temperature. The performance deterioration of the PVB LG beams is significant particularly in a temperature range from 25℃ to 40℃, while that of the Ionoplast LG beams is appreciable only when the ambient temperature is higher than 60℃.

• In the temperature range from 25℃ to 80℃, the flexural behavior of the PVB LG is constantly between that of monolithic glass and layered glass. In other words the PVB LG acts as partially composite sections in the studied temperature range. On the other hand, the Ionoplast LG behaves close to fully composite sections in the temperature range from 25℃ to 50℃ while it acts as partially composite sections when the temperature elevates above 50℃.

• At 25℃ the effective thickness of the PVB LG is approximately 10% lower than that of the monolithic glass having the same nominal thickness; while at 80℃ it is approximately 15% higher than that of the layered glass having the same nominal thickness. The effective thickness of the Ionoplast LG is slightly higher than that of the monolithic glass of the same nominal thickness until the temperature elevates to 50℃; at 80℃ the effective thickness of the Ionoplast LG is about 12% lower than that of the monolithic glass.

• In the particular case of this study, from 25℃ to 80℃ the shear transfer coefficient of the PVB interlayer is found in a range from 0.62 to 0.14 and that of the Ionoplast interlayer is in a range from 1.00 to 0.56.

Acknowledgements

E.I. DuPont de Nemours & Co. Inc is gratefully acknowledged for providing the LG testing samples.

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