Determination of PVB interlayer’s shear modulus and its effect on normal stress distribution in laminated glass panels

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Abstract. Noticing the current architecture, there are many examples of glass bearing members such as beams, panes, ribs stairs or even columns. Most of these elements are made of laminated glass from panes bonded by polymer interlayer so the task of transferring shear forces between the glass panes needs to be investigated due to the lack of knowledge. This transfer depends on stiffness of polymer material, which is affected by temperature and load duration. It is essential to catch the safe side with limit cases when designing these members if the exact material behaviour is not specified. There are lots of interlayers for structural laminated glass applications available on a market. Most of them exhibit different properties, which need to be experimentally verified. This paper is focused on tangent shear modulus of PVB (polyvinyl-buthyral) interlayer and its effect on the stress distribution in glass panes when loaded. This distribution may be determined experimentally or numerically, respectively. This enables to design structural laminated glass members more effectively regarding price and safety. Furthermore, this is the way, how to extend the use of laminated glass in architectural design.

1. Introduction
Laminated glass is the subject of a current research [1-3] and is composed of two or more glass plies bonded by transparent polymeric foil in autoclave at 0,8 MPa pressure. In case of load bearing structural elements, laminated glass is necessary because of its load bearing capacity. When laminated glass cracks under a certain load, the glass fragments tend to adhere to the interlayer and don’t fall down, potentially causing an injury. So laminated safety glass is suitable for roofing installed above the heads of users and for other structural elements such as staircases and balustrades. Structural engineers design laminated safety glass regardless shear coupling of the plies with the exception of wind load. This approach results in conservative and too expensive laminated glass constructions due to the lack of foil’s properties. There are different PVB interlayers with different properties for structural laminated glass applications available on a market. Properties of structural PVB interlayers were determined by static loading tests regarding temperature and loading rate to find out the initial shear modulus. This enables engineering calculations of laminated safety glass. This paper introduces the experimental data gained from static loading tests performed in Klokner Institute CTU in Prague, proves the dependence of shear modulus of PVB interlayer on temperature and loading rate and shows its effect on normal stress redistribution along the cross-section of laminated glass panel perpendicularly loaded.
2. Experimental programme

2.1. Materials and equipment

Two types of PVB foils (Trosifol BG-R-20 and Trosifol Extra Strong) were selected as representative structural interlayers. Trosifol BG-R-20 will be denoted as PVB and Trosifol Extra Strong will be denoted as PVB ES hereafter in the text. Test specimens were made of 2 annealed float glass panes bonded by transparent interlayer with thickness 0.76 mm at shear area 50 x 50 mm in autoclave, see figure 1. Potentiometric linear transducers MMR 1011 were stuck on the sides of the specimen to be able to measure the relative slippage of the glass plies \( u \) in (mm), see figure 2. There were totally 100 specimens with PVB ES and 120 specimens with PVB interlayer tested.

![Figure 1. Nominal dimensions of the specimen.](image)

![Figure 2. Specimen with potentiometric linear transducers and its fixing in metal jaws.](image)

2.2. Test set-up

Test specimens were put into the metal jaws of the testing device TIRA and continuously loaded until their collapse. The experiments were performed as short duration tests where the acting force was permanently increased in three different loading rates and the experiments were controlled by the plies displacement. The loading rate was considered as 2 mm/min - short term, 0,5 mm/min - medium load and 0,125 mm/min - long term load. Moreover, the specimens were loaded at four different temperatures 0, 20, 40 and 60 °C such as room temperature multiplies to provide sufficient range of results. The ambient temperature was measured by Pt 100 sensor. The initial shear modulus was measured as the function of temperature and loading rate.

2.3. Evaluating method

Force transferred between glass plies caused shear strain of the interlayer. This strain can be calculated from the relative slippage \( u \) of the glass plies and the interlayer thickness \( t \), check figure 3. Additional bending moment resulting from the geometry of the testing device was neglected due to its low effect.
For initial shear modulus assessment, the appropriate value of shear stress obtained from the experiment for each specimen needed to be defined. Its acceptable value was determined as the intersection of the circle of 0.4 MPa radius with the corresponding strain-stress curve. This procedure is indicated in figure 4 where one can find out that stress-strain curves are not linear even in relatively low strain values. Therefore, all initial shear modules presented hereafter should be considered as the secant ones.

3. Results and discussion
Specimens were tested in different loading rates at every temperature mentioned above, see table 1. The following charts summarise the most important stress-strain curves obtained from the experiments. Chart in figure 5 shows representative stress-strain curves for structural PVB interlayer. It is obvious that when the temperature increases, the material softens considerably. Suffice it to say, molecular movement and rearrangement are thermally activated processes and temperature increase causes polymer’s relaxation time reduction as mentioned in [4]. When PVB is loaded at 0 °C, it is almost one hundred times stiffer than when loaded at 60 °C as one can notice in figure 5.

Figure 3. Shear strain of the interlayer and shear strain calculation.

\[
y \approx \tan \gamma = \frac{u}{\tau}
\]  

(1)

Figure 4. Initial shear modulus evaluation where temperatures \( T_1 > T_2 > T_3 \).

Figure 5. Representative stress-strain curves for PVB interlayer.
Figure 5 also depicts the influence of the loading rate on the representative stress-strain curves of structural PVB. For example, PVB stiffness increases about 40% in every loading rate step when loaded at 20 °C. Polymer interlayers are visco-elastic materials so lower the rate of the load, the effect of viscosity prevails as mentioned in [5]. When talking about specimens with PVB ES interlayer, these have stiffer stress-strain curves in comparison with those ones having simple PVB. It becomes obvious when comparing figure 5 with figure 6. The clearest difference in stiffness is at 20 °C and 60 °C. These charts also prove that stress-strain curves, as it has been intimated, exhibit non-linear dependence especially at higher values of strain.

![Figure 6. Representative stress-strain curves for PVB ES interlayer.](image)

Figure 5 and figure 6 also show clear effect of temperature on stiffness decrease. It is worth noticing that stress strain curves at 60 °C are rather flat so the shear stress 0.2 MPa must have been taken as the value for initial shear modulus evaluation as explained in paragraph 2.3. On the other hand, stress-strain curves at 0 °C for PVB ES are, apart from softer PVB, really steep and their measurement was on the edge of the testing device accuracy. It is why the average value of PVB ES shear modulus is hereafter stated for all loading rates at 0 °C. The initial secant shear modulus was determined for every stress-strain curve obtained from the experiments according to the following equation

$$G = \tau/\gamma; \quad (2)$$

where $\tau$ is the limit value of shear stress according to figure 4 and $\gamma$ is the corresponding shear deformation determined by equation (1). Table 1 summarises the average values of the initial secant shear modules calculated according to equation (2) from the experimental stress-strain curves.

Table 1 also proves that the initial shear modulus is, as expected, temperature and loading rate dependent. When the temperature is increased, stiffness reduces and when the load is applied faster, stiffness increases. This behaviour is in correlation with visco-elastic assumptions of polymers among which PVB and PVB ES interlayers undoubtedly belong. Depending on the chemical composition, PVB foils have different material properties. PVB ES is in comparison with simple PVB much stiffer in the whole range of temperatures and exhibits sufficient stiffness at 20 °C, which means that the plies in laminated glass panels with PVB ES interlayer are able to carry the load together at this temperature. The highest reduction of PVB ES stiffness is between 20 and 40 °C and for PVB it is between 0 and 20 °C. Both interlayers have negligible stiffness when loaded at higher temperatures than 40 °C. So the plies in laminated glass panels with these interlayers carry the load quite separately at high temperatures because the interlayer is not able to provide sufficient shear coupling. This fact
has significant influence on the structural behaviour of laminated glass panes perpendicularly loaded, especially on the stress redistribution along their cross-section.

Table 1. Initial secant shear modules obtained from experimental data for PVB and PVB ES

| Temperature (°C) | PVB, G (MPa) | PVB ES, G (MPa) |
|------------------|--------------|-----------------|
| 0 °C, Short term  | 144.13       | 1887.94         |
| 0 °C, Medium load| 103.31       | 105.22          |
| 20 °C, Short term| 1.7          | 225.46          |
| 20 °C, Medium load| 1.09       | 61.30           |
| 20 °C, Long term | 0.79         | 0.90            |
| 40 °C, Short term| 0.46         | not specified   |
| 40 °C, Medium load| 0.44       | 0.60            |
| 40 °C, Long term | 0.31         | 61.30           |
| 60 °C, Short term| 0.25         | 0.46            |
| 60 °C, Medium load| 0.14       | not specified   |
| 60 °C, Long term | 0.11         | 0.37            |

3.1. Failure mode
When the sample with PVB was loaded at 0 °C, it collapsed because of glass failure in tension due to the moment evoked by load eccentricity, see figure 1. No delamination was found as displayed in figure 7. On the contrary, when the samples were loaded at 60 °C, the interlayer delamination caused their failure. Delamination of PVB interlayer is shown in figure 8.

4. Effect of visco-elastic interlayer on normal stress distribution in laminated glass panel
The effect of experimentally measured properties of PVB and PVB ES on normal stress distribution is going to be investigated. Double laminated and simply supported glass panel along its four edges with dimensions 3.0 x 2.0 m is shown in figure 9. The cross-section consists of 2 x 10 mm thick heat toughened glass plies and 0.76 mm thick PVB or PVB ES interlayer. Numerical 3D FEM model in Dlubal RFEM was created using brick solid elements with the length 0.1 m without net refinement. This laminated glass panel was loaded perpendicularly to the plane of slab. Nominal value of
uniformly distributed load was 5 kN/m². Thermally toughened glass plies with its nominal strength 120 MPa, Young’s modulus 70 GPa, shear modulus 28.5 GPa and Poisson’s ratio 0.23 were connected by PVB or PVB ES interlayer. Nominal values of secant initial shear modulus of the interlayers were considered according to the measured ones, see table 1, and their Poisson’s ratio was taken as 0.49.

Figure 9. Double laminated glass panel.

To illustrate the stiffness difference between PVB and PVB ES, one may have a look at figure 10 and figure 11. These pictures show values of the main normal stress at the lower edge of the lower glass ply. The load was applied slowly (0.125 mm/min) at 20 °C. The highest values of the main normal stress may be found in the middle area of the slab. The values of the main tensile normal stress at glass plies laminated with PVB are higher in comparison with PVB ES in the whole area. This reflects higher PVB ES shear stress modulus, which provides better shear coupling of the plies. Figure 12 shows main normal stress distribution along the critical cross-section. It is obvious that normal stress distribution is quite homogenous in case of PVB ES and the cross-section is uniform. In case of PVB, glass plies carry the load almost separately. Normal stress changes linearly along the cross section of each ply, which leads to higher tensile normal stress at the lower edge of lower ply. The situation is almost the same when the load is applied slowly at 60 °C according to figure 13. But here, the glass plies function separately in case of both interlayers. Normal stress is linearly distributed along the cross-section of each ply. Considering PVB ES, it is not even able to provide sufficient shear coupling at this high temperature but, in comparison with PVB, it provides lower stress values. Several simple approaches enabling to calculate normal stress distribution along the cross-section in laminated glass panes are specified in [6].

Figure 10. PVB, main stress lower edge of lower glass ply, 20 °C, long term loading.

Figure 11. PVB ES, main stress lower edge of lower glass ply, 20 °C, long term loading.
The same value of uniform load (5 kN/m²) was applied to show the different main normal stress distribution along the cross section at different temperatures. It becomes imaginative that normal stress increases with increasing temperature along the cross section with PVB interlayer. This fact is proven in figure 14. The same applies to PVB ES. The highest values of main tensile stress are reached on the edge of the lower glass ply for all temperatures. The absolute highest value was merely 16.3 MPa which is far below the normal stress resistance of thermally toughened glass. The FEM calculation was executed by 1 st order. If one observes maximum deflection in the middle of the span, the situation becomes interesting too. Higher the temperature is, higher deflection occurs. This may be understood as increasing bending compliance of this glass panel. Rising deflection-temperature curves for PVB are drawn in figure 15. The exact deflections were calculated for measured temperatures. The deflection-temperature dependence is almost linear which indicates that the growth of compliance is almost linear too.
5. Conclusion

In this paper, details regarding initial shear modules of PVB and PVB ES depending on temperature, loading rate and their effect on normal stress distribution along the cross-section of the laminated glass panel were elaborated. Stress-strain curves obtained from the static shear load tests proved strong dependence of these interlayers on temperature and loading rate. This is the sign of visco-elastic behaviour which should be kept in mind when designing laminated glass panels. The paper also showed several examples of normal stress distribution along the cross-section of double laminated glass panel simply supported along its four edges as well as the comparison of the effect of PVB and PVB ES different properties on its normal stress distribution and maximum deflection. PVB ES seems to be stiffer than PVB because of lower normal stress values and lower deflection when used in laminated glass. Long time static shear loading test should be executed in order to illustrate time dependent behaviour of PVB interlayer. In practice, it is important to check the type of used polyvinyl-butyl interlayer regarding the use of laminated glass element because not all of them have the same properties. Stiffer interlayers should be used mainly in case of load bearing structural elements such as floors, roof panels, staircases and balustrades. Softer interlayers can be used in short term loaded laminated glass elements such as facades and windows.

Acknowledgement

This research was supported by grant CTU No. SGS16/136/OHK1/2T/11 and grant No. 16-17461 S of the Czech Science Foundation

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