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RESEARCH ARTICLE

Finite element analysis of laminated structural glass plates with polyvinyl butyral (PVB) interlayer

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Abstract

The study deals with the mechanical behaviour of laterally loaded structural glass laminated with polyvinyl butyral (PVB) interlayer. To evaluate the influence of the mechanical behaviour of PVB in structural glass plates, a finite element model was developed. The numerical model was verified on the basis of the results from the literature and by own experimental results, completed in accordance with the standard EN 1288-3. The glass plates were loaded by four-point-bending. In each case the specimens had the same ichnographical size, however the thickness of the glass plates and the laminating film was different. The fundamental aim of the experiment was to evaluate the behaviour of different structural configurations and to validate the numerical model. The PVB film was considered to be a non-linear elastic hardening material in the numerical analysis.

The final goal of the study was to conduct a parametric examination of a two-layered glass plate bent in two directions. By reducing the thickness of laminating film, the structure becomes more rigid, so that deflection has reduced. During the parametric studies asymmetrically built-up plates were examined. The results showed that the maximum value of tensile stress – on the bottom surface of the lower layers – is reduced by 15-20%, if the lower layer is thinner and the upper layer thicker.

Keywords

structural glass; modelling and simulation; polyvinyl butyral; non-linear behaviour laminate

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1 Introduction

The article and the results are based on the M.Sc. Thesis of Gergely Molnár [1]. Glass may be one of the most popular materials in architecture. After the Neolithic, Bronze and Iron Ages, we can confidently claim the new millennium as the Glass Age. Due to the architectural trend of transparency, the use of glass is becoming widespread. Thanks to the evolution of mechanics, glass can be used not only for windows, but facade walls, and roofs above large spaces. Structural glass should be viewed as a sandwich, since modern design in architecture uses laminated glass. The first limit in design to be verified should be the deflection limit. Therefore, we must first understand the elastic behaviour of structural glass. Most of the studies done with laminated structural glass are based on experimental results [2–9]. However, the architectural design methods [10] use an analytical formula based on Wölfel's method on sandwich structures [11]. Compared to the complexity of the topic, there are relatively few comprehensive numerical examinations of laminated structural glass [12–14].

The present study aims to develop a numerical model verified by experimental results and to examine the elastic mechanical behaviour of structural glass laminated with PVB film.

After the short introduction of the mechanical behaviour of the laminated structural element, the laminating films material properties and the laminating technology will be reviewed. The overview on experimental setup will be presented which will be used to verify a finite element model developed for a parametric study conducted on laminated structural plates. Finally, the results and a brief summary closes the paper.

2 Mechanical behaviour

From the mechanical point of view, single layer and laminated glass plates must be treated differently. The flexible behaviour of monolithic glass is a well-defined, basic strength of materials problem. Laminated structures are different; to define the extra load bearing capacity caused by the interaction of the interlayer is a continuing challenge.

After lamination, the plate is between two states. The lower limit is when there is no connection between the glass layers.

When the laminates behave like a monolithic plate due to the bond connecting them, the laminate has reached the upper limit. Fig. 1 illustrates the relationship between deflection and stress of a two-layered glass laminate.

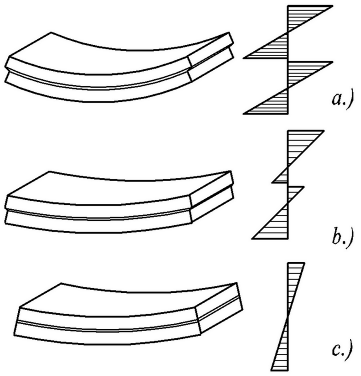


Fig. 1. Interaction between the glass layers (a. none; b. partial; c. complete)

3 Laminated structural glass

3.1 PVB film

Initially the material model provided by Kuraray Europe GmbH was used (Fig. 2). It was assumed that the PVB is an isotropic, homogenous material. Polyvinyl-butyral is a hyperelastic material with a hardening profile. The laminating layer must have at least 20 N/mm^2 tensile strength, the ultimate strain should be more than 250% at 23°C [15].

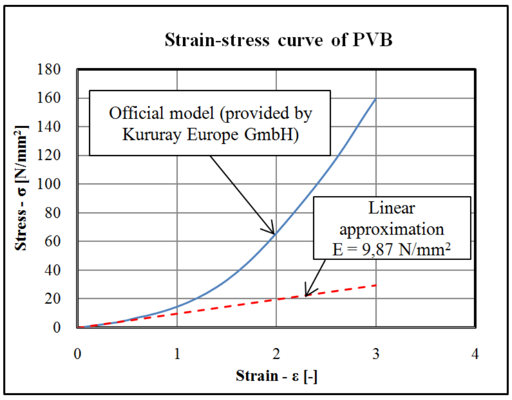


Fig. 2. Strain-stress curve of PVB [15]

The authors of reference [16] completed mechanical testing on different kinds of aged samples, uniaxial tensile tests on solely aged interlayer material on one hand, and tests on aged laminated glass samples on the other hand. Their results showed that with a rise in temperature, the shear modulus is reduced (Fig. 3). When the environment is humid, or there is significant UV radiation the film loses its stiffness too.

As shown in Fig. 3, PVB loses its stiffness as time passes. Therefore a different reducing factor for long and short term loads must be defined.

It is common to use multiple layers of film (0.38 mm, 0.76 mm, 1.52 mm) to laminate the glass plates, as in most applications a single layer is not safe, because after failure the PVB film plays a significant role in the resistance of the structural element [16].

Laminated glass is used in architecture as well as in the automotive industry. The reason of the popularity is that it combines the strength and transparency of the glass and the safety of the laminating film. It makes glass structure resistant after failure. When the laminated safety glass breaks, the fractured pieces remain attached due to the interlayer. Safety of property and people means limiting the risk of injuries in the case of failure as well as protects against vandalism and burglary. A laminated plate consists of two or more glass planes and interlayer films between them. The interlayer is also transparent, but it has a hyperelastic mechanical behaviour, so it can reduce the loss of stability after fracture.

3.2 Manufacturing of laminated glass

There are two major air removal processes from the laminating film and the glass surfaces: the nip-roll or calendar method and the vacuum process. The first is more common for architectural purposes because of the large, flat laminated glasses. Nip-roll de-airing ovens have one or two heating zones and one or two pairs of robust, rubber-surfaced cylinder rollers. First the glass sandwich is rolled on 35°C in the first part of the oven, than the sandwich is passed into the second part, where it gets rolled on 60–70°C. The aim of the process is to remove all the air from the PVB and glass surface and make a full-surface adhesion between the surfaces, to avoid premature separation in the autoclave process. Then it is important to continuously seal the edges of the laminated glass so that no air can penetrate during the autoclave process.

De-airing in a vacuum is commonly used in the automotive industry. The specimens for the present experiment were also manufactured in this way. First, the sandwich plate was placed in a vacuum-bag, then most of the air was evacuated. This process is the "cold vacuum" part of the procedure. The duration of the process is 10 minutes, and the intensity of the vacuum is 0.1-0.2 bar. After the cold evacuation procedure the bag was sealed, heated up to 100°C–120°C for a period of 20 min, with the intensity of the vacuum the same as in the "cold" process.

The autoclave process is the last step in the production of laminated glass. To achieve the best quality, the correct temperature and pressure must be chosen. According to the layer structure and the glass thickness the procedure characteristics are different. The optimal temperature is approximately at 140°C, and the right pressure is 12 bars. But the duration of the process can last 1 to 6 hours. At the end of the process the glass and the PVB film are bonded chemically by hydrogen bonding bridges. The PVB-glass adhesion depends on the hydrogen bonding bridges between the water-compatible groups of the glass surface and the polymer (Fig. 4). Thus, it is very important to clear the glass surface before the whole procedure.

Two-layer laminated glass plates, fabricated by this procedure are studied experimentally in the current research.

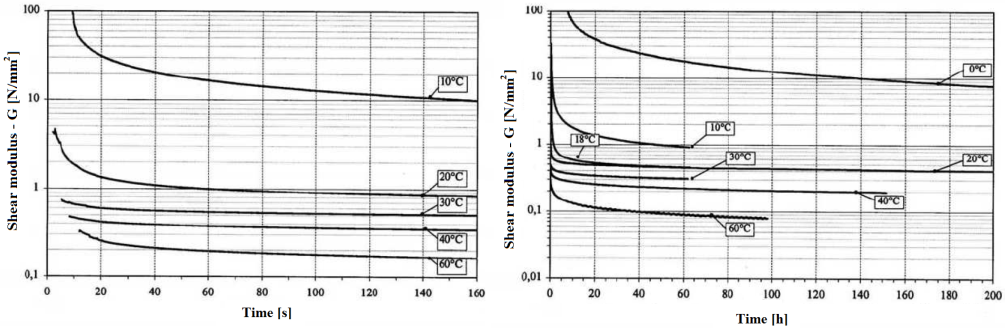


Fig. 3. Shear modulus versus time and temperature [16]

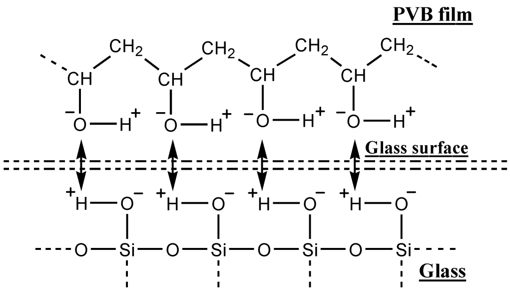


Fig. 4. PVB-glass adhesion [15]

4 Experimental study

4.1 Test setup

As explained in the introduction, the aim of the project was to develop a numerical model capable of making parametric analysis on the mechanical behaviour of two-layer laminated glass plates bent in two orthogonal directions (biaxial bending).

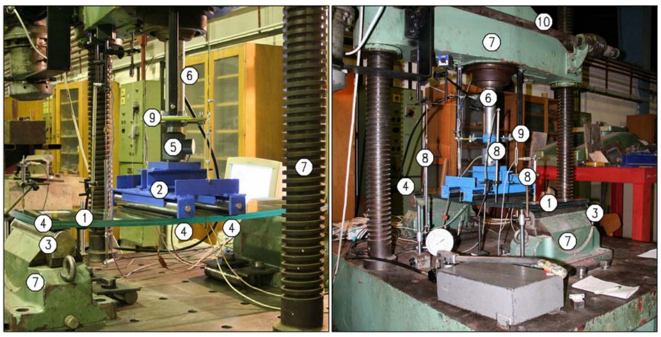


Fig. 5. Method of test by four-point-bending – EN 1288-3:2000 [17] (numbering is in Fig. 6)

The experiments were done in the Structural Laboratory of BME Department of Structural Engineering. Because of the complex mechanical properties of the laminating film, the numerical model must be calibrated with experimental results. For this reason a series of measurements based on the standard EN 1288-3:2000 [17] (Fig. 5 and 6) were undertaken. A displacement driven by hydraulic load equipment was used, and the deflection at the middle of the board and at supporting rolls was measured.

In each case, the specimens had the same ichnographical size (1100 mm × 360 mm), but the thickness of the glass plates and the laminating film was different. The laminates also had different layer structure. All laminates were symmetrical, constructed with two identical glass layers and a PVB layer (a 2-layer-10 mm thick plate consists of 2 layers of 10 mm thick glass plates), as detailed in Tab. 1.

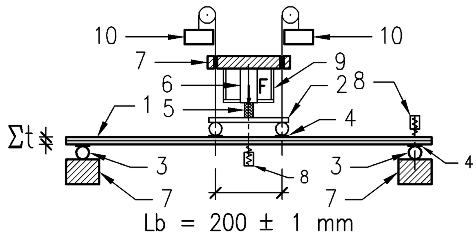


Fig. 6. Method of test by four-point-bending (EN 1288-3:2000 [17]) where, 1. specimen (1000 × 360 mm), 2. loading frame, 3. steel rollers, 4. rubber stripes (3 mm thick, 40 ± 10 IRHD according to ISO 48:1994), 5. transducer (MOM LOAD CELL 7924 A), 6. hydraulic jack (LUKAS HP 10/150), 7. supporting frame, 8. inductive transducer (HBM WA 100 TK), 9. bracing for the hydraulic jack, 10. counterweight

In every case the PVB film had a 0.38 mm thickness, but for safety reasons, 2 or 4 films as a layer were applied.

Tab. 1. Specimens

No.	Thickness of glass plates	Thickness of PVB layer
[-]	[mm]	[mm]
1	6	0.38
2	6	0.76
3	6	1.52
4	8	0.38
5	8	0.76
6	8	1.52
7	10	0.38
8	10	0.76
9	10	1.52

4.2 Failure mode of glass plates in bending

Glass itself does not have any ductility, so on its failure it immediately disintegrates. But in most cases the laminated structural element may have some residual load-bearing capacity, as the laminating film prevents disintegration, and ensures locking between the glass particles. The failure process of laminated glass plates have three phases, as shown in Fig. 7.

The first stage is where both glass layers carry the load. The

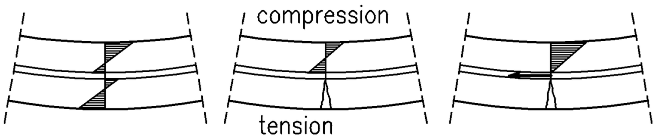


Fig. 7. Theoretical failure stages (stage 1 – left, stage 2 – middle, stage 3 – right) [18]

stress distribution is illustrated in Stage 1 in Fig. 7. At this stage the only load on the laminating film is from the shear stress.

As the second stage in Fig. 7 begins, the bottom – tensioned part – plate breaks, when the lower glass can no longer carry the load. The stress distribution in the upper layer becomes symmetrical, the stress value being the same on both edges. In this stage the laminate can carry less load, its stiffness is decreased, but it is capable of resisting more deflection. In Fig. 8 the second stage could be recognised, the lower glass plate has failed, but the upper glass layer still carries the reduced load.

In the third stage the upper glass plate fails, so the balance off the cross-section is only held by the tensile strength of the PVB foil. Due to the locking between the particles in the upper glass layer it can take compression, so the cross-section maintains its equilibrium.

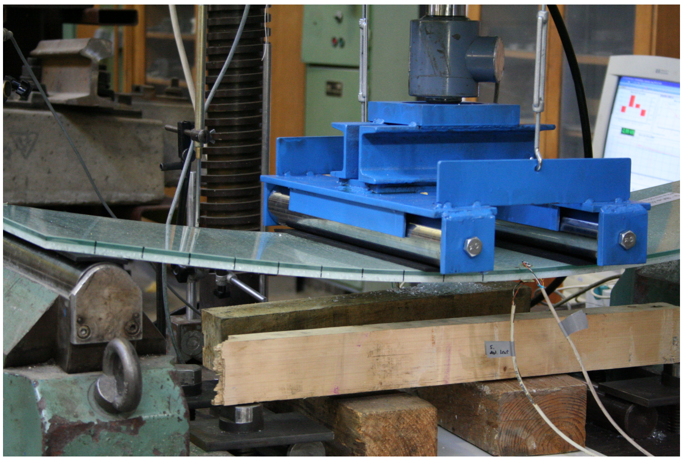


Fig. 8. Failure stage 2 – broken lower glass plate

4.3 Experimental results of bending test

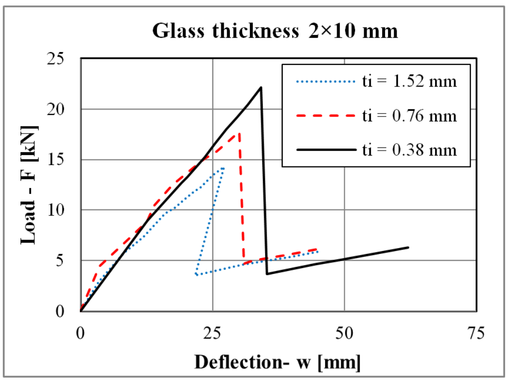


Fig. 9. Deflection-load curves in the function of PVB thickness

The deflection values shown in Fig. 9 are calculated using the middle deflection minus the deflections at the supports.

The summary of the experimental values of the effective bending stiffness and the effective strength taken from the load-deflection curves, is given in Tab. 2 made by the numerical model presented below and the experimental results.

Tab. 2. The effective strength versus effective bending stiffness calculated as a monolithic beam

No.	Effective Stiffness [Nm^2]	Effective strength [MPa]
1	6.22	185.88
2	5.89	168.59
3	6.80	180.23
4	14.26	166.23
5	13.51	200.08
6	13.59	210.55
7	25.43	198.61
8	23.20	165.55
9	20.71	134.00
Average	14.40	178.86
Standard deviation	7.40	23.32
Relative standard deviation	51.36 %	13.04 %

Tab. 2 shows that the effective strength has no correlation with the effective stiffness of the laminated glass plate. The effective strength was calculated with the numerical model, at the final load state.

The deflection values show in Fig. 9 that, after the failure of each glass plate, the laminate still has stiffness and load-bearing capacity. Stage 2 commences as the lower plate fails, leaving only one glass layer to resist the load. The effective stiffness of the structure is being reduced, the variance PVB thickness has no relevant effect on the effective thickness in stage 2. In stage 3 the plates could no longer carry any significant bending load.

Deflection values show in Fig. 9 that, as the thickness of the PVB layer grows the bending stiffness of the structure decreases.

The experimental results are used as a basis of numerical model development.

5 Finite element model

5.1 General

During the analysis the material model of the PVB was highlighted during the experiment, since there is no standardized set of requirements for film production; and the quantity of the PVB resin has a significant effect on the mechanical properties of the film. The structural glass plates are relatively slim compared to the rest of their size; therefore they easily go through large deflections. For this reason, membrane stresses has to be taken into consideration, because of the non-linear geometrical behaviour. Imperfections were not considered, since the present structure is not sensitive to stability problems. Therefore a numerical model was built in geometrical and physical non-linearity with ANSYS 12.0 finite element software.

5.2 Model development

First, a numerical model for the preliminary calculation of the experiment was developed. The geometry used to validate the finite element model (denoted as first model) is shown in Fig. 10/b. But the parametrical study is conducted on plates bent in two directions (denoted as second model) (Fig. 10/a).

An assumption was made that the glass has a linear elastic material model, with the modulus of elasticity of 70 000 MPa and the Poisson's ratio of 0.22 [11]. The glass and the PVB are considered to be isotropic and homogeneous. In contrast to the glass, the PVB has a non-linear elastic hardening behaviour, which was approximated by a multi-linear material model. The stress-strain curve is shown in Fig. 2, and it is given in tabular format in Tab. 3, [15]. The values presented in Tab. 3 are given for 23°C. A value of 0.45 is used for the Poisson's ratio of PVB. There is no information about the triaxial behaviour of the PVB material. However, as the PVB is homogenous, isotropic and elastic material, the unidirectional tensional characteristic is used in the finite element model.

The finite element model was built of SOLID95 element. The element has 20 nodes, and each node has three degrees of freedom (3 displacements). The element type can handle large deformations, large displacements, the creep and relaxation, as well as the initial stress field in the plates.

Tab. 3. Multi-linear model of PVB film

ε [-]	σ [N/mm^2]	ε [-]	σ [N/mm^2]	ε [-]	σ [N/mm^2]
0.1	0.98	1.1	17.45	2.1	73.86
0.2	1.96	1.2	20.61	2.2	82.08
0.3	2.93	1.3	24.24	2.3	90.46
0.4	3.91	1.4	28.39	2.4	99.07
0.5	5.32	1.5	33.11	2.5	108.03
0.6	7.11	1.6	38.49	2.6	117.46
0.7	8.55	1.7	44.51	2.7	127.55
0.8	10.27	1.8	51.13	2.8	138.34
0.9	12.31	1.9	58.28	2.9	149.13
1	14.69	2	65.89	3	159.30

Each glass plate and the PVB film were meshed one by one with one element in vertical sense. The numbers of the elements must match on the connector surfaces. The thickness of the glass plates and the laminating film could be significantly different. Therefore, the finite elements width-to-height ratio of the laminating film is high, but those of the glass layers are low, which can lead to shear lock effect. The width/height ratio of the PVB film was 20 in order to avoid such shear locking.

The boundary conditions are shown in Fig. 10/a and Fig. 10/c, the supported nodes in z direction were on the bottom edge of the bottom glass plate. The model was supported in a statically determined way in the $x-y$ plane (Fig. 10 and 11).

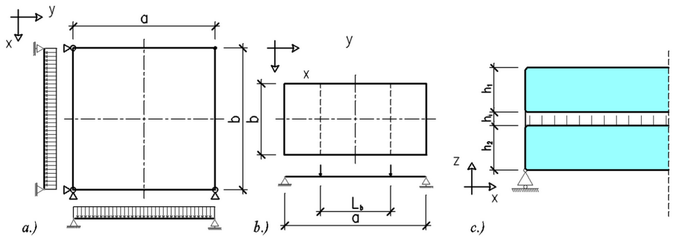


Fig. 10. Schematic geometry used for the numerical models (a. parametrical model; b. experimental set; c. cross-section of the glass plate)

5.3 Model verification

To validate the material model of the PVB interlayer the uniaxial bending experimental results presented above were used. Next, to verify the biaxial bent plate model, the displacement results were used [13]. Finally, the validated PVB model from the uniaxial model, and the sandwich model (biaxial bent model) from the second was combined. The parametric study is executed on the validated numerical model, on laterally loaded laminated structural glass bent in two directions with constant pressure.

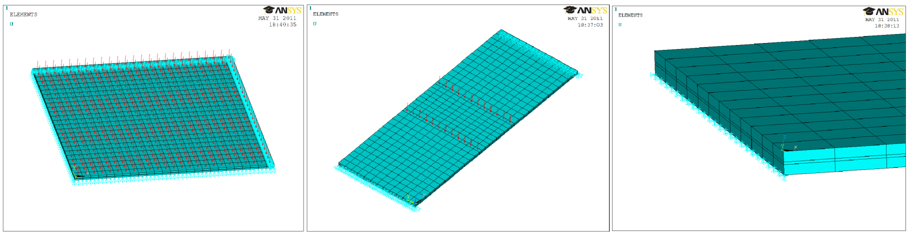
5.3.1 Material model of PVB

By the first finite element model, the displacement for the failure load was calculated at the end of the first state. Then the measured value of deflection is compared to the calculated one. Thus, the elastic behaviour of the experimental setup was analysed numerically. Tab. 4 shows that the standard deviation of the differences is high, but the averaged error is low, therefore the measured and the calculated values match. It may be assumed that the glass, and the loading sequence have not had a large deviation, therefore it appears that the material model for the PVB is correct, but the elasticity of PVB has a large deviation itself. It is observed that the numerical model has large differences with thin plates at large deflections. So the use of the model is recommended with larger glass planes at middle intensity load.

Tab. 4. Difference between the calculated and the measured values at the failure of the lower glass

No.	Layer structure	Difference	Absolute difference
1	6 - 0.38 - 6	8.32%	8.32%
2	6 - 0.76 -6	6.65%	6.65%
3	6 - 1.52 - 6	-9.58%	9.58%
4	8 - 0.38 - 8	3.79%	3.79%
5	8 - 0.76 - 8	0.41%	0.41%
6	8 - 1.52 - 8	-10.99%	10.99%
7	10 - 0.38 - 10	6.85%	6.85%
8	10 - 0.76 - 10	3.47%	3.47%
9	10 - 1.52 - 10	0.55%	0.55%
Average		1.05%	5.62%
Standard deviation		6.98%	3.79%

Fig. 11. Numerical models in ANSYS 12.0 (a. quarter of the biaxial bent plate; b. experimental set; c. cross- section of the glass plate)



5.3.2 Biaxial bending

The second finite element model was verified according to the results of Aşik [13], based on the following setup: the glass plate's ichnographical size was 1 600 mm × 1 600 mm, it had two layers of glass and each layer was 5 mm thick. The thickness of the PVB was 1.52 mm, with the modulus of elasticity of 689.5 kPa. The load was a constant pressure on the top plate's top surface.

The comparison shows in Tab. 5 that the differences are decreasing with the increment of the load. The error comes from the different geometrical equation. The author [13] uses only the modification presented of Karman, but the ANSYS applies the whole Green-Lagrange-tensor. Based on these results it can be assumed that the finite element model follows properly the elastic mechanical behaviour of the structural glass plates bent in one or two direction.

Tab. 5. Differences of the current model and the reference [13]

Load	Deflection (Aşik)	Deflection (current set)	Difference
[kPa]	[mm]	[mm]	[%]
6	22.08	23,60	6,44
7	24.06	25,48	5,57
8	25.89	27,21	4,85
9	27.57	28,82	4,34
10	29.23	30,32	3,59

6 Parametric study

6.1 General

The parametric study completed on a two-layered glass plates bent in two directions, as a function of the PVB and glass thickness, using a 1500 mm × 1500 mm plate, with 6 – 0.76 – 6 mm layer structure and 10 kPa surface pressure as a reference setup.

The stress results have an adequate match to [13]. According to the numerical tests, the first principal stress reaches the maximum value at the middle of the laminated plate's lower glass's bottom surface (Fig. 12, Fig. 13). But in every other case the maximum peak of the tension stresses concentrates to the glass plate's corner, near to the supports. Also the in-plane shear stress has the maximum value near the corner (Fig. 13).

The reason of this phenomenon is the corner lifting force which is the result of the concentrating torsional moments. The bending load tries to lift the rectangular plate's corner, but the simple support keeps the edge in place. The behaviour could be recognised in monolithic plates, but in the case of high width-to-thickness ratio the governing non-linearity increases the effect of the concentrating torsional moments.

6.2 Width-to-thickness ratio

Because of the governing non-linearity the error between the deflection values calculated with small displacement theory and large displacement theory is growing by raising the load (Fig. 14). The reason of the phenomena is in the geometrical equations. The whole Green-Lagrange-tensor includes quadratic parts of the deflection. Small displacement theories neglect these values. Increasing the width-to-thickness ratio of the plate, these quadratic values grow, and give more membrane rigidity to the structural element. Fig. 14 shows that using small displacement theory gives accurate results only at low load intensity.

6.3 Thickness of the PVB layer

In architectural practice, the thickness of the laminating film is not constant. It is true that a PVB layer's thickness is 0.38 mm, but for safety reasons two PVB layers (0.76 mm) are used for roof glazing, and four layers (1.52 mm) for glass bars. Therefore, the effect the reducing of the PVB film thickness is to be investigated.

The numerical investigation showed that the maximum value of deflection is a function of the PVB thickness as cubic polynomial curve. Fig. 15 illustrates that the decrement of the thickness of the laminating film increases the shear rigidity of the laminating film. The minimum film thickness, however, shall be chosen carefully: although the thickness decrease improves the rigidity, one has to consider the residual strength demand for safety reasons as the interlayer carries 100% of the tension in the third stage.

6.4 Thickness of the glass plates

The results confirmed that the value of maximum deflection is independent from the asymmetrical layer structure. The deflection value was the same with the layer structure $h_1 = 6$, $h_2 = 10$ mm, $h_1 = 8$, $h_2 = 8$ mm and $h_1 = 10$, $h_2 = 6$ mm, as shown in Fig. 16. The maximal strain values, however, showed different evolution. Fig. 17 confirms that the maximal principal stress on the bottom plate's bottom surface is decreasing by making the bottom plate thinner. The stress distribution in Fig. 18 illustrates the reason of the phenomena. This result is significant, because the effective tensile strength of the glass is much lower than its compressive strength. It shows that would be advantageous to use asymmetrical layer structure at laterally loaded laminated structural glass plates.

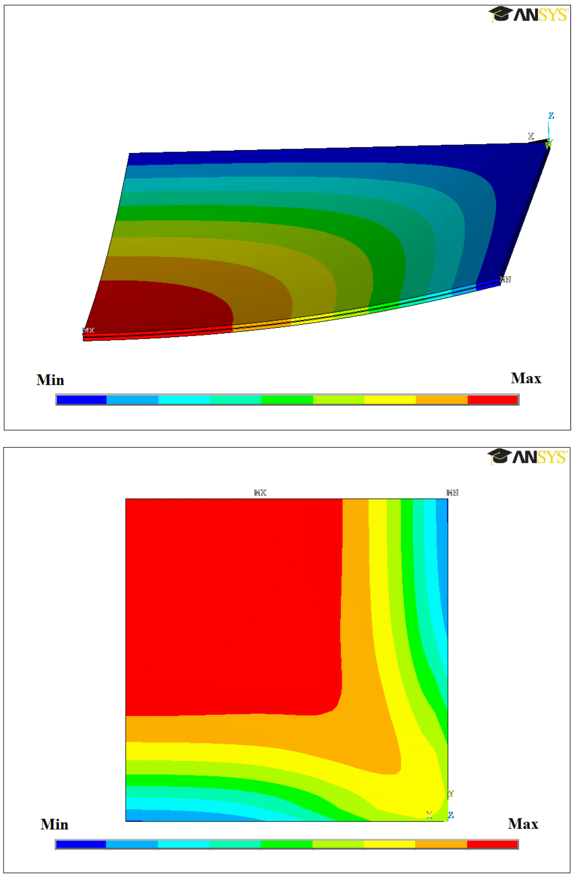


Fig. 12. Results of a biaxial bending – quarter of the reference plate (top – deflection; bottom – 1. principal stress on the bottom layer bottom surface)

7 Conclusion

In the current research, experimental and numerical studies are completed on two-layer glass laminated plates. The typical failure stages of the laminated glass elements are observed in the experiments.

Numerical model of laminated glass with PVB was developed and verified on the basis of experimental results. The model is used in a parametric analysis to investigate the mechanical behaviour of the laminated structural glass plates.

The glass planes undergo large deflections, so the geometrical non-linearity appears. Neglecting the quadratic components of the Green-Lagrange-tensor gives false results at high load intensity over the width-to-thickness ratio of about 60, therefore large displacement theory is needed.

The PVB material has a hardening non-linear characteristic, according to the experimental results it is not perceptible until the glass fractures, therefore the non-linear model for PVB cannot be used until failure. It is confirmed by the experimental and numerical studies that increasing the thickness of the PVB the effective rigidity of the structural element is decreased. The result showed that the maximum value of tensile stress – on the lower layers bottom surface – is reduced by 15-20%, if the lower layer is selected thinner and the upper layer is selected thicker with the ratio of 2 to 1. It is advantageous to use asymmetrical layer structure at laterally loaded laminated structural glass plates.

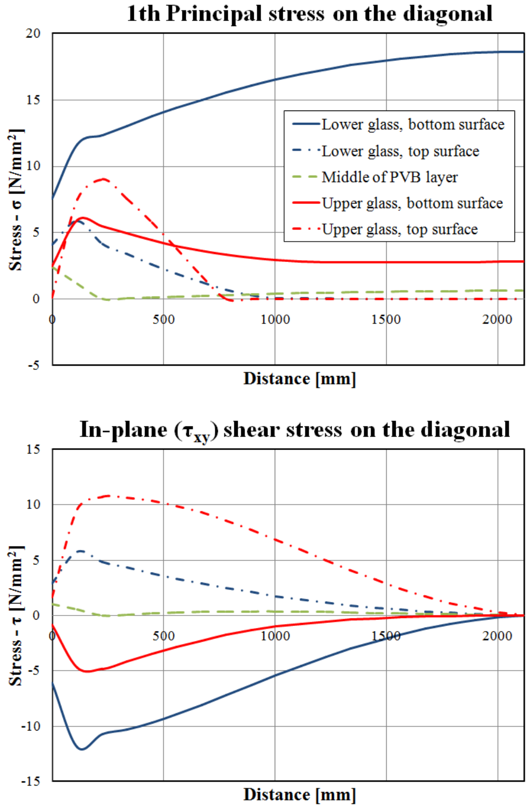


Fig. 13. Stress distribution along the half of the plates diagonal (top – 1. principal stress; bottom – in-plane shear stress)

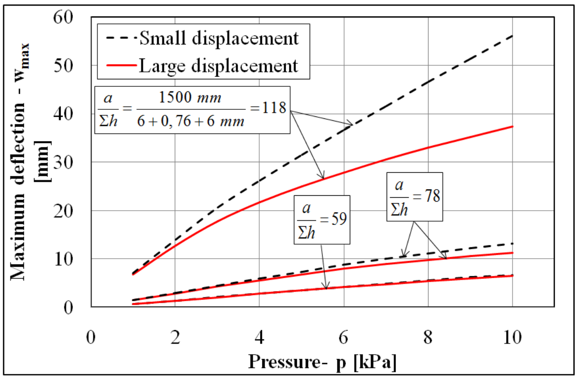


Fig. 14. Maximum deflection in the function of the width-to-thickness ratio

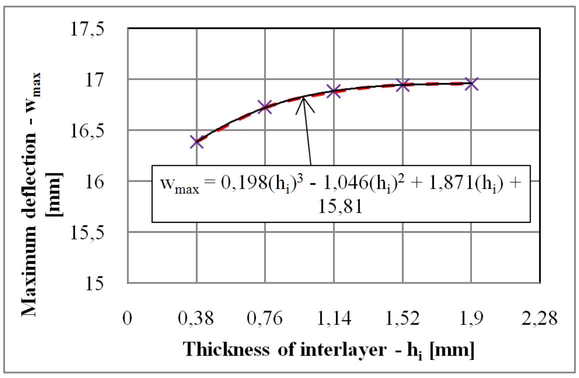


Fig. 15. Deflection versus thickness of PVB film

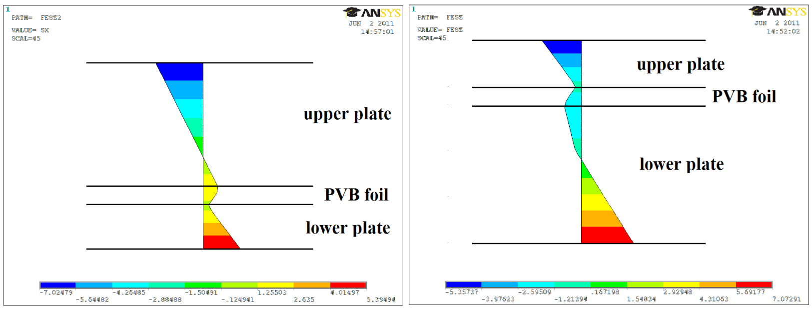


Fig. 18. Schematic axial stress distribution in the glass plates

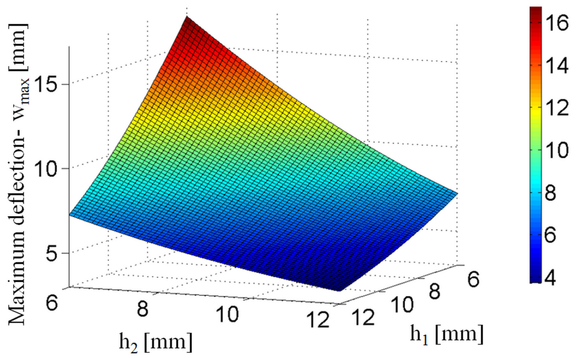


Fig. 16. Maximal deflection function of glass thicknesses

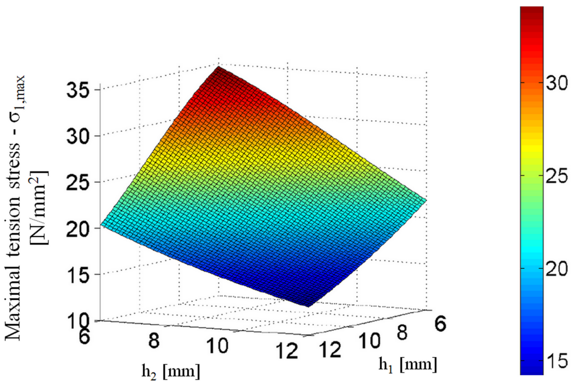


Fig. 17. Maximal principal stress function of the thickness of the glass layers

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