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FOUR POINT BENDING TESTS OF DOUBLE LAMINATED GLASS PANELS

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Abstract: *Looking at a current architecture, we may notice many examples of glass load bearing structures such as beams, panes, balustrades, columns or even stairs. These elements are mostly made of glass panels laminated together by polymeric interlayer. Laminated glass is a suitable structural element because of its residual load bearing capacity when overloaded. Glass fragments stay adhered to the interlayer and do not fall down potentially causing an injury. Objectively, there is still an overall lack of knowledge in task of shear forces transfer between the panels profoundly preventing more extended use of laminated glass in practice. Furthermore, glass as a structural material exhibits a wide range of tensile strength which becomes a crucial fact when designing laminated glass panels. Civil engineers currently tend to design laminated glass members on the safe side regardless the individual plies interaction. This paper is focused on double laminated glass panels in four point bending test - particularly normal stress distribution along the critical cross section, maximum tensile strength of different glass types and residual load bearing capacity. Experimentally verified tensile strength of different glass types and interlayers stiffness help engineers to design safer and more economical laminated glass constructions.*

Keywords: laminated glass, tensile strength, polymeric interlayer, normal stress, residual capacity

1. Introduction

Laminated glass composed of two or more glass plies bonded by transparent polymeric interlayer is the subject of a current research (Serafinavičius and Lebet et al. 2013; Serafinavičius and Kvedaras et al. 2013). Process of bonding is usually performed in autoclave under constant pressure of 0.8 MPa. Currently, the use of laminated glass instead of single layered glass becomes necessary because of its residual load bearing capacity. Glass fragments stay adhered to the interlayer thus the use of laminated glass above the heads of users such as roof panels, staircases and balustrades is enabled. Moreover, in case of one glass ply breakage, the remaining ones are still able to carry a part of the load possibly enabling the users to leave an endangered area. There is not any officially approved European code determining the design strength of glass regarding its production process or composition not even talking about interlayers shear stiffness significantly influencing stress distribution in laminated glass. Therefore, engineers are these days considerably limited in task of laminated glass design which leads to expensive and robust laminated glass elements. This paper introduces the experimental data obtained from four point bending tests of double laminated glass panels performed at Faculty of Civil Engineering CTU in Prague, describes the experimental programme and compares the experimental data of one representative specimen to the analytical calculation.

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2. Experimental programme

2.1. Materials and equipment

Three types of glass were examined in four point bending tests such as float glass – 10 specimens, thermally strengthened glass – 4 specimens and thermally toughened glass – 5 specimens. Both plies in the laminated panels were made of the same glass type. Plies were laminated with two types of the interlayer such as EVALAM and PVB 0.76 mm thick. Static schema of four-point bending test is shown in Fig. 1. Nominal dimensions of glass panels were 1100 x 360 mm. The tests were performed in MTS loading device. There were totally 8 strain gauges LY 11-10/120 attached to the glass surface - 5 strain gauges in compression (upper glass ply) and 3 strain gauges in tension (lower glass ply) as displayed in Fig. 2. Vertical deflection was measured by displacement sensors. Their position is, as well as transversal cross section of the test specimen, shown in Fig. 3.

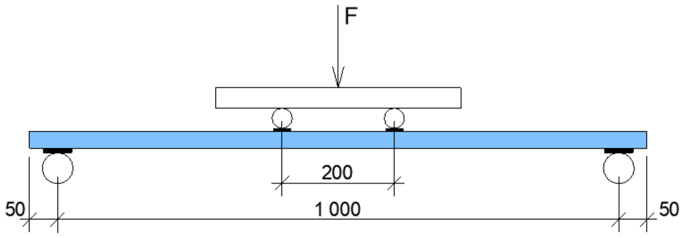

Fig. 1: Static schema of four point bending test

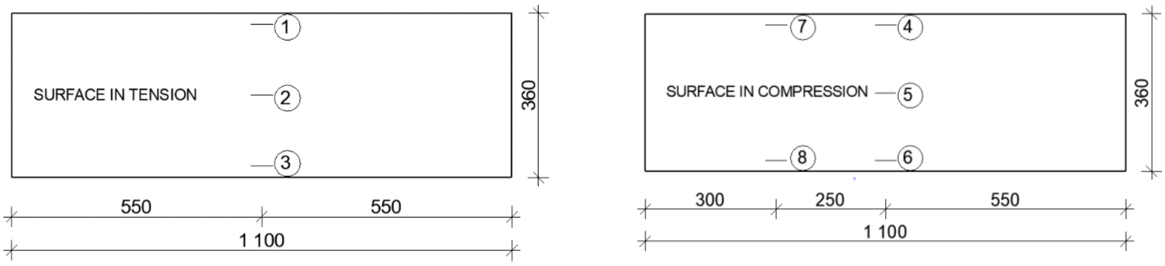

Fig. 2: Strain gauges position on the test specimen

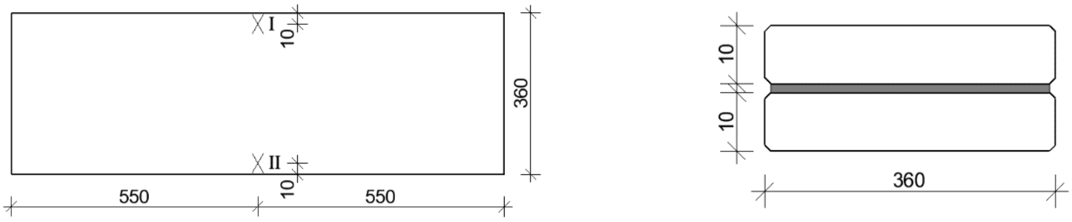

Fig. 3: Displacement sensors position on the test specimen and laminated panel cross section

2.2. Test set-up

The loading was in displacement mode controlled with the cross-head speed 1.8 mm/min. Every test specimen was loaded in two steps. The first loading step led to the lower glass ply breakage when its tensile strength was exceeded. Then the specimen was unloaded and each loaded again in the second step to find out its residual load bearing capacity. As soon as it was achieved, the whole laminated panel collapsed. Values of all strain gauges and displacement sensors were offset before each loading step. Temperature during the experiments was in range of 20-22 °C.

3. Results

The following paragraph concludes representative experimental data achieved in the experiments. Chart in Fig. 4 shows the first loading step stress-force relationship of double laminated thermally strengthened glass panel with EVA interlayer measured by strain gauges number 2 and 5. Maximum tensile stress value measured at lower glass ply breakage was 83.8 MPa at the acting force 9.1 kN. Analytical calculation considering full shear coupling of the laminated panel and taking Navier hypothesis into account would predict tensile stress to be 76.0 MPa which indicates that EVA interlayer was actually not able to provide full shear coupling of the glass plies because measured tensile stress was higher than the calculated one. When comparing the shapes of experimental stress-force curves, it is noticeable that they are linear and almost symmetrical along the force axis. It proves the fact that normal stress was almost symmetrically distributed along the cross section during the whole loading step. This is furthermore supported by the maximum pressure 84.5 MPa measured by strain gauge number 5. When checking the remaining strain gauges data placed symmetrically to each other along the cross section, symmetrical normal stress distribution is confirmed, as displayed in Fig. 5.

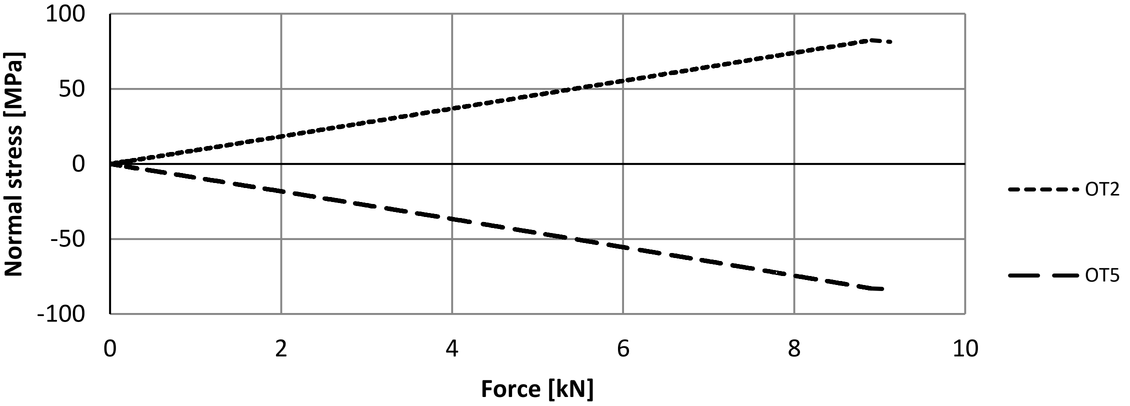

Fig. 4: Stress-force relationship of the representative test specimen made of thermally strengthened glass laminated with EVA loaded in the first step measured by strain gauges 2 and 5

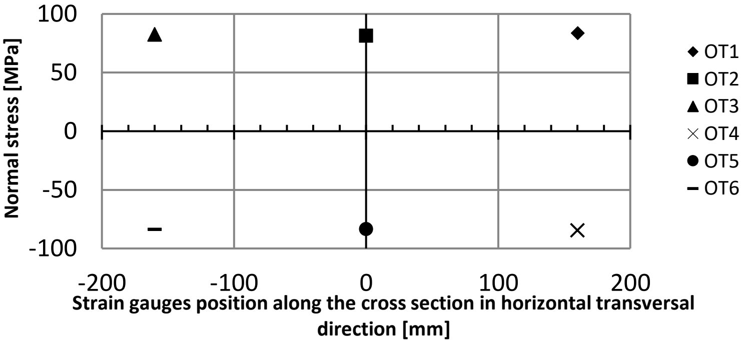

Fig. 5: Normal stress distribution along the cross section in the middle of the span-glass failure, 1^{st} step

Chart in Fig. 6 shows deflection-force relationship of this test specimen (thermally strengthened glass, EVA interlayer) loaded in the first step. Both displacement sensors show almost linear dependences up to the lower glass breakage. Maximum vertical deflection at this moment was measured by sensor number I – 15.8 mm. Analytical calculation anticipating full shear coupling of the plies would predict maximum deflection 10.7 mm which means that EVA interlayer actually decreased bending stiffness of the laminated panel.

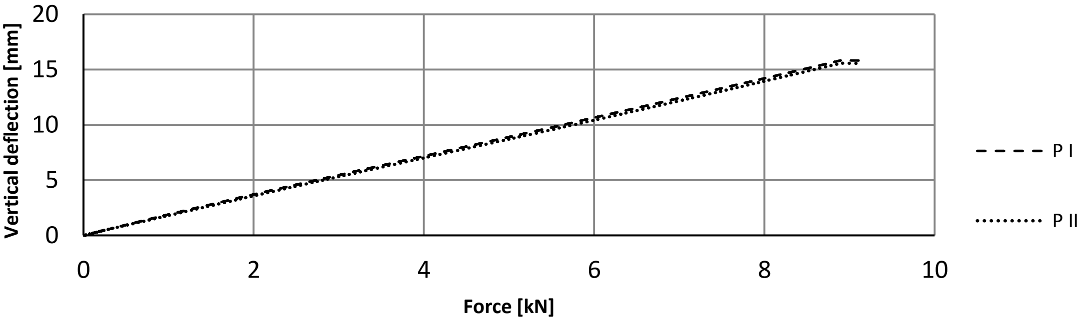

Fig. 6: Deflection-force relationship of representative test specimen - thermally strengthened glass

Tab. 1 summarizes the maximum and minimum measured tensile stresses, acting force value and vertical deflections at the lower glass ply breakage for float glass (FG), thermally strengthened glass (TVG) and thermally toughened glass (ESG) obtained from all experiments.

Tab. 1: Minimum and maximum values measured at the lower glass breakage for different glass types

Specimen	Stress [MPa]	Force [kN]	Deflection I [mm]	Deflection II [mm]
FG-PVB-04	68.7	5.85	17.4	17.0
FG-PVB-07	27.3	2.37	6.8	6.5
TVG-PVB-01	96.2	7.46	21.5	22.0
TVG-EVA-03	81.3	9.12	15.8	15.5
ESG-PVB-01	167.5	13.10	37.2	36.8
ESG-EVA-01	118.5	15.37	26.9	26.2

The lowest tensile strength dispersion was achieved at thermally strengthened glass – 15 MPa. On the contrary, the highest tensile strength dispersion was achieved in case of thermally toughened glass – 49 MPa. Type of glass experimentally tested was guaranteed by the producer. Tab. 2 shows the maximum and minimum load bearing capacity in case of the whole laminate collapse. The most significant dispersion of this value was reached in case of thermally toughened glass – almost 4.0 kN.

Tab. 2: Residual load bearing capacities of the second loading step – whole laminated panel collapse

SPECIMEN	MAX. FORCE [kN]	MIN. FORCE [kN]
FG-PVB-07	2.5	--
FG-EVA-04	--	1.0
TVG-PVB-01	5.3	--
TVG-PVB-05	--	2.6
ESG-PVB-01	9.0	--
ESG-PVB-03	--	5.1

4. Conclusions

In this paper, important experimental results concerning four point bending tests of double laminated glass panels performed at CTU in Prague were elaborated. Experiments showed almost symmetrical normal stress distribution along the cross section in case of all tested specimens. Measured stresses and deflections were compared to the analytical calculation taking full shear coupling of the plies into account. Possible enhanced ways of analytical laminated glass calculations may be found in (Galuppi 2012). Measured stresses were as well as measured deflections in all cases higher than the calculated ones therefore both types of interlayers were actually not able to provide full shear coupling of the plies. Moreover, maximum instantaneous normal tensile stress in case of lower glass ply breakage was also depicted. Results showed the highest tensile strength dispersion in case of thermally toughened glass and the lowest one in case of thermally strengthened glass. Generally, thermally modified glass tensile strength profoundly depends on manufacturing process. Experimentally verified glass tensile strength and interlayers stiffness together with progressed manufacturing process is the way how to extend the use of laminated glass in practice.

Acknowledgement

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