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Experimental Analysis of Fire Resistance of Laminated Glass Beams

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Abstract

The paper deals with experimental verification of the behaviour of laminated glass beams under fire load according to the ISO 834 standard temperature curve. Two fire tests were performed on laminated glass beams. The first test involved a three-layer beam made of float glass. The second test specimen had the same composition, but with the addition of a protective outer layer of borosilicate glass. Both test specimens were loaded with a point load in the middle during the experiment. During the tests, the time development of temperatures in the cross-section and the deformation of the beams were monitored. In the unprotected sample, all glass panes gradually cracked and collapsed within 900 seconds. The protected sample exhibited different temperature and failure behaviour, with the test lasting 1800 s. The measured data form the basis for subsequent numerical simulation of heat transfer and thermo-mechanical response of laminated glass.

Keywords

Fire, Glass, Experiment, Temperature, Displacement

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1. Introduction

Glass as a structural material is increasingly used not only in infill but also in load-bearing applications. In addition to assessing the ultimate limit state and serviceability limit state, it is also necessary to verify the fire resistance of these load-bearing structural elements. The issue of fire resistance of laminated glass has so far been addressed only to a limited extent in the literature, especially in relation to real structural elements and combined compositions with fire-resistant layers. During fire exposure, uneven heating of the cross-section occurs in glass structural elements. Temperature differences between exposed and unexposed parts lead to significant temperature gradients. These gradients induce internal stresses that can exceed the tensile strength of the glass and cause its sudden failure.

In laminated glass, this phenomenon is accompanied by a change in the mechanical properties of the polymer interlayer. The result is a change in the stress distribution across the cross-section, an increase in deflection, and a gradual degradation of load-bearing capacity (Bedon, Louter, 2023).

The authors conducted experimental testing of glass beams under continuous load exposed to fire (Louter et al., 2021). Based on this research , it was found that laminated glass beams under long-term mechanical loading and exposure to fire could withstand loads for approximately 34–51 minutes before failure, defined by the limit deflection speed, and that reducing the protection of the upper zone or increasing the load significantly shortens this time to failure (Louter et al., 2021).

The use of fire-resistant borosilicate glass as an outer layer can affect the heating process of float glass laminates, reduce the rate of temperature increase, and modify the formation and development of failure mechanisms.

The aim of the pilot experiments was to verify the behaviour of the glass beam under standard fire load and to compare the response of the unprotected beam with that of the beam equipped with external layers of PYRAN® S borosilicate glass (SCHOTT, 2023). At the same time, the aim was to obtain temperature and deformation data that could be used for subsequent validation of the numerical model of heat transfer and thermo-mechanical response of structural elements.

2. Geometry and sample preparation

Two laminated glass beams, designated as sample A and sample B, were manufactured for the pilot experiment. Laminating was performed in a vacuum bag in an oven at a temperature of approximately 140 °C and a pressure of approximately 0.8 MPa. A steel wire was laminated in the middle of the span, which was used during the test to mount a linear potentiometer for measuring vertical deformation.

Sample A (Fig. 1) consisted of three float soda-lime glass plies with a thickness of 3×10 mm. The plies were laminated by a polymer interlayer EVA (ArmiGlass, 2020) with a thickness of 2 × 0.38 mm, i.e., a total thickness of 30.76 mm. The height of the beam was 0.25 m and its length was 1.6 m. Five thermocouples (T11 to T15) were used in sample A, see Fig. 2. The thermocouples were placed in the middle of the beam span, see Fig. 2. In the cross-section, they were distributed along the height of the cross-section, with the first thermocouple located 25 mm from the upper edge and the others mounted vertically with a spacing of 50 mm, see Fig. 2.

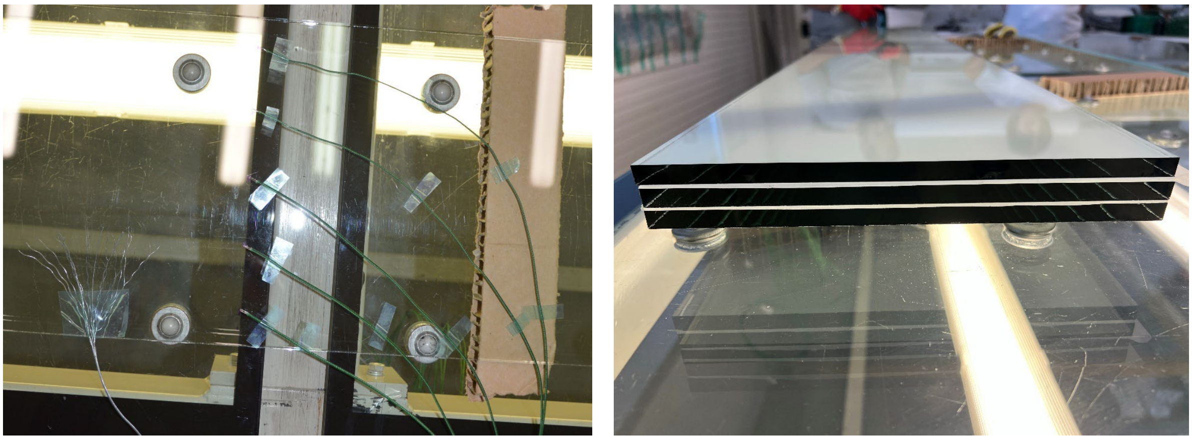

Fig. 1: On the left, thermocouples and measuring cables are attached to record deflection during the fire test; on the right, the prepared sample before lamination.

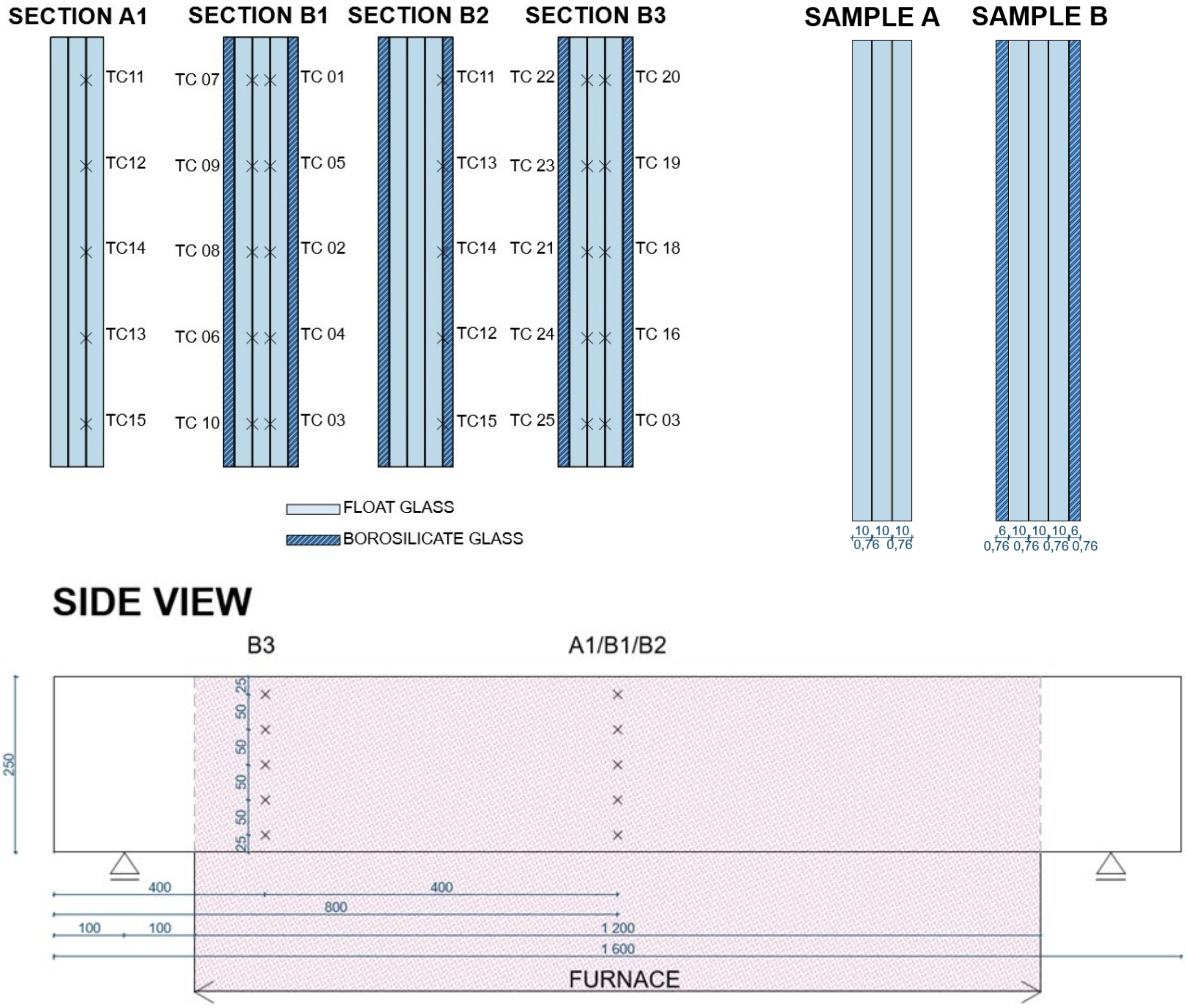

Fig. 2: Position of thermocouples (cross sections and side view).

Sample B (Fig. 3) was based on the composition of laminated glass with a total thickness of 30.76 mm. Two panes of 6 mm thick PYRAN® S (SCHOTT, 2023) borosilicate glass were added to the outer sides, see Fig. 2. The interlayer was again made of EVA (ArmiGlass, 2020) foil with a total thickness of 0.76 mm.

A total of 25 thermocouples were used in sample B. Five thermocouples were placed in the interlayer between the borosilicate glass and float glass, which were located in the centre of the beam span (section B2). Another ten thermocouples were installed in the middle interlayer between the float glass panes in the same position, see Fig. 2, section B1. The remaining 10 thermocouples were placed at a distance of 400 mm from the centre of the beam between the float glass panes, section B3. All thermocouples were distributed along the height of the cross-section in the same way as in sample A, i.e., the first thermocouple was placed 25 mm from the edge and the following thermocouples were distributed at a vertical distance of 50 mm between them, see Fig. 2.

Fig. 3: Sample B: on the left, the PYRAN® S borosilicate glass label; on the right, the attachment of thermocouples and a measuring cable for recording deflection during the fire test.

3. Experimental equipment and fire test procedure

Fire tests were performed in a medium-sized MiniFur 3 furnace (AFIRE s.r.o., 2024), Fig 4. The internal dimensions of the furnace were 0.8 × 1.2 × 0.8 m. The burners were located on the longer side walls of the furnace. The gas temperature was monitored by eight thermocouples located in the upper and lower parts of the working space. The furnace power control was set to correspond to the standard temperature curve. (ISO 834-1,1999).

The test specimen was clamped between two steel plates, see Fig. 5, which were attached to the steel support structure using screws, creating the slight pressure needed to fix the beams in place. A soft, heat-resistant pad was inserted at the attachment point to prevent direct contact between the glass and the steel, protecting the surface from damage and eliminating the formation of local stress peaks. The steel frame provided sufficient rigidity to prevent unwanted movement during the test. The glass was guided along the axis of the furnace between the vertical and horizontal arms of the frame to prevent deflection. Mineral wool was installed around the perimeter of the test furnace to a height of 250 mm (beam height) and formed the side walls of the furnace. At the same time, it was used as an upper insulating cover, thus providing thermal insulation.

Three weights with a total mass of 30 kg were placed on the upper surface of the beam using wooden pads and plasterboard. This load simulated an accidental load in the event of a fire and allowed the interaction of thermal and mechanical stress to be monitored.

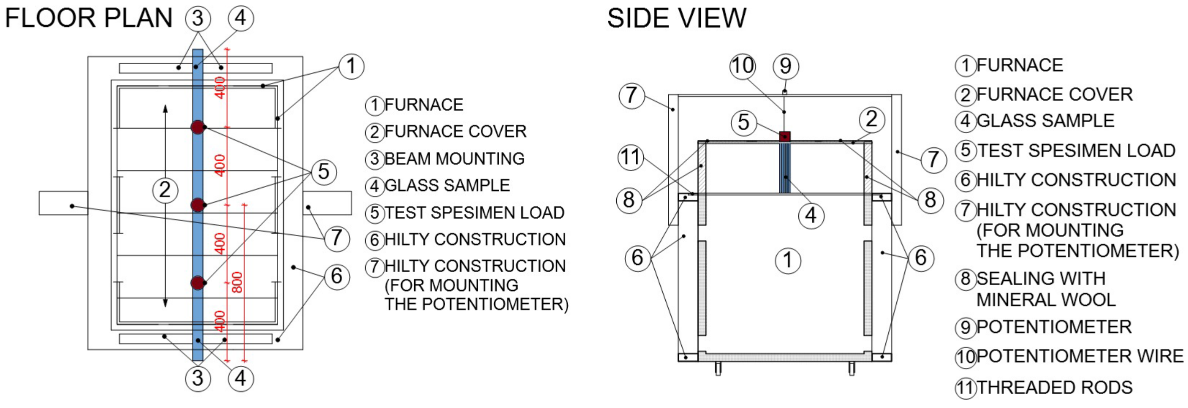

Fig. 4: Floor plan and furnace side view, including test specimen.

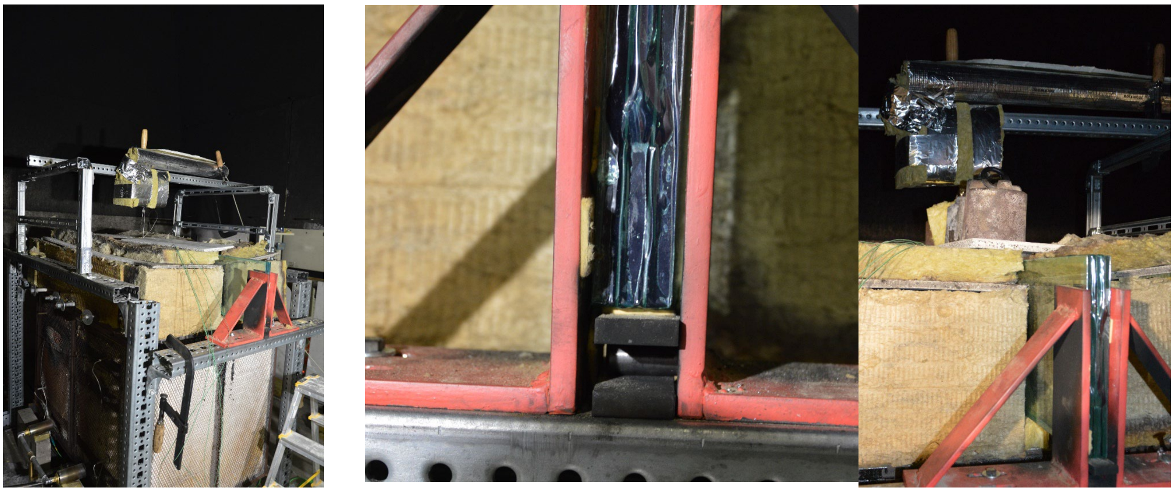

Fig. 5: Set up of the experiment, detail of sample support, load placement.

4. Fire test evaluation

4.1. Sample A

The fire test of test specimen A (Fig. 7) was started by activating the heating at time t = 0. In the initial phase, no significant visual changes were observed on the surface of the glass beam. Approximately 60 seconds after the start of heating, slight fogging of the glass occurred.

At approximately 225 s, the maximum glass temperature of around 96 °C was recorded without any damage to the glass panes. The first noticeable glass breakage was observed approximately 330 s after the start of the test. At around 423 s, the glass temperature reached approximately 200 °C.

During the rest of the test, the individual glass plies gradually began to break. After approximately 600 seconds, cracks were recorded in all glass plies of the beam. At around 840 seconds, part of the glass broke off and fell. The test was terminated at 900 seconds due to the total collapse of the beam. The temperature-time dependence for individual thermocouples during the test is shown in Fig. 7. The dependence shows that, after reaching a certain height, uniform heating occurred, except for thermocouple T11, whose temperature was significantly lower than the others throughout the test. This thermocouple was probably damaged or shaded and did not show the correct temperature during the experiment.

Fig. 6 shows the deflection curve for samples A and B, along with a comparison of the temperature profile in the furnace during fire tests A and B.

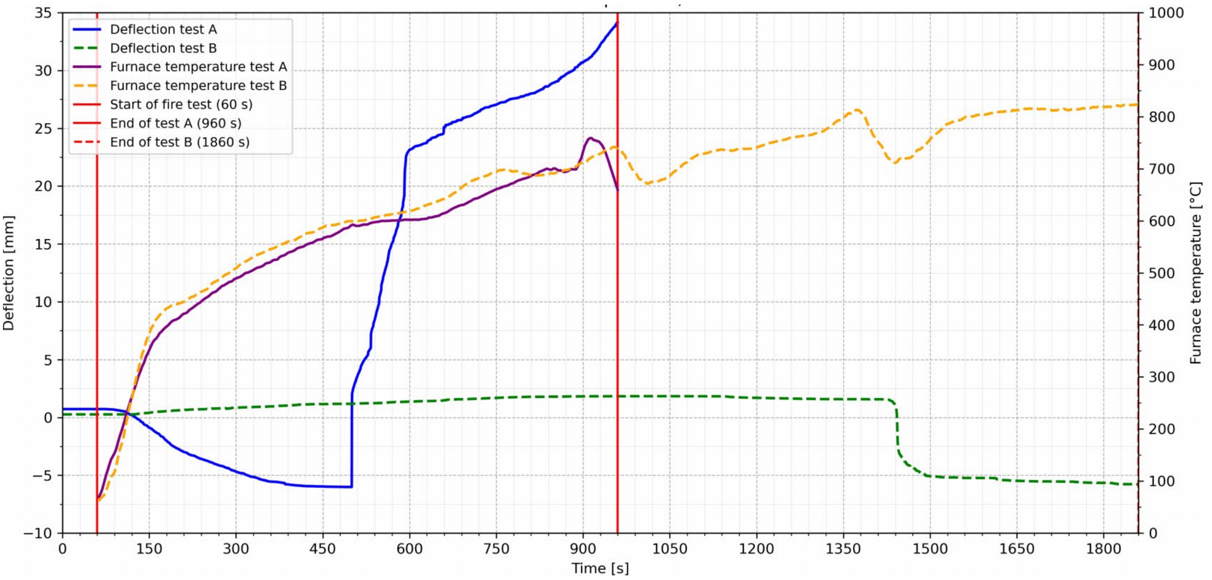

Fig. 6: Comparison of deflection and temperature profiles from the fire test furnace for samples A and B.

4.2. Sample B

The fire test of test specimen B (Fig. 7 and 8) was started by turning on the heating at time t = 0. In the initial phase, there were no significant visual changes on the surface of the glass beam. After approximately 455 s, clouding of the fire-resistant glass was observed.

At time 528 s, the temperature in the furnace reached approximately 645 °C. At around 740 s, flames were observed in the area under the beam support, accompanied by a drop in furnace power. From 880 s, more intense dripping of the molten polymer interlayer was observed.

During the test, repeated acoustic signals indicating the breaking of glass plies were recorded at 900 s, 1200 s, 1500 s, and 1700 s. The test was terminated after 1800 s. After its completion, the cooling process of the sample was further monitored. Comparison of temperatures at the same thermocouple positions from sections B1 and B2 is shown in Fig. 8.

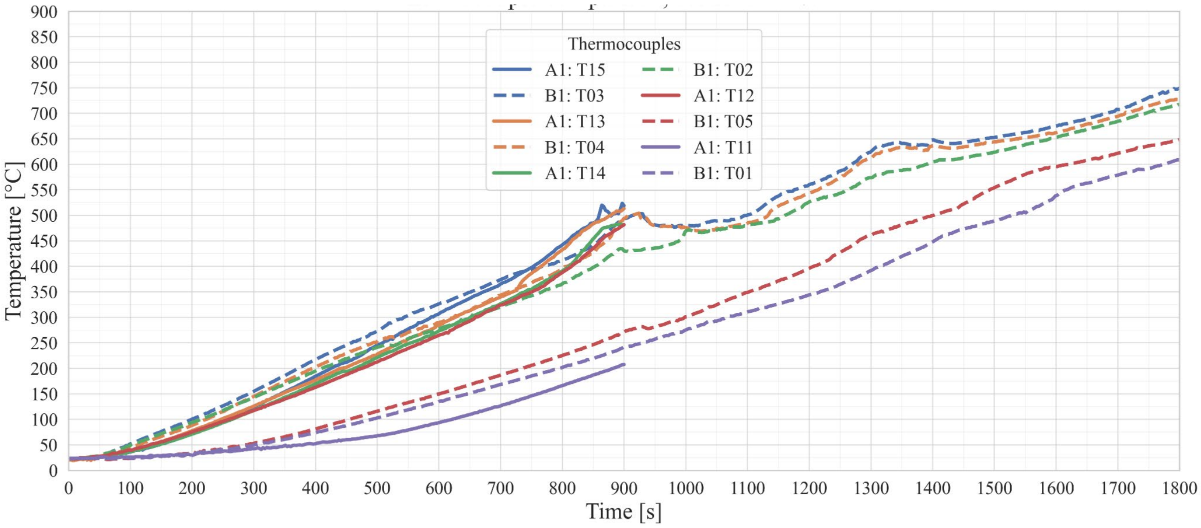

Fig. 7: Comparison of temperatures at the same thermocouple positions from sections A1 and B1.

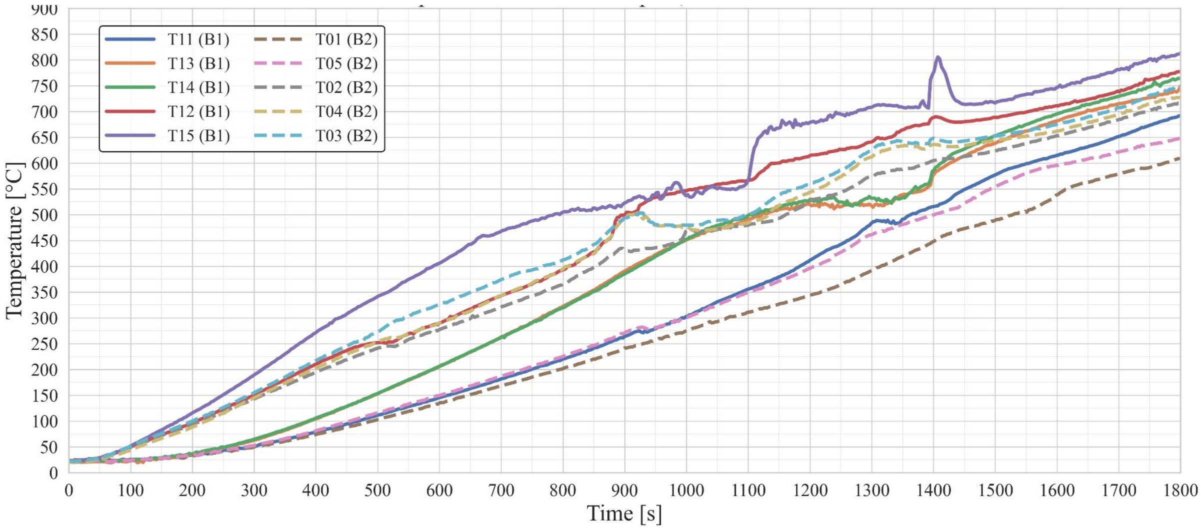

Fig. 8: Comparison of temperatures at the same thermocouple positions from sections B1 and B2.

5. Conclusion

Two fire tests were performed on glass beams made of laminated float glass, one without fire protection and the other with an outer layer of PYRAN® S borosilicate glass. Both elements were subjected to a constant mechanical load of 30 kg and exposed to the standard temperature curve ISO 834 (ISO 834-1,1999).

The unprotected beam gradually developed cracks in all glass plies (Fig. 9) and collapsed completely after 900 seconds. Significant temperature gradients of up to 300 °C were recorded in the cross-section, leading to intense thermal stress and collapse. The increase in temperature was accompanied by a progressive increase in deflection, and after the individual plies cracked, the layers were no longer able to transfer the load.

Fig. 9: Sample A – Deformation of the sample after the fire test.

Failure mode was different for the beam with a borosilicate protective layer (Fig. 10). The presence of external layers modified the temperature field in the cross-section and influenced the time development of defects. The test lasted 1800 s without the element collapsing during exposure. Here, too, a correlation was observed between the temperature increase, the degradation of the EVA (ArmiGlass, 2020) interlayer, and the change in the nature of the deformation, but the time course was different from that of the reference sample.

The experiment confirmed that the combination of a significant temperature gradient and constant mechanical loading represents a critical stress state for laminated glass beams. At the same time, the importance of using borosilicate protection in terms of modifying the fracture process was demonstrated (Fig. 7). The temperature and deformation data obtained form the basis for future experimental research and subsequent numerical modelling of heat transfer and thermo-mechanical behaviour of laminated glass under fire load.

Fig. 10: Sample B – left: deformation of the sample after uncovering, right: deformation of the middle ply of float glass.

Acknowledgements

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