Simple Laminated Glass Panels with Embedded Point Connection under Short-Term Load

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Abstract. Glass is a very attractive material for contemporary architecture. The trend is to achieve a maximum transparency of structures; therefore it becomes common to use glass as a material for load-bearing structural elements. Glass facades, roofs, beams or columns are widely used in buildings. The problematic part of a glass structure design is the connection between the glass pieces or between the glass elements and substructures from another material (e.g. steel, concrete etc.). The connection must be capable of bearing the stresses performing during the lifetime period and it should be as unobtrusive as possible at the same time. The ongoing research at the Faculty of Civil Engineering of the Czech Technical University in Prague is focused on an embedded laminated point connection for glass structures. Within this research, the real-scale glass panels were tested. The samples consisted of two glass plies bonded with the EVA foil. For the undrilled ply, the float glass was used in all cases. The thermally toughened or the heat strengthened glass was used for the pre-drilled ply. There was one embedded steel countersunk bolt with HDPE liners placed in each corner of the sample. During the experiment, the samples were horizontally placed using the embedded bolts. The load-bearing capacity of the six tested specimens was determined. The load was applied in several loading and unloading cycles until the collapse of the first embedded connection. If the glass panel failed before the connection, the sample was completely unloaded and then the load was gradually increasing until the collapse of the connection. Vertical deflection and the stresses at two different points were measured during the loading cycles. The humidity and the temperature were also monitored. The experiment showed the way of collapse and a short-term load-bearing capacity of a laminated glass panel with four embedded point connections.

1. Introduction

Modern architecture often works with glass facades, roofs or balustrades. Its goal is to achieve as much transparency as possible and massive steel supporting systems or metallic frames are no longer acceptable. The trends require minimizing the surface of the glass structures connections, which led to a development of the point connections. However, the connections are the most problematic part of a structural glass design. Generally, they can be divided into three large groups – mechanical, adhesive and laminated connections.

The most popular point fixing system is a mechanical connection based on the classic or countersunk-head stainless steel bolts. Soft rubber or plastic pads are used to prevent the direct contact between the steel and the glass parts. Nevertheless, this type of connection suffers from
the need of a drilling process. The heat strengthened glass has to be used due to high local stresses in the bolt-hole area. [1]

Adhesive bonding represents another way of a structural glass connecting. It uses a layer of an adhesive material placed between the steel and the glass element or two glass parts. This connection provides more uniform transfer of loads. The absence of the drilling process is also a big advantage. However, the strength and durability of adhesives can be affected by many factors, such as temperature, humidity, UV radiation and also the type and duration of loads. [2]

Laminated connection is a combination of the mechanical and the adhesive fixing system. A steel element (a bolt or a plate) is connected to the glass pane by an interlayer represented by a thin foil. The steel element can be embedded between two glass panes, or it can be connected to the glass surface itself. The interlayer foils are typically made of Ethylene Vinyl Acetate (EVA), Poly Vinyl Butyral (PVB) or transparent Ionomers (SentryGlas). The manufacturing process is identical as for the common laminated glass. This type of connection needs no curing time, so it is suitable for immediate application. [3]

Glass fixing systems are still developing and laminated connections belong to the most progressive ones. However, the design procedure is mostly based on experiments. This paper is dealing with a set of experiments focused on determining the short-term load capacity of a real-scale laminated glass panels with the embedded point fixing system.

2. The tests of the real-scale laminated glass panels with embedded point connections

Within the ongoing research at the Faculty of Civil Engineering of the Czech Technical University in Prague, a set of laminated real-scale panels with embedded connections was tested. The experiment was focused on the panel’s characteristics under a short-term load. This type of glass panels is suitable for facades, balustrades or roofs and canopies.

2.1. Description of the samples

Six equally sized laminated glass panels were provided for the experiment (figure 1). The length and the width of each sample were 1500 mm. The thickness of each glass ply was 8 mm.

![Figure 1. Scheme of the sample](image)

All the samples consisted of two glass plies bonded together with two layers of the EVA foil with the total thickness of 0.76 mm. One ply was weakened by previously drilled holes for placing the embedded fixing system. There was one embedded steel element (point fixing) in each sample’s corner. Two HDPE (high density polyethylene) liners prevented the direct contact between the steel element and the glass ply (figure 2).
There were two sets of samples, which differed in the type of the weakened glass ply. Each set consisted of three samples. The first type was made of the thermally toughened glass, and the second type was made of the heat-strengthened glass. The undrilled ply was made of the float glass in all cases.

Before the experiment, all the samples were checked in order to reveal the production defects. Most frequently, this type of connection suffers from small bubbles surrounding the edge of the steel element, or the HDPE liner, or both. Sometimes they may have even bigger bubbles in the area of the steel element. These defects do not have an influence on the performance of the connection. However, they might be unacceptable for the aesthetical reasons.

2.2. Arrangement of the experiment

The goal of the experiment was to determine the short-term load bearing capacity of the laminated glass pane with four embedded laminated steel bolts and the way of collapse.

All the samples were horizontally suspended using the threaded bars. The load was applied by a single hydraulic jack and was distributed to the specimen by a steel X-shaped grid (figure 3). The load was applied at a constant speed of 0.1 kN/s.

During the whole experiment, a vertical deflection of the steel cross was recorded as well as the vertical deflections (D1, D2) and she stresses (S1, S2) at two different points located according to the figure 4. The temperature was also monitored.
2.3. The testing procedure
The testing process included two loading and unloading cycles with 5 kN increments. After every load step, the load was kept at a constant value for 1 minute. Then the load was continuously increasing until the collapse (figure 5). The experiment was performed at the temperature of 30°C.

There were two expected scenarios of failure:
- the float glass pane breaks but the panel remains in the position without collapse;
- at least one connection fails and subsequently the glass pane breaks.

In cases when the glass pane was fractured without the collapse of the whole system, the sample was unloaded to 5 kN. Then the load was increasing at a constant speed until the failure of the first connection, meaning a collapse of the structural elements.

3. Results
The experiments proved brittle failure of all test specimens. However, there was a difference between the samples with thermally toughened (ESG) and heat strengthened (TVG) glass plies. All the samples with the ESG weakened glass ply collapsed in the same way. First, the lower float glass ply fractured due to reaching the tensile strength limit in the mid-span caused by the bending of the sample.
The ESG glass remained undamaged. After unloading, the load was again continuously increasing. When reaching a certain value, the local stresses near the point connections led to a fracture of the ESG glass. The ESG ply fractured in small, relatively harmless dices typical for this type of glass (figure 6b). The panel collapsed as all four connections were pulled-out of the ESG glass ply. The foil remained undamaged.

Majority of the samples with the TVG glass ply collapsed due to falling out of the connections. All the connections failed at the same time and the foil remained undamaged. The obtained results imply that the strength of the TVG glass around the connection was reached about the same moment as the tensile strength of the bended float glass. Nevertheless, there was a case of an identical failure as for the ESG samples.

In spite of different failure modes, the total resistance of TVG and ESG samples was basically in the same range. On average, the TVG samples were capable to resist the load of 21,6 kN. The average resistance of the undamaged ESG samples was 20,92 kN and the post-fracture resistance (after the fracture of the float glass ply) is 15,04 kN on average. Figure 7 compares the vertical deflections (D1, D2 and the deflection of the steel cross) of one of the the ESG (7a) and one of the TVG (7b) samples.
According to the graphs (figure 7), both types act alike until the moment when the float glass fractures. In case of the sample with the ESG glass, the fractured panel is able to withstand about 70% of the total load before the complete collapse. In case of the sample with the TVG glass, there is a noticeable drop of stiffness due to the fracture of the float glass. Then the load starts to rise again, however, the strength of the TVG glass is reached almost immediately and the sample collapses.

4. Conclusions
A set of the real-scale laminated glass panes with four embedded point fixings was tested in order to determine the short-term load bearing capacity. Deflection and stresses in two points were measured during the experiments. Two types of samples differing in the weakened glass ply (ESG or TVG) were used, which allowed to compare obtained results.

The experiment revealed the difference in the failure modes between the ESG and TGV samples. The panes with the ESG weakened ply proved the ability of withstanding relatively high surface loads even with the float glass ply fractured. On the other hand, the majority of samples with the TVG weakened ply collapsed immediately after the first visible sign of any kind of fracture.

Nevertheless, more tests should be performed to determine the exact collapse load and mode of failure. Further research consisting of more full scale tests for applications and numerical modelling is in progress.

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