Tensile tests of embedded laminated glass connections

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Abstract. The trend of modern architecture is heading towards maximum transparency of structures, which makes glass a popular building material. It becomes common to use glass as a material for load-bearing components. Glass facades, roofs, beams or columns must be able to bear stresses occurring during the lifetime period and meet high aesthetic standards at the same time. The most problematic parts of the glass structure design are usually the connections. A lot of alternative connection types have been developed so far. The embedded laminated glass connection is the most modern one and there are many ongoing researches focused on its characteristics. This paper is dealing with series of tests focused on embedded laminated glass connections under short-term tensile loads. Different combinations of glass panes and types of foils were tested. The main goal of the experiment was to determine the tensile resistance of this type of connection. However, all the visible changes of appearance (development of bubbles in the connection area or possible delamination) that occurred during the test and the mode of failure were carefully observed and noted. There were three failure modes that were expected to arise. First one is the failure of the weakened glass pane due to reaching the tensile resistance limit. Second way is represented by the failure of foil caused by reaching the normal stress resistance limit and the last failure mode is caused by delamination. It occurs when the tear resistance limit is reached, and the steel element separates from the foil. The samples were subjected to several loading and unloading cycles. During the tests, the deflection of the glass panel was measured at two points. The experiment shows that the majority of samples collapsed because of the failure of weakened glass pane. Nevertheless, further research consisting of additional tests and numerical modelling is in progress.

1. Introduction

The glass as a building material has been used for many centuries. The manufacturing process as well as the purpose of the glass components has changed rapidly through the years and the glass does no longer serve only as a window pane. Nowadays, it becomes common to use glass as a material for load-bearing components.

The modern architecture works with glass facades, roofs, beams, columns and many more glass components which must be able to bear stresses occurring during the lifetime period (snow, wind). As their popularity increase, they also have to meet high aesthetical requirements. The emphasis is being put mostly on the transparency and glass panes mounted onto metallic sub-frames are not acceptable anymore. Alternative mechanical and adhesive point fixing systems have been developed in recent decades to increase transparency of glass components and their connections. Generally, due to the specific characteristics of glass (such as fragility), connections represent the most...
critical part of the glass structure design. There are many possible ways of connecting glass elements and the major difference is in the material that is used to join them. [1]

Mechanical connections are based on the classic or countersunk-head stainless steel bolts and convenient softer interlayers preventing the direct contact of steel and glass parts. Although being widely used, this type of connection suffers from inefficiency caused by small contact area and the need of a drilling process. The use of a tempered glass is required as high local stresses in the bolt-hole arise. [2]

Adhesive connections work with a layer of adhesive material between the steel and the glass part or even between two glass parts. The advantage of adhesive connections is the absence of a drilling process and more uniform transfer of loads. On the other hand, the strength of adhesive materials is affected by many factors, such as temperature, humidity, UV radiation and the type and duration of loads. [3]

Laminated connections are considered to be the most modern way of glass component fixing. This type combines mechanical and adhesive connections as it consists of a steel element fixed to a glass part by an adhesive interlayer. The steel element (bolt or plate) can be both - connected to the glass surface or embedded between two glass panes. In this case, the adhesive interlayer is represented by thin foils. Typical interlayer foils are made of Ethylene Vinyl Acetate (EVA), Poly Vinyl Butyral (PVB) or transparent Ionomers (SentryGlas). Connection is realized using the same process as for the standard laminated glass panes. It allows the connection to be used right after the laminating process, which makes this connection suitable for immediate in-situ application. [2]

Glass connecting systems are currently still developing and those combining the embedded steel bolts and the lamination process belong to the most progressive ones. There are many ongoing researches dealing with the characteristics of this fixing system and the design procedure is mostly based on experiments. [4]

2. Tensile tests of embedded laminated glass connections
Within the ongoing research at the Faculty of Civil Engineering of Czech Technical University in Prague, a series of experiments focusing on tensile strength of the embedded laminated glass connections have been performed.

2.1. Samples description
For the experiments, several equally sized sets of glass panels with embedded laminated fixing system were provided. The length of each panel was 500 mm, the width was 300 mm and the thickness of each glass pane was 10 mm (Figure 1).

All panels consisted of a steel fixing element, two HDPE liners preventing the direct contact between glass and steel (Figure 2), two glass panes with previously drilled hole in one of them for the embedded fixing system. Glass panes and the steel element were bonded together with two layers of foil.

The sets of glass panels differed in the type of used glass panes and in the type of interlayer foil as well. Some of them consisted of one pane made of the float glass and the other pane made of tempered glass and in some cases, the panels consisted of float glass and semi-tempered glass. EVA and SentryGlas foils were used as the bonding material. The EVA foils were of two types – clear and opaque.
Figure 1. Scheme of the samples [5]

Figure 2. Detail of the steel element [5]

All samples were carefully checked before the tests to reveal the defects of production. Some of the samples suffered from smaller or bigger bubbles on the edge of steel element or HDPE liner. In some cases, there were bigger bubbles in the area of the steel element (Figure 3). These defects do not influence the performance of the connection but might be unacceptable for aesthetic reasons. As bubbles develop during the loading, precise record of the initial state was essential for the evaluation of the tests.
2.2. Tests arrangement description
In these experiments, the load-bearing resistance in tension was tested. The steel bed with two cylindrical supports and plastic pads was used to accommodate the samples (Figure 4). To apply the tensile load, a special frame with detachable bottom part was manufactured (Figure 5).

![Figure 3. Details of the production defects](image)

![Figure 4. Experiment scheme [5]](image)
2.3. Testing procedure
The main goal of the experiments was to determine the resistance of the connection under the short-term tensile loads. Moreover, all the visible changes of appearance in the connection area were carefully observed and noted. The observation was focused on the failure mode as well.

The testing process included numerous loading and unloading cycles with 1 kN or 2 kN load increments. The load was cyclically increasing (and decreasing) until the collapse (Figure 6). After every increase or decrease cycle, the load was kept on a constant value for 1 minute. The experiments were performed at the temperature of 30°C.

There were three failure modes expected to occur:
- failure of weakened glass pane caused by local stress peaks in the area around the connection,
- delamination of the embedded steel element and the foil due to reaching the tear resistance limit,
- failure of the foil caused by reaching the normal stress resistance limit.
3. Test results
During loading, the deflection of two specific points of the samples were measured (Figure 7). First point was situated on the top of the upper glass pane. Measured deformation represents bending of the glass panel. Second point was placed on the top of the bolt and its deflection represents the total deformation. The bending of the glass pane and the delamination of the steel element are included in this value.

Figure 6. Scheme of loading

Figure 7. Force - deflection diagram for sample T1-01

The course of the experiments was more or less the same for all samples. With the increasing load, the number of arising bubbles increased as well. They were gradually merging into bigger bubbles. However, no visible delamination occurred during the tests.
Majority of samples failed suddenly due to the local stress peaks in the weakened glass pane (meaning that the tensile resistance limit of the lower glass pane around the drilled hole was reached). Only the weakened glass collapsed and the upper float glass resisted. There were also few cases when both glass panes collapsed at the same time.

The tempered glass fractured in granular chunks (Figure 8) and the fracture of the semi-tempered glass had a shape of a spider with centre in the area of the connection (Figure 9).

![Figure 8. Fractured tempered glass panes](image1)

![Figure 9. Fractured semi-tempered glass pane](image2)

In most cases, the steel element was pulled out of the glass but it was still bonded to the foil. They separated due to the self weight of the steel element and there was no part of the foil left on the surface of the steel element. Few steel elements were still bonded to the foil even though the glass around collapsed and could not be pulled out (Figure 10). It happened randomly and does not seem to have any relation to the type of the foil.
4. Conclusions

The embedded laminated glass connections were tested to determine the resistance under the short-term tensile loads. Except of that, all the changes in appearance in the connection area and the mode of failure were observed. The tests show that the most common failure mode is reaching the tensile resistance limit of the weakened glass pane. However, more tests need to be performed to determine the exact point of collapse. The further research consisting of more experiments and numerical modelling is in the progress.

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References

[1] W. Laufs and A. Luible, *Introduction on Use of Glass in Modern Buildings*, EPFL-ICOM, Lausanne, 2003, ISBN 80-01-02849-6.

[2] Ch. Bedon and M. Santariseiro, *Transparency in structural glass systems via mechanical, adhesive and laminated point fixings - Existing research and developments*, Manuscript Draft, 2018.

[3] M. Haldimann, A. Luible and M. Overend. *Structural use of glass*. Zurich, Switzerland: International Association for Bridge and Structural Engineering, 2008. ISBN 3857481196.

[4] P.L.L. Carvalho, P.J.S. Cruz, E. Silva and C. Casal, *Embedded glass fixing system*, In Jens Schneider & Bernhard Weller (eds.), Engineered Transparency; Proc. intern. symp. Düsseldorf, Germany, 29-30, pp. 213-220, September 2010.

[5] M. Zdražilová, *Analýza skrytého kotevního bodu pro vrstvené skleněné konstrukce*, Praha, Česká Republika, Master Thesis, in Czech Language, České vysoké učení technické v Praze, 2019.