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# Experimental Analysis of Laminated Embedded Steel Insert in Load Bearing Connections

Josef Bajtek, Michal Netušil, Martina Eliášová
*Faculty of Civil Engineering, Czech Technical University in Prague, Czech Republic*

Use of glass as a load bearing structural elements has increased significantly in last years. The glass is brittle material, which behaves elastically until brittle failure which occurs suddenly without any warning. Therefore, special emphasis shell be devoted to the connections with load bearing role. Their inappropriate design can lead to local peaks of stress or eccentricity of the connections and the generation of additional moments, resulting in a reduction of the load-bearing capacity. Currently, mechanical (clamped, friction-grip and bolted connections) or adhesive joints are commonly used, the latter being characterized by a more uniformly distributed stress along the connection and the undisturbed surface of the glass panels. The disadvantage of polymeric adhesives is however the sensitivity of the load-bearing capacity to the ageing, technology of the production - the proper cleaning of the surfaces as well as the application of adhesive, UV stability during the lifetime etc. Although, there is still a lack of information about all aspects of the adhesive behaviour in the load bearing joint, their use in structural applications is considered very promising. In the last years, a novel typology of enhanced adhesive connections, known as laminated adhesive connection, has been developed. These connections are formed during the lamination process of the laminated glass fabrication and they are characterized by transparency and high aesthetic appearance especially when the size of the laminated metal insert is limited. Paper is focused on the experimental investigation of novel embedded laminated connection with thick steel plate and built-in internal thread pre-prepared for common bolts, used to assembly glass element to another one, or directly to the steel or concrete substructure. Mechanical behaviour of this connection is main goal of the research. Small scale test specimens were tested to obtain mechanical behaviour of the connection. Embedded stainless steel plate in laminated glass is in vertical position and enables connection between the glass cantilever beam and supporting structure. The specimens were loaded until maximum strength of connection was reached.

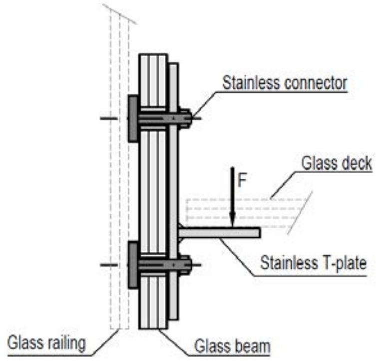
**Keywords:** Glass Structures, Adhesive Connection, Laminated Connection

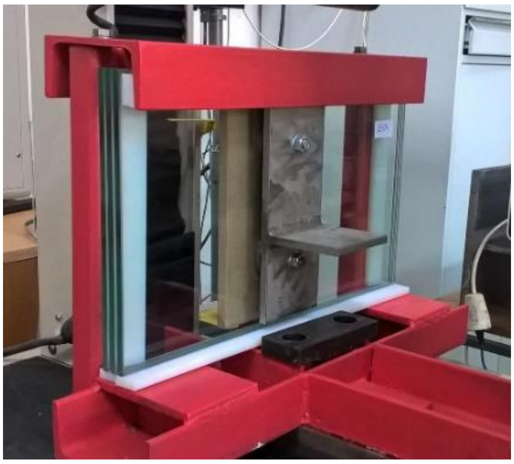
## 1. Introduction

### *1.1. Motivation for our research*

Authors of paper were interested in evaluation of load-bearing capacity (LBC) of traditional connections for the load-bearing glass structures in recent years. Many experiments have been carried out in the field of bolted connection. It is worth mentioning the experiment of determination LBC of footbridge connection (Fig. 1). It was traditional bolted connection, thru steel plate to laminated glass pane. Polyamide inserts were used to protect the hole in the glass. The glass pane and steel plate were separated by rubber interlayer. The LBC of connection was approximately 21 kN without crack in glass pane. After that, impacted crack was initiated by hard tipped rod to obtain the post-breakage behaviour. The loading reached 27 kN after initiation of crack without any damage on the remaining intact glass panes and so the experiment ended. LBC of connection was enough for safe footbridge connection purpose.

But there is a question of design what if the modern laminated connection with embedded insert could serve same way keeping filigree design of the glass structures. For example, the T-plate (Fig. 1a) could be replaced by a glass cross beam (fin). This cross beam would be attached to the glass beam by mean a laminated connection. This solution would bring several benefits. The massive appearance of connection is reduced as the first, which leads to aesthetical improvement of appearance. Furthermore, the glass cross would stabilize the glass beam in the sense of lateral buckling. Besides, the glass deck would be linearly supported as opposed to the local support provided by the T-plate. This simple example shows that the usage of the laminated connection in load-bearing glass structure leads to aesthetic and more effective solution. Unfortunately, the lack of knowledge about mechanical behaviour of laminated connection was limiting for the safe design of the glass footbridge. Authors of paper were motivated by this fact to research in the field of laminated connections.



a) b)

Fig. 1 a) Scheme of footbridge connection and b) mounted small-scale specimen of glass footbridge.

### *1.2. Recent research*

Laminated metal-to-glass connection can be sorted to two types. The first type is laminated connection with embedded metal part, which is integrated in a laminated glass pane. This metal part can be very thin steel sheet, which is placed between interlayers, or thick steel plate, which have same thickness as inner glass sheet. The next type is laminated connection with external steel connector, which is bonded with outer glass pane surface in lamination process. In this paper, the research about laminated connection with thick embedded insert (LCEI) will be presented.

Significant knowledge about mechanical behaviour of adhesive connections was made in PhD thesis (Santarsiero 2015). Part of this thesis was about embedded inserts in small specimens, which were investigated in climatic chamber. Results of mentioned thesis was later used for realization of full-scale experiment of moment connection in the middle of glass beam (Santarsiero et al. 2017). The research investigated three types of moment connection with different location and geometry of metal embedded insert. Results of this experiment was used for numerical analysis of full-scale specimens during cracking regime (Bedon and Santarsiero 2018). Overview of the connections, that are used today, is given in state-of-art (Bedon and Santarsiero 2018).

### *1.3. Application on real structure*

Several load-bearing glass structures with LCEI have been successfully performed yet. One of the first was Apple store in New York (Fig. 2). Apple cube 2.0 is detailly described by O´Callaghan and Bostick (2012). Other interesting usage of LCEI is entrance pavilion for an office building in Madrid (Texidor et al. 2018), where metal inserts were embedded to glass fins and cladding panels. Similar design was used for facades of the new Medical School of Montpellier (Torres et al. 2017), where embedded inserts were only in fins. We could find many other applications of LCEI in the world. The application is wide and future research will have to answer many questions about the safe design of such connections.

a) b) c)

Fig. 2 Apple store in New York - a) Global view of the project, b) LCEI between column and façade panels (detail) and c) LCEI between roof beams (detail). Photos are published in Bedon and Santarsiero (2018).

## 2. Performance

In the beginning of the new connection type research, emphasis was aimed to determine material and geometrical properties of LCEI for glass beams and fins. Mechanical behaviour of LCEI in overall connection is mainly influenced by properties of interlayer and position of metal insert in cross section.

### *2.1. Material performance*

The structural laminated glass member should consist of at least three glass sheets for the application of LCEI. The glass should be heat treated with polished edges. Inner glass ply, where is embedded insert, should be fully tempered to ensure high LBC and minimal thickness should be about 12 mm, because there must be prepared screw thread in embedded insert for load-bearing bolt. Heat Soak Test is recommended for fully tempered glass sheets. External glass plies should be only heat-strengthened for ensure safe post-breakage behaviour of structural glass member.

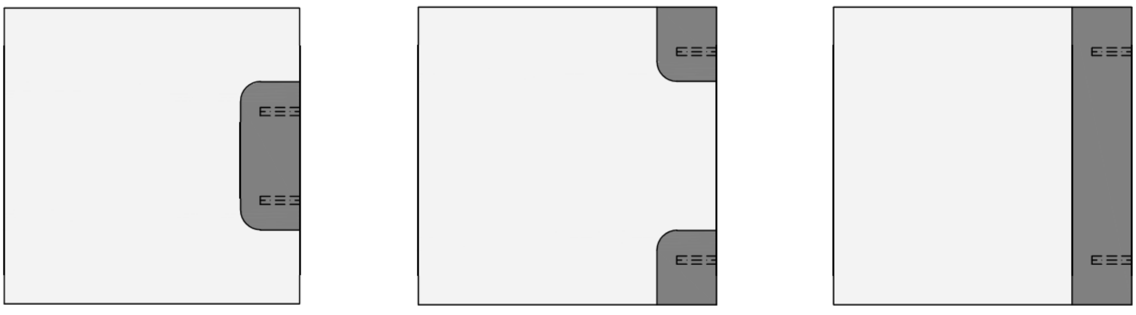
The properties of interlayer foil have a great influence on the mechanical behaviour of LCEI. Ionomer-based interlayers are commonly used for LCEI, because they provide a very rigid connection between embedded insert and glass sheet. Furthermore, ionomer interlayers are resistant to moisture and they have higher shear modulus with increasing temperature than other foils. Research in the field of LCEI with ionomer interlayer is for example in (Santarsiero 2015; Santarsiero et al. 2017; Bedon and Santarsiero 2018) and it was also used for LCEI of façade in Madrid (Teixidor et al. 2018) and in Montpellier (Torres et al. 2017). Another option is to use stiff structural polyvinyl butyral (PVB) interlayer, which provides a much smaller rigid connection than ionomer-based interlayer. Main disadvantage of PVB foil is the absorption of air humidity, which can cause delamination. Another disadvantage of PVB foil is the lowering of the shear modulus with increasing temperature and in general, low shear contraction stiffness. LCEI with PVB interlayer has not been investigated yet. PVB interlayer was used in research of metal-to-glass behaviour of thin metal sheet embedded in laminated glass (Cruz et al. 2011; Louter 2019). Last option is ethylene vinyl acetate (EVA) interlayer, but this interlayer is mainly used for non-structural glazing and LCEI with EVA interlayer has not been investigated yet. Although EVA foils have a very low shear modulus in compared to PVB foils, we can use it, where rigid connection is not needed or where is no risk of pulling the embedded insert from the glass member. Main advantage is that EVA foils are more resistant to moisture than PVB foils. Therefore, the first step was investigated possibilities of EVA foil in our research.

Material of metal insert should be anticorrosive for aesthetic and technological reasons. The optimal choice is the stainless steel or alloy steel (Cr, Cu, Ni alloy) because their surface is clean and minimum treatment is required before process of lamination. The steel edges must be grounded cause elimination of stress peaks. The minimal thickness of plate is 12 mm because there must be prepared screw thread in insert for load-bearing bolt. Position in cross section and geometrical features of insert will be discussed in further text.

### *2.2. Geometrical performance of insert*

The rigidity of LCEI is mainly influenced by position and contact lateral surface of insert. The contact surface determines how much the laminated glass interacts in connection zone. The corners of insert should be rounded for better stress distribution, where are in contact with inner glass sheet (Fig. 4 - rounded edge). The position of insert in the cross-section will be investigated for following types in future research:

- Middle insert (Fig. 3a)  universal and most aesthetic LCEI, which can be used for horizontal (out-of-plane loading) or vertical (in-plane loading) glazing.
- Corner inserts (Fig. 3b) – in global more rigid LCEI than with middle insert. This type of LCEI can be used for beams or fins covering bending moments.
- Full height insert (Fig. 3c) – special type of LCEI, which can be used in the end region of facade fins or for stair steps, etc.



a) b) c)

Fig. 3 a) Middle insert, b) corner inserts and c) full height insert.

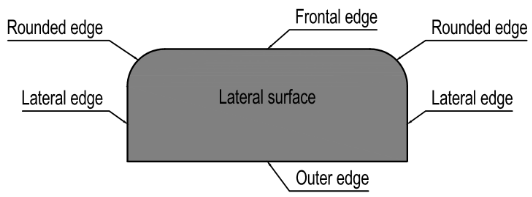



Fig. 4 Definitions of the part of the insert.

*2.3. Pilot specimen*

The pilot specimen was laminated glass pane with stainless steel insert (Fig. 5). The pilot specimen represented middle insert type of LCEI (Fig. 3a). Laminated glass pane was made of the three fully tempered glass plies with 10-12-10 mm thickness. The edges of annealed glass sheets were polished and the space for insert was cut out in middle glass sheet before thermal treatment. Glass plies were bonded together by EVA interlayer foils. The dimensions of laminated glass pane were 300 x 300 mm. Embedded insert was made from stainless steel 1.4301 with nominal thickness 12 mm. The dimensions of steel insert were 150 x 60 mm with rounded corners (radius 20 mm). There were two holes with screw thread (M10) drilled into the insert. The specimen was assembled in process of lamination. The layers were stacked on top of each other and insert was inserted to prepared space in middle glass layer. Unbonded specimen was placed in oven with vacuum system to ensure that there were no air inclusions between the layers.


a) b) c)

Fig. 5 a) Scheme of specimen, b) photo of real specimen and c) detail of steel insert.

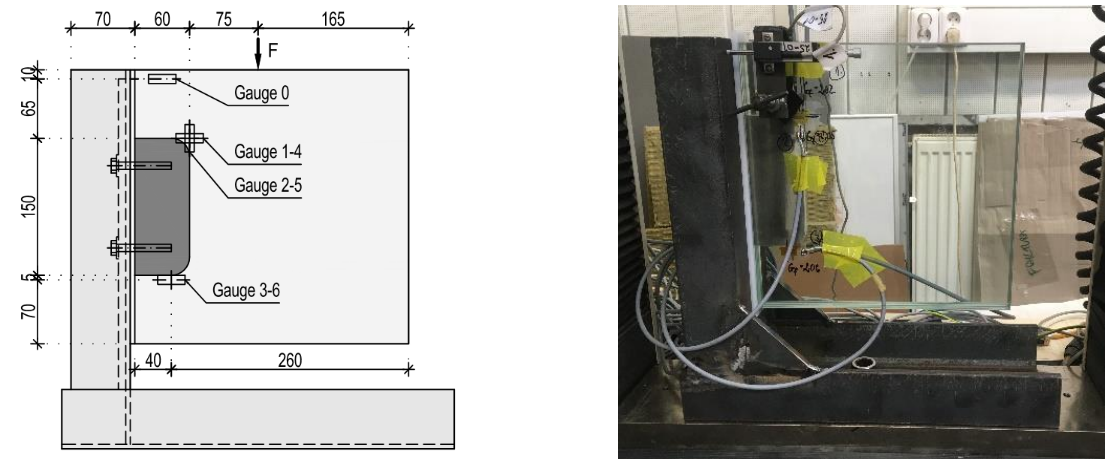
## 3. Experiment

This section describes experimental analysis of LCEI, which is aimed to determine shear LBC and mechanical behaviour of LCEI with middle insert. The specimen was loaded until LBC of the connection was reached.

*3.1. Experiment configuration*

The pilot specimen was connected to steel stiff frame by stainless bolts M10 in vertical position and acts as a cantilever. The polyamide insert (5 mm) was placed between pilot specimen and frame to avoid contact glass with steel. Hydraulic jack was used to apply load and the location of the force was 140 mm from anchorage of cantilever. The force was applied on upper edge of laminated glass pane. The polyamide sheet (5 mm) was placed between jack and glass to avoid stress peaks in the load introduction point. The electrical load cell measured applied force during test.

The horizontal displacement (Gauge 0) was measured by potentiometric linear transducer, which was placed to upper edge of laminated glass pane. Strain gauges were used to measure stress distribution on the outer surfaces during test. Strain gauges were placed to location, where maximal stress was expected. The first pairs of strain gauges were placed nearby upper rounded edge of insert (Gauge 1-4 in horizontal direction and Gauge 2-5 in vertical direction). The second pair of gauges were placed nearby bottom lateral edge of insert (Gauge 3-6 in horizontal direction). The position of gauges is shown in Fig. 6. All measurements were recorded at a frequency of 10 Hz. The specimen was tested under monotonic loading and the test was conducted in displacement control. The displacement rate was 1,0mm/min. The specimen was loaded until LBC of connection was reached.

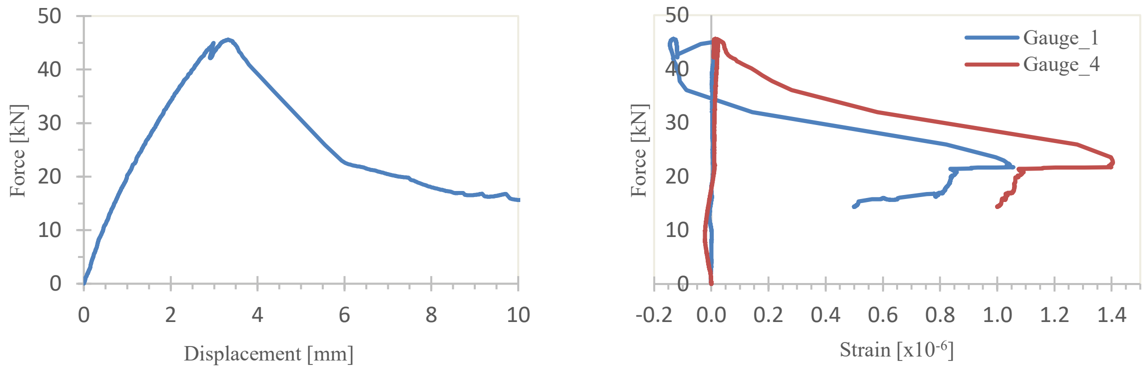



a) b)

Fig. 6 a) Scheme of experiment and b) photo of test setup.

*3.2. Evaluation*

This section presents the results of test, which was aimed to determine LBC and mechanical behaviour of LCEI with middle insert. The load was applied in distance of 140 mm from anchorage of cantilever with the respect to the real beam behaviour with high shear rate. The specimen was loaded until LBC of connection was reached. Figure 7a shows the load-displacement curve. The inner glass ply cracked under approximately 45 kN load and horizontal displacement was approximately 3,2 mm. The force was decreasing after the inner glass ply cracking until the force was redistributed to the outer glass plies. This fact is shown in Fig. 7b, where is no stress in the outer glass plies until the inner glass ply crack. The stress in outer glass ply was increasing after the inner glass cracking, but embedded insert was pulling out until adhesion between interlayer and lateral surface of insert failed. The pulling out effect was mainly due to the bending moment. The remaining strain gauges confirmed behaviour of outer glass ply.




a) b)

Fig. 7 a) Load-displacement curve and b) load-stress curve – Gauge 1-4.

Figure 8a shows crack pattern on the inner glass ply. The whole inner glass ply cracked instantly when main stress reached the tensile strength of glass, which shows detail of crack pattern above embedded insert (Fig. 8b) where is initiated breakage in the area of rounded corner of insert. Immediate breakage of inner glass ply was caused by use of fully tempered glass. The detail of crack pattern shows that main tensile stress is perpendicular to the line which connect the load location and rounded corner. That means that shear LBC of LCEI is limited by shear area of inner glass ply above insert for this specimen.

a) b)

Fig. 8 a) Crack pattern on inner glass ply and b) detail of crack pattern above embedded insert.

## 4. Future research

Based on the evaluation of experiment can be stated that the EVA interlayer is not the best way for LCEI where there is a risk of pull-out effect. LCEI with EVA foil is feasible for desks, stair steps etc. The EVA interlayer has low shear modulus and it is not good for rigid connection with bending moment. That is why the future research will be aimed on the investigation of LCEI with much stiffer interlayer (ionomer-based). Furthermore, next steps in research will lead to the determination of mechanical behaviour of other insert types of LCEI and it will be used digital image correlation for the observation of stress field of outer glass ply. Also, other application of load introduction is planned to enlarge the scope of possible use of this innovative connection (stair steps, fins, frame corners etc.)

It is also necessary to investigate adhesive connection between thick steel plate and interlayer in LCEI. Therefore, this connection will be investigated in pull out tests at different temperatures. Some tests were made by other researchers but that is not enough for a full understanding of the issue. Nevertheless, some basic rules of the interlayer behaviour and changing properties under different conditions are already known and can be extrapolated to this issue.

## 5. Conclusion

Experimental analysis of the pilot specimen with innovative LCEI with middle metal insert was presented. The mechanical behaviour of LCEI was investigated under monotonic loading of laminated glass cantilever, which was anchored to the stiff frame. LCEI is laminated to surrounding glass panes with EVA interlayer. The experiment confirmed that EVA interlayer in not the best solution for this purpose, because this interlayer has relatively low shear modulus compared to other parts of the connection. The maximum LBC is approximately 45 kN, when the inner glass ply cracked. This ultimate force can be promising for some applications. However, the LBC was only determined from one pilot experiment and more tests are necessary to further study.

In general, this study showed that laminated connection with embedded steel insert is very promising in the field of connecting of structural glass members.

## 6. Acknowledgements

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## 7. References

Bedon, C., Santarsiero, M.: Transparency in structural glass systems via mechanical, adhesive and laminated point connections – Existing research and developments. Adv. Eng. Mater., 20: 1700815 (2018)

Bedon, C., Santarsiero, M.: Laminated glass beams with thick embedded connections – Numerical analysis of full-scale specimens during cracking regime. Composite structures 195, 208-324 (2018)

Carvalho, P., Cruz, P.J.S., Veer, F.: Perforated steel plate to laminated glass adhesive properties. Glass Performance Days 2011, pp. 281-285 (2011)

Louter, C.: Metal-to-glass bond strength of structural PVB. Glass Performance Days 2019, pp. 49-55 (2019)

O´Callaghan, J., Bostick, C.: The Apple glass cube: version 2.0. Challenging glass 3, pp. 57-67. IOS Press (2012)

Santarsiero, M., Louter, C., Nussbaumer, A.: Laminated connections for structural glass components: a full-scale experimental study. Glass Struct Eng 2, pp. 79-101. Springer (2017)

Santarsiero, M.: Laminated connections for structural glass applications. PhD thesis n° 6828. Ecole Polytechnique Federale de Lausane (2015)

Teixidor, C., Torres, J., Estupina, L.: All-glass entrance pavillion for an office building in Madrid. Glass Struct Eng 3, pp. 275-287. Springer (2018)

Torres, J., Guitart, N., Teixidor, C.: Glass fins with embedded titanium inserts for the facades of the new Medical School of Montpellier. Glass Struct Eng 2, pp. 201-219. Springer (2017)

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