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Experimental and Numerical Investigation Into the Mechanical Behavior of Embedded Laminated Connections

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Embedded laminated connection (ELC) is a novel type of connection in structural glass and its application increases the transparency and surface flatness of structural glass elements. In this study, laboratory tests have been conducted to investigate the mechanical behavior of embedded laminated connections. Two groups of ELC, i.e. ELC laminated with triple annealed glass layers (TA-ELC), ELC laminated with double outmost tempered glass layers and one mid annealed glass layer (DT-ELC). The data of the pull-out force and displacement of the ELC under the pull-out load was collected and analyzed. The experimental results reveal that the TA-ELC group exhibits brittle failure, whereas DT-ELC group significantly improves the maximum loading capacity. Compared to TA-ELC group, the outmost tempered glass layers in DT-ELC group can render greater ductility. The study also indicates that the crack initiation as well as the final failure of the TA-ELC are both induced in the outmost glass layers. The crack initiation of the DT-ELC is firstly observed in the mid glass layer and the final cracking at failure is generated in the outmost glass layers. A numerical study was also performed to simulate the entire failure process. It is then found that materials in TA-ELC group keeps behaving in an elastic manner before the crack initiation. In DT-ELC, the stable stage of the pull-out force is caused by the yielding of SG layers.

Keywords: Structural glass, Embedded laminated connection, Pull-out load, Laboratory test

1. Introduction

Laminated glass has been increasingly used as structural elements in the past decades due to its excellent transparency and aesthetics (Feldmann et al. 2014). For structural glass elements, there are a number of studies and methods available in literatures on its capacity and robustness design (Galuppi and Royer-Carfagni 2014; Wang et al. 2018; Foraboschi 2013). In addition, connections also play an important role in structural glass applications and provide an alternative path for load transfer and accommodate the dimensional tolerance between glass elements. However, because of the brittle nature of glass material, the connection behavior of structural glass components represent one of most significant aspects in engineering practice.

Laminated connections use polymeric or ionic interlayers to bond substrates with glass sheets. Laminated connections improve the in-plane flatness and transparency of the glass components. It can provide additional capability to transfer shear loads and avoid the contact stress concentration. Recently, this novel connection has been popular for applications in connecting structural glass elements. When a metal insert is directly laminated inside the multilayer laminated glass, i.e. 'embedded', this type of laminated connection is called as the embedded laminated connection (ELC) (Santarsiero et al. 2018), which can also be regarded as a novel adhesive connection.

The interlayer foils used to bond the metal insert and glass is commonly same as that used between the glass layers. The autoclave process is also applied to produce the adhesion between metal insert and glass layer. The ELCs make the use of interlayers to transfer shear and tension load from metal to glass layers. Santarsiero et al. (2016, 2017b) investigated the loading capacity behaviors of metal adhered to glass by SG and TSSA under tension and shear load. The studies show that the tensile and shear capacity of SG layer is greatly influenced by temperature, whereas the mechanical properties of TSSA are relatively stable under temperature ranging from -20°C to 80°C. Several researchers have performed experimental and numerical investigations on the mechanical behavior of 'thin' metal foil inserted in interlayer under pull out and bending tests (Santarsiero et al. 2013; Puller and Sobek 2012; Carvalho et al. 2012). The 'thin' metal foil was only inserted in the interlayer and the out-of-plane stiffness of the 'thin' metal foil is very low. The 'thick' metal insert had same thickness as mid glass layer. Santarsiero et al. (2018) experimentally investigated the mechanical behavior of thick ELCs under the pull-out load and various loading temperatures. The bending behavior of three types of glass beam connected by ELC were experimentally and numerically investigated.

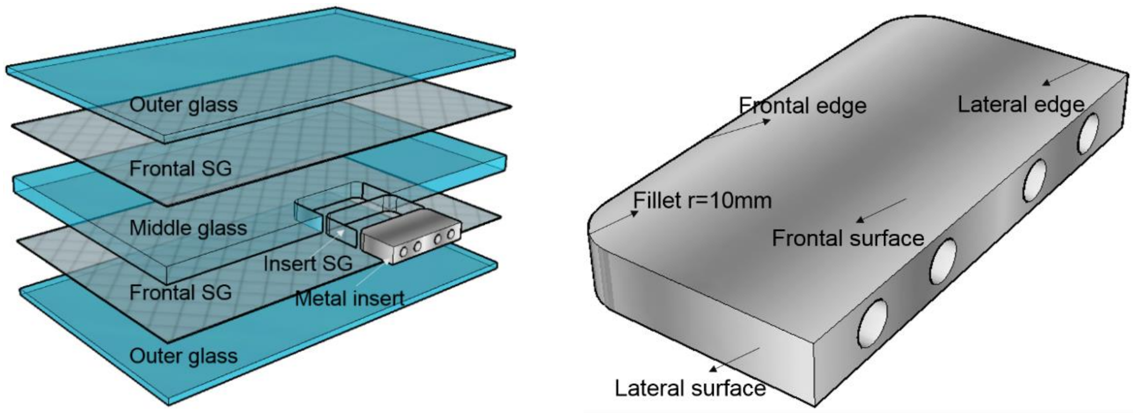
Results indicate that the location and geometry of the metal insert both affect the failure process and the maximum load of the specimens (Santarsiero et al. 2017a; Bedon and Santarsiero 2018). Recently, there has been an emerging trend to apply hybrid glass make-ups in laminated glass for the better performance in the post-breakage stage. To avoid brittle failure, hybrid glass make-ups can be used to induce the gradual failure pattern and to achieve 'ductility' in an alternative way. However, most existing research focuses on ELCs with annealed layers. Researches on the effects of different glass configurations are still limited. Therefore, it is necessary to investigate the influence of the glass configurations on the mechanical behavior of ELC.

In this paper, mechanical behavior of ELCs with SG as adhesive were experimentally investigated. ELCs with different outmost glass layers were tested under the pull-out loading. The pull-out behavior including the relationship between the pull-out force and displacement and the failure process were recorded. The key aspects of the mechanical performance of different groups were collected and compared. A thorough experimental program and numerical study were conducted to investigate the effects of the type of outmost glass layer.

2. Experimental program

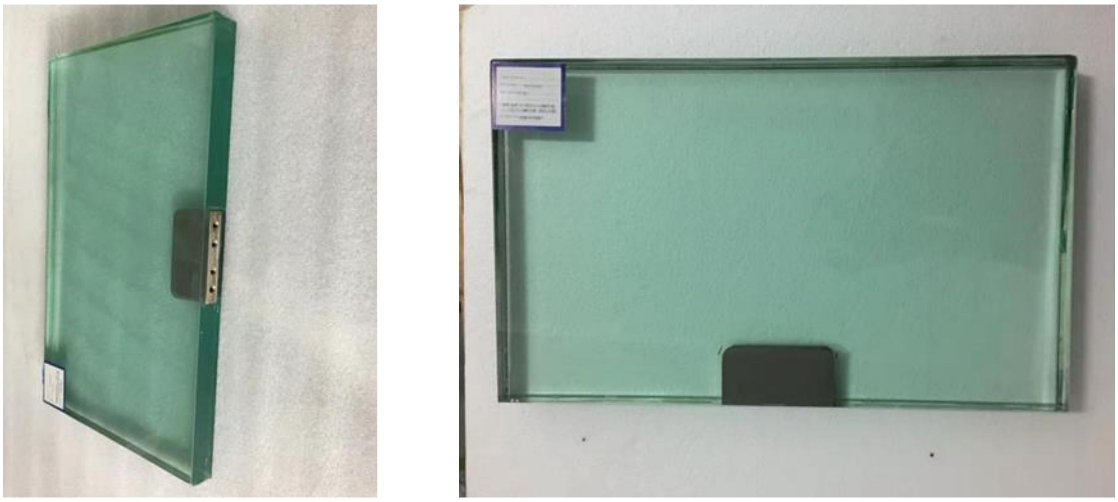
2.1. Specimens design

Testing specimens of the ELC in this study consists of three piles of glass with a metal insert embedded in the prefabricated notch of mid glass. In this study, the specimens have nominal dimensions of 500×300 mm^2. The thickness of the outmost and mid glass piles are 19 and 8 mm, respectively. The metal insert is made of 314 stainless steel with nominal dimensions of 100×50 mm^2. The metal insert has the same thickness as the mid glass layer. The frontal edge of the metal insert has two fillets with a radius of 10 mm. The adhesive surfaces of the metal insert are machined with a roughness of 10 um. The dimensions of notch in the middle glass are slightly larger than the metal insert (5mm larger in the frontal edge and 3 mm larger in the lateral edge). The assembly schematic diagram of ELC is presented in detail in Fig. 1. The frontal SG layers having a thickness of 1.52 mm are used to bond the glass piles and the metal insert. The gap between the metal insert and the mid glass layer is filled with SG material. The dimensions of the insert SG are same as the dimensions of the reserved gap. Both annealed glass and fully tempered glass are used in this study. Due to the notch, all the specimens only use annealed glass as mid glass layer. The outmost glass layers use annealed glass or fully tempered glass to make different configurations in this study. The diagram of the specimen are presented in Fig. 2.



(a) Assembly schematic diagram of specimen. (b) Schematic diagram of metal insert.

Fig. 1 Schematic presentation of the specimen.

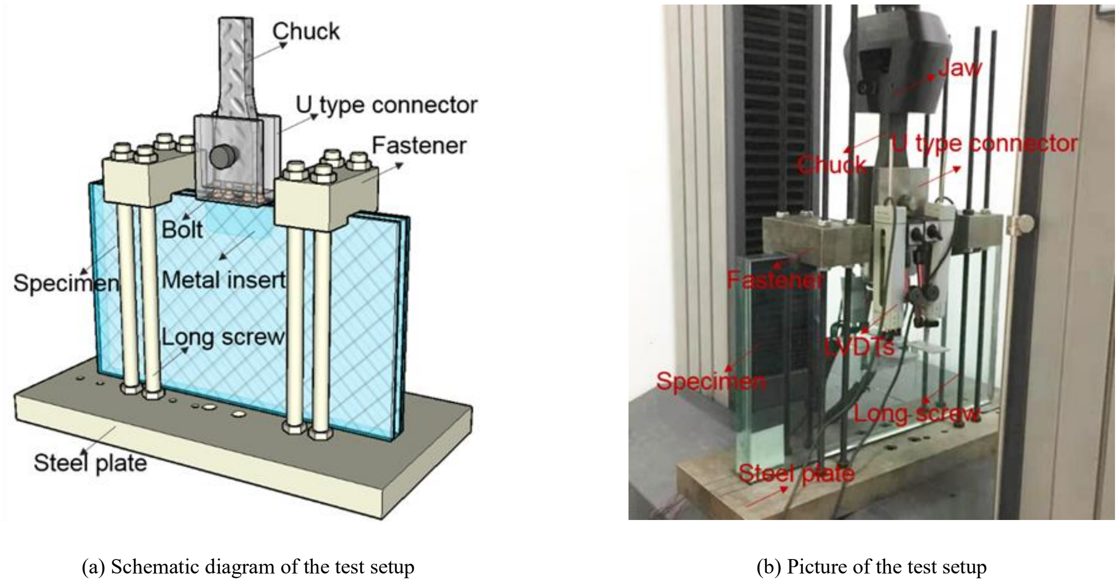


(a) Lateral view (b) Frontal view

Fig. 2 Pictures of ELC specimens.

2.2. Experimental setup and method

In order to investigate the mechanical behavior of the ELC, pull-out tests were carried out by the universal testing machine with a set of specially designed fixing devices (as presented in Fig. 3). Those tests were conducted at the room temperature of around 20℃. A thick steel plate, fixed to the chassis of the universal testing machine by the countersunk bolts, was used for clamping the laminated connection specimen with the long screws and fasteners. A U-type connector was designed to connect the metal insert and chuck. The chuck was clamped by the jaw of the universal testing machine. A constant loading speed of 1mm/min was used for the loading head. Four linear variable differential transformers (LVDTs) were placed in the frontal and rear sides of specimen to record the relative pull-out displacement of the metal insert. Such set up can eliminate the deviations from the eccentricity or rotation of the specimens due to the installation and fabrication errors. A data acquisition system (DAQ), DHDAS 3821, was employed to record the pull-out displacement data with a sampling frequency of 2 Hz.



(a) Schematic diagram of the test setup (b) Picture of the test setup

Fig. 3 Test setup.

3. Experimental results and discussion

3.1. Overview

The experimental results including the pull-out force and displacement of the testing specimens are given and compared. A qualitative comparison of the force-displacement curve, crack initiation and final failure mode of the specimens is presented in Table 1. Two typical failure modes were found based on the pull-out force vs. displacement curves and experimental behavior in this study. The first one is purely brittle and characterized by linear elastic behavior before final failure, and it is hence named as the brittle failure mode (BFM) in this study. The overall behavior of BFM is linearly elastic. BFM corresponds to the TA-ELC specimens. The second type of failure mode is characterized by the linear elastic behavior followed by plastic-like behavior. The term ‘plastic-like’ describes the stage from the end point of the linear elastic stage to the force dropping point. This type of failure mode is named as progressive failure mode (PFM) in this study, which corresponds to the DT-ELC specimens.

Table 1: Qualitative comparison on the mechanical behavior of the investigated specimens.

Groups	Overall behavior	Crack initiation	Final failure mode
TA-ELC	Linear elastic	Outer glass layer	Outer glass layer cracking
DT-ELC	Linear elastic + plastic-like	Mid glass layer	Outer glass layer cracking

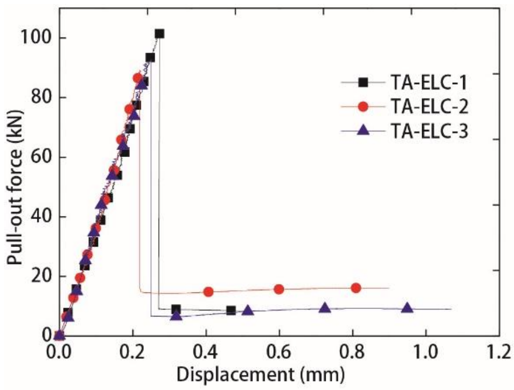
A quantitative comparison was subsequently carried out by considering several key aspects of the mechanical performances of the specimens. The key aspects include initial uncracked stiffness K_{el} i.e. the calculated slope of the linear elastic stage, the initial cracking displacement (u_{in}) and initial cracking force (F_{in}), the maximum pull-out force (F_{max}) and the failure displacement (u_{fail}) (as presented Table 2). It is obvious that by using the fully tempered glass as the outmost glass layers greatly improves the pull-out loading capacity such as the maximum pull-out force F_{max}.

Table 2: Quantitative comparison of key aspects of mechanical behavior of the investigated specimens.

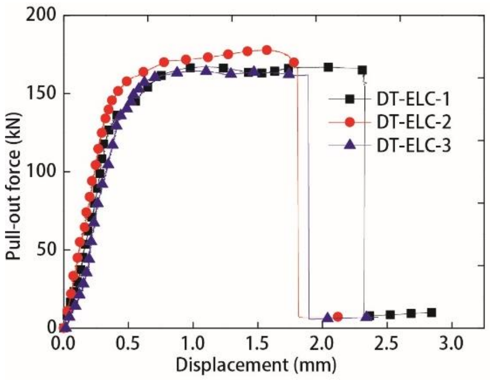
Groups		K_{el} (kN/mm)	u_{in} (mm)	F_{in} (kN)	F_{max} (kN)	u_{fail} (mm)
TA-ELC	Mean	384.4	0.247	94.5	94.5	0.247
	Std	16.5	0.022	6.30	6.30	0.022
DT-ELC	Mean	362.73	0.385	138.87	169.26	2.01
	Std	33.89	0.023	5.21	5.99	0.222

3.2. *Effect of outmost glass layer*

The strength of the outmost glass layer is one of the most important factors affecting the mechanical behavior of the ELCs. The mechanical behavior of TA-ELC group or DT-ELC group is compared and discussed in this section. The pull-out force vs. displacement curves of TA-ELC and DT-ELC are compared and presented in Fig. 4. It is seen that specimens with different outmost glass types present greatly different mechanical behavior. Group TA-ELC is characterized by the linear elastic trend before the pull-out force reaches the peak followed by a sudden drop in the load capacity of the specimens. Before the sudden cracking of glass layers and the dropping of the resistance, there is no visual change observed by the naked eyes. This is a typical brittle failure process and correspond to BFM as mentioned above. The curves of DT-ELC present a gradual failure process and correspond to PFM. Compared to TA-ELC, DT-ELC has almost the same initial uncracked stiffness (with a deviation of 5.4%), whereas its initial cracking force is 47% higher in the linear stage. The DT-ELC reaches higher pull-out force in the followed ductile stage which is absent in TA-ELC. The ductile stage of TA-ELC can be divided into two stages, i.e. the slow increasing stage and the stable stage. The slow increasing stage refers to the pull-out force’s slow increasing phase after the linear stage and the stable stage refers to the pulling-out phase almost remaining constant.



(a) TA-ELC



(b) DT-ELC

Fig. 4 Pull-out force vs. displacement curves of TA-ELC and DT-ELC.

The brittle behavior of TA-ELC can be caused by the sequential cracking of the mid glass and outmost glass layers. Comparing the experimental results of the specimens (as presented in Table 2), the maximum force in the linear stage (before the occurrence of the first crack in glass layer) of DT-ELC is greater than that of TA-ELC. DT-ELC has higher strength of outmost glass compared to TA-ELC. It indicates that the first occurrence of cracks in TA-ELC is in the outmost glass layers, and the cracking sequence of TA-ELC is basically the initial cracking of the outmost glass layers followed by the mid glass layer. The final failure pattern of TA-ELC is presented in Fig. 5. When the outmost glass layers are cracked, the ELC loses most of its shear resistance contributed by the failed outmost glass. The normal tensile and shear stresses in the lateral and frontal adhesive surfaces of the insert has a drastically increase. This has triggered the cracking of the mid glass layer consequently and results in final brittle cracking. For TA-ELC, both the glass crack initiation and the loading capacity controlling factors are the strength of the outmost glass layer. The outline of the cracking pattern is an inverted trapezoid and the acute angle is about 45°.

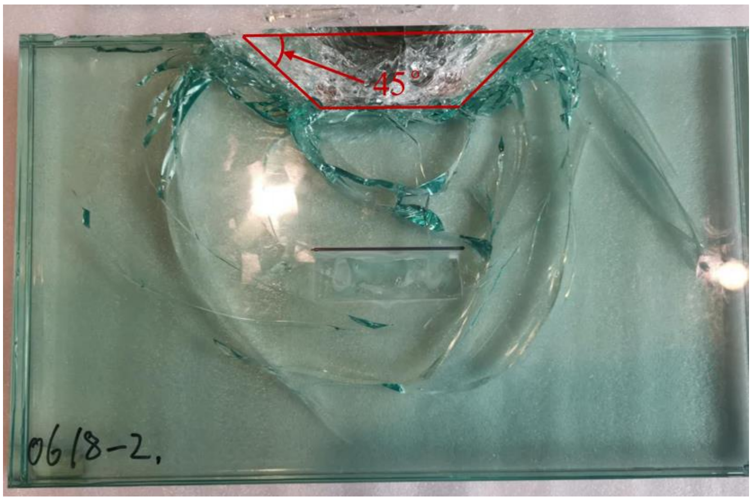
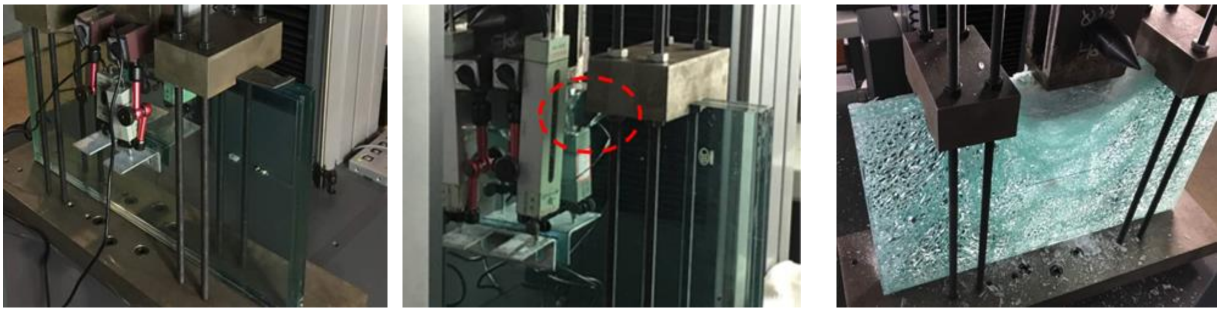


Fig. 5 Final failure pattern of TA-ELC.

In the gradual failure process of DT-ELC, all the glass layers (outmost and mid glass layers) and all the SG interlayer (frontal SG and Insert SG as indicated in Fig. 1(a)) are intact in the linear stage. The turning point from the linear stage to the nonlinear stage is caused by the initial cracking in the mid glass layer, as shown in Fig. 6 (b). After the initial cracking, the pull-out force still keeps increasing with a smaller slope compared to the linear stage until the pull-out force almost becomes stable. In this period, because the frontal SG layers and the outmost glass layers remain intact and the fragments of the mid annealed glass are very large. The cracked mid glass layer provides partial resistance due to the adhesion between SG layers and large fragments. The intact frontal SG and outmost glass layers still supply shear force from the frontal surface of metal insert directly and sustain the force transferring from the large mid glass fragments. The final failure is also induced by the sudden cracking of outmost tempered glass and the final cracking pattern is presented in Fig. 6 (c). For DT-ELC, the controlling factor of the initial cracking is the strength of mid glass layer and that of the final resistance is the strength of outmost glass layers.

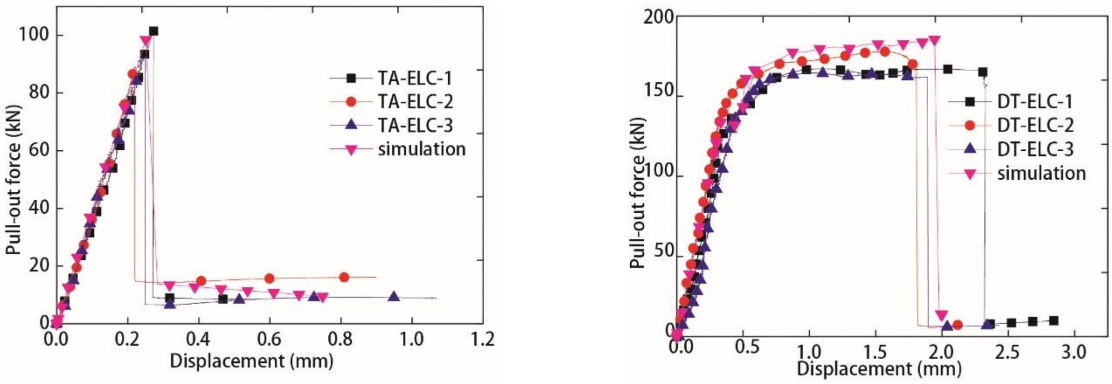


(a) Intact specimen (b) Initial cracks (c) Final cracking

Fig. 6 The progressive failure of specimens with tempered glass as outmost layer.

4. Numerical study

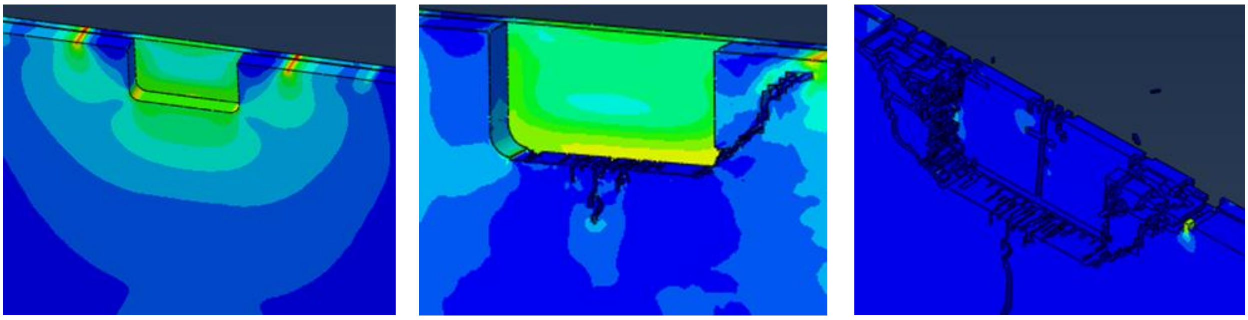
A finite element (FE) analysis for further investigation of the mechanical behavior of the ELC was carried out by using ABAQUS/Explicit module. The geometry of the FE model is same as the dimensions of specimens and the experimental setup. C3D8R elements, which denote the 8-node linear brick elements with reduced integration and hourglass control, are used for both glass and SG interlayers. The constitutive laws of both the brittle glass and ductile SG interlayers (for static load) are in accordance with those described by Feldman et al. (2014) and Wang et al. (Wang et al. 2017). In this numerical study, the Young's modulus of SG interlay is 120MPa, and the Poisson ratio is 0.45. Glass materials applies the property of Brittle Cracking and the facture controlling factor of glass is the maximum principle tensile stress. Only linear elastic properties are used for the metal insert. Because there is no obvious delamination phenomenon during the test, this numerical study adopts share-nodes type interaction for glass-SG and metal-SG interfaces ("Tie" interaction in ABAQUS), which represents perfect bonding between interaction surfaces. The comparison of the force-displacement curves from the FE model and experimental data is presented in **Fig. 7**. The FE simulation results have good agreement with the experimental data.



(a) TA-ELC (b) DT-ELC

Fig. 7 Curves of pull-out force vs. displacement of TA-ELC and DT-ELC.

The numerical results of TA-ELC show that all the SG layer and glass layers remain elastic before glass cracking and this corresponds to the purely elastic stage of the pull-out force vs. displacement curve. The final cracking of the outmost glass is shown by the sudden drop in the pull-out force. The simulation results also reveal that the maximum tensile stress in the outmost glass is greater than that in the mid glass in TA-ELC. This indicates the cracking sequence of the TA-ELC, which starts by the cracking of the outmost glass layer first and has a following cracking of the mid glass layer. For DT-ELC, simulation results also exhibit a gradual failure process, which agrees with the experimental phenomenon as presented in Fig. 8. The results show that both glass and SG materials behave elastically in the linear increasing stage and the turning point of this stage is caused by the occurrence of the first crack in the mid glass layer. In the slow increasing stage, the cracks propagate in the mid glass and the cracks existence in the mid glass induce a decrease in the curve slope. However, the frontal SG layers still remain in elastic stage. In the force 'stable stage', all the SG layers enter plastic stage. This hence results in a very slow increase in the pull-out force with large pull-out displacement. The final cracking is still induced by cracking of the outmost glass layer.



(a) Intact specimen. (b) Initial cracks. (c) Final cracking.

Fig. 8 Gradual failure of specimens with tempered glass as outmost layer in FE model.

5. Conclusions

In this paper, laboratory tests were carried out to investigate the mechanical behavior of ELCs with various types of outmost glass layers under the pull-out load. A numerical study was also conducted to provide more insightful information within each part. The failure process of the ELC was thoroughly analyzed. The effect of the glass type of outmost layers was discussed in detail. Several key finding drawn from this study are:

a) The embedded laminated connection with all annealed glass layers presents purely brittle behavior and the critical factor for this type of connection is the strength of the outmost annealed glass layer.

b) Using tempered glass as outmost glass layer of the embedded laminated connection can significantly increase the loading capacity.

c) The hybrid glass make-ups of the embedded laminated connection using tempered glass can induce a gradual failure process.

d) The severely damaged region in the outmost glass occurs near the frontal edge of the metal insert and such cracking always firstly initiates in the inner surface of the outmost glass layer.

e) For embedded laminated connection with triple annealed glass layers, the controlling factors for cracks initiation and final failure are strength of the outmost glass. For that with outmost tempered glass layers, the controlling factor for cracks initiation is the strength of the mid glass layer and the controlling factor for final failure is the strength of the outmost glass.

Conflict of interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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