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Developments in GFRP Reinforced Bolted Joints in Glass

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The brittle material behaviour of glass means the inefficiency of contemporary mechanical connection technologies hampers the exploitation of full potential of glass for delivering energy efficient buildings. This paper presents the results of an experimental investigation of the use of adhesively bonded Glass Fibre Reinforced Polymer (GFRP) strips as a mean improving strength and ductility of bolted joints in glass. The peak load and the post-peak ductility of GFRP reinforced joints in annealed glass in double-lap tension joint configurations were experimentally investigated and compared with equivalent unstrengthened reference bolted joints in annealed glass and fully-toughened glass. The results show that the peak load of the reinforced joints in annealed glass increased up to 250%. The reinforced joints also showed a notable ductility compared to the reference annealed glass and fully-toughened glass test specimens.

Keywords: Bolted joints, Connections, Ductility, Failure, Glass, Reinforcement

1. Introduction

Due to the distinctive combination of fascinating physical and chemical properties together with recent advances in glass technologies such as low emissivity, solar control, smart glass, etc., it is envisaged that glass will play an increased and central role in future energy-efficient buildings. However, the brittle material behaviour of glass means the inefficiency of contemporary mechanical connection technologies hampers the exploitation of full potential of glass as a construction material. The structural and architectural roles of the glass in buildings and other structures where out-of-plane and in-plane loads as well as additional stresses developed due to the movement of the main structure and dimensional tolerances mean the provision of safe and reliable joints has become increasingly difficult. Although adhesive bonding offers the potential to be an attractive connecting methods in glass (Overend, 2013), the use of adhesives in structural glazing has not been fully proven. In particular, the durability and the long-term structural behaviour of adhesive joints are not fully understood and largely considered to be unreliable.

Mechanical fixings such as clamp and bolted joints are used in contemporary glass designs where glass panels are fixed in to a sub-frame support structure behind the glass panes. In particular, bolted fixings are a popular method of connections for glass elements owing to the aesthetic requirements of minimizing the negative visual impact of the glass panel supports. Over the past few decades, there have been various developments and refinement in bolted connections for glass structures. This has resulted in a wide variety of bolted connections such as counter sunk bolts and architectural bolted connections (IStructE, 2015). However, poor structural efficiency of contemporary bolted joints in glass structures remains a problem.

Surface flaws and the consequent stress concentrations cause by drilling holes and the inevitably present localized high stress concentrations due to the local contacts significantly weaken glass in the vicinity of bolted joints. Despite isolating the bolts and other metallic materials from glass via the use of softer materials such as plastic and rubber, all of which redistribute stresses to a certain extent, the bolted joints still subject to high localised stresses (Haldimann et al., 2008). The selection of the stiffness of the bushing materials and the required closeness of the fit (i.e. the bolt diameter relative to the hole diameter) affect the actual stress distribution around a joint. The determination of these stress concentration is usually not attainable to analytical or numerical analyses since the exact contact condition of a joint cannot be known. Consequently, design and the provision of structurally efficient reliable bolted joints remains as a key challenge in structural use of glass.

In practice, only the fully-toughened glass (also known as tempered glass) are used with bolted joints. Laminated glass have to be used when glass has a structural role. Toughened glass is processed by expensive and energy consuming controlled thermal treatments of basic annealed glass. Despite the higher cost and additional difficulties due to improper surfaces, fully-toughened glass has poor failure behaviour with no residual capacity after an initiation of failure. Low degree of toughening around the bolt holes (Nielsen et al. 2010) and squeezing of polymer interlayers in laminated glass due to the pressures exerted on glass in the vicinity of joints can further weaken glass. The existing real-life applications of the bolted joints in glass structures were largely driven by very conservative rules of thumb designs, rather than the incorporation of bolted joints into the design phase. New developments of bolted joints have generally been undertaken based on expensive build and test and ab initio, mainly as a consequence of client confidentiality.

This paper presents results from an experimental investigation of the use of adhesively bonded Glass Fibre Reinforced Polymer (GFRP) strips as a mean improving strength and ductility of bolted joints in annealed glass. The peak load and the post-peak ductility of GFRP reinforced joints in double-lap tension joint configurations in annealed glass were experimentally investigated and compared with equivalent unstrengthened reference bolted joints in annealed glass and fully-toughened glass. The results show that the peak load of the reinforced joints in annealed glass increased up to 250%. Moreover, the reinforced joints showed a notable load-resistance beyond the peak load – i.e. ability to resist load even after the initiation of first failure – compared to the reference annealed and fully-toughened test specimens.

2. Materials

2.1. Glass

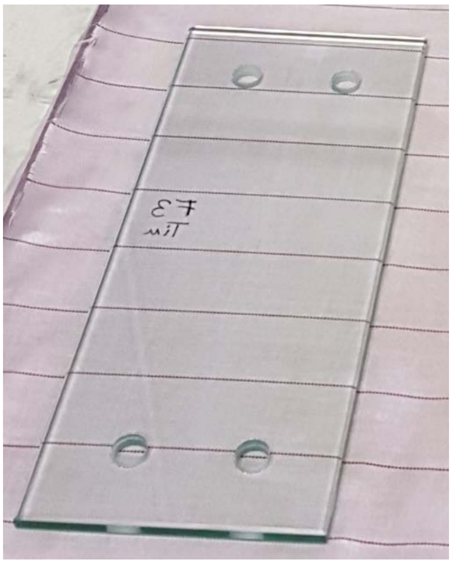
6 mm thick annealed glass and fully-toughened glass cut in to the dimensions of 250 mm x 100 mm, purchased from a commercial supplier was used in the present study. The glass specimens had four 11 mm diameter holes, drilled by the commercial supplier, at both ends as shown in Fig. 1a. All edges of the glass specimens and the inner surfaces of the drilled holes were polished up to the industrial standard use by the commercial supplier.

2.2. GFRP

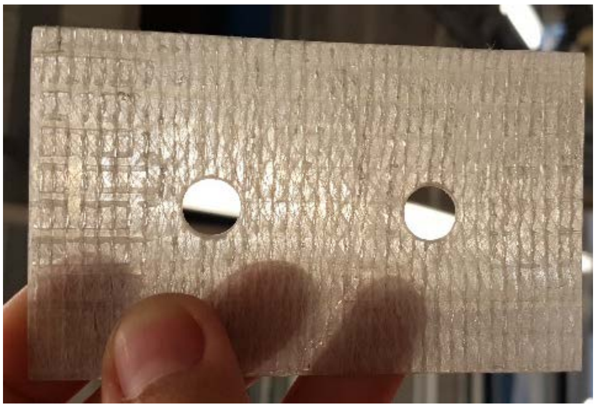
Prefabricated GFRP strips were used in the present study to reinforce bolted joints in annealed glass. The GFRP laminate that was used in the previous research of the first author on glass–GFRP composites (Achintha and Balan 2017; Achintha and Bessonov 2017) was used to reinforce the bolted joints. The GFRP strips were fabricated by impregnating unidirectional 'E-glass' dry fibre sheets using a commercially available epoxy resin by means of a hand lay-up method. The average thickness of the final cured GFRP laminate was ~1.35 mm. The fibre volume fraction of the GFRP was calculated to be ~33%, and the Young's modulus and the Poisson ratio of the GFRP were 450 MPa, 24.5 GPa and 0.10 respectively (Achintha and Balan, 2017). The width of the GFRP strip was taken to be the same as that of the glass sheet (i.e. 100 mm) and the length was taken to be 60 mm. 11 mm holes were also drilled in GFRPs in order to match with those in the glass (see Fig. 1b).

2.3. Adhesive

The GFRP strips were bonded to glass specimens by using structural epoxy adhesive, "Araldite 2020" (Araldite 2020, 2015). The previous studies of the first author (Achintha and Balan, 2017) showed the excellence performance of "Araldite 2020" in glass–GFRP composites beams where an adhesively bonded thin GFRP layer was used to reinforce annealed glass beams. The details of the early strength gain characteristics and the mechanical properties of the harden adhesive can be found in Achintha and Balan (2017).



a)



b)

Fig. 1a) 250 mm x 100 mm glass specimens with four 11 mm diameter drilled holes, b) 60 mm x 100 mm GFRP strip with two 11 mm diameter drilled holes

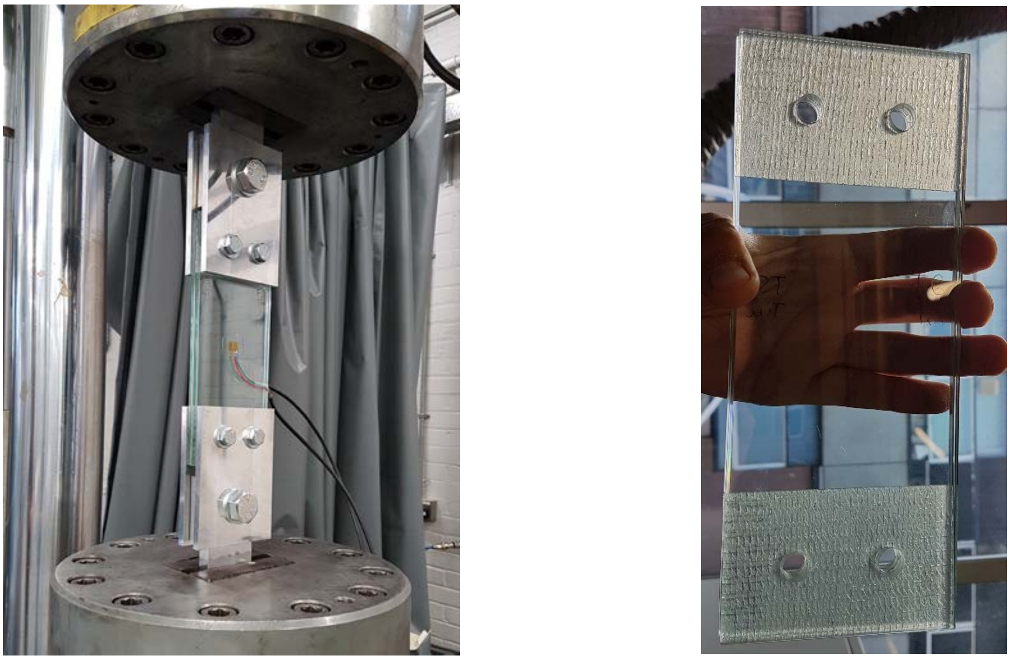
3. Test Specimens

3.1. Reference test specimens

Fig. 2a shows the arrangement of the reference test specimens (i.e. bolted joints in annealed glass and tempered glass specimens without GFRP reinforcement). As shown in the figure, two glass pieces and two aluminium pieces, each with the same thickness and width as the glass specimens, were connected together using four bolts. 10 mm diameter (M10) bolts were used in the present study. EPDM rubber was used as a bushing material between the bolt shank and the internal surface of the holes. M10 EPDM rubber washers were also placed on the both external surfaces of the glass assembly. This allowed a gap of ~2 mm between the glass and the aluminium pieces in the joint areas. In order to fix the test assembly into a test machine, a thicker aluminium piece each was connected at each end of the test specimen using larger bolts (see Fig. 2a). 20 mm diameter (M20) bolt was used for this connection. This arrangement of the test specimens ensured the thick aluminium plates were connected to the two sides of the test machine whilst eliminating the need for connecting glass directly into the test machine. The thickness of the thicker aluminium plates was chosen such that the test specimen can be loaded in tension without an eccentricity or out-of-plane loading on bolted the joints.

3.2. Reinforced test specimens

The GFRP reinforced annealed glass test specimens were prepared in the same way as the reference test specimens. However, prefabricated GFRP strips (shown in Fig. 1b) were bonded to the glass specimens prior to connecting the aluminium plates and the bolts. The GFRP strips were bonded to glass and cured using the methodology employed in the previous successful research works on glass–GFRP composites (Achintha and Balan, 2017; Achintha and Bessonov, 2017). Prior to the bonding of the GFRP, the bonding surfaces of the glass and the GFRP were first thoroughly cleaned and degreased using acetone. The volume of the adhesive required to obtain a thin layer of ~0.1 mm adhesive was evenly spread using a spatula over the inner surface (i.e. bonding surface) of each glass specimen. The GFRP strip was carefully bonded to the glass surface, between the two glass pieces whilst ensuing no air bubbles were trapped in between and the holes in the glass and the GFRP strip were perfectly aligned. The GFRP strips were bonded at both ends of the glass pieces covering areas in the vicinity of the bolted joints. The test specimens were then secured using a few small clamps and cured using the same curing procedure used in the previous study of Achintha and Balan (2017) (24-hour oven curing at 40˚C temperature and atmospheric pressure, followed by further six days of curing under ambient conditions). Fig. 2b shows one of the fully-cured GFRP bonded glass test specimen prior to connecting the aluminium pieces and the bolts.



a) b)

Fig. 2a) Test arrangement of a reference test specimen, b) Two glass pieces with an adhesively bonded GFRP strip between the two glass pieces

3.3. Testing

Two linear strain gauges were attached on the front and back outer glass surfaces at the mid-height of the test specimens (see Fig. 2a). Strain gauges were used on both sides in order to estimate possible eccentricity (if any) during the loading and also to make corrective measures for small eccentricities. All the reinforced and the reference bolted joint test specimens were tested in tension, displacement control at a slow displacement rate (1 mm/min), which is believed to be representative of a static load. The applied load values were recorded in the in-built digital data storage in the test machine, and the strain gauge data was recorded using a digital data acquisition system. During the testing, graphical information of glass around the bolted joints was recorded using a digital camera. For each test specimen, the recorded strain gauge data suggested that the applied load–longitudinal strain relationships of both sides of the test specimen were largely the same. This ensured the effect of potential eccentricity of the applied load was negligible, and the use of the average values of the two data sets is representative of the actual behaviour of the test specimen.

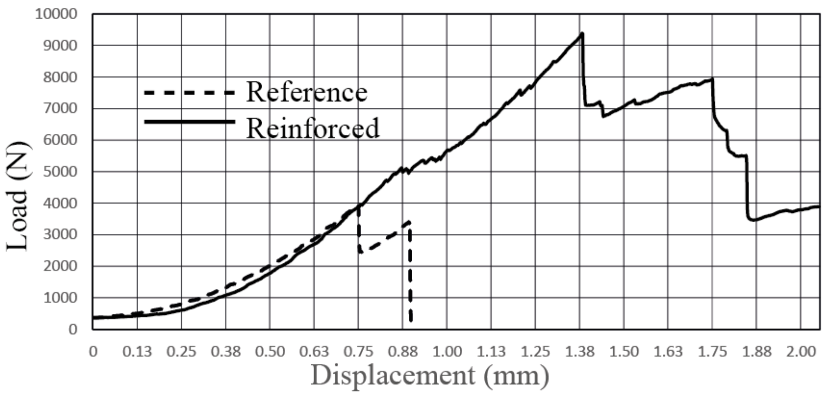
4. Results

Three tests specimens each from reference annealed glass and tempered glass, and GFRP reinforced annealed glass were tested. The results showed that for each category of the test specimens, the observed load response and the failure behaviour of all three test specimens were largely similar. For brevity, only the results of one test specimen from each category of the test specimens are presented in this paper.

4.1. Reference Annealed Glass Test specimens

In annealed glass test specimens, a complete failure of glass across the bolted joint caused the failure of the test specimen. Fig. 3a shows the failure pattern observed in the vicinity of the bolted joints in a reference annealed glass test specimen. The applied load–axial displacement relationships shown in Fig. 3b suggests the load capacity of the reference annealed glass test specimen was ~ 3800 N. In this test specimen, one glass piece was failed first causing a drop in the load resistance (see Fig. 3b). Although the other glass sheet then started to carry the load, it also failed soon after the failure of the first one. As the load-displacement relationship shown in Fig. 3b suggests the final failure of reference annealed glass test specimen was brittle. However, as shown in Fig.4, the glass only failed in the vicinity of the bolts where the mid-length regions of the glass specimens remained intact.

a)



b)

Fig. 3a) Failure of glass in the vicinity of the joint in annealed glass reference test specimen, b) Applied load –displacement relationships of the reference and reinforced bolted joints in annealed glass

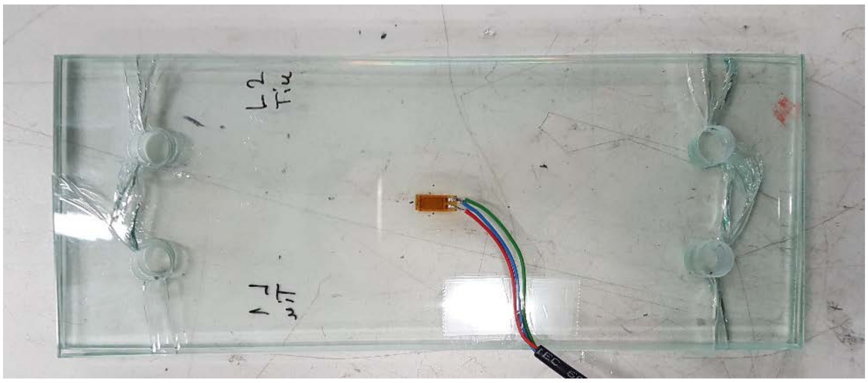
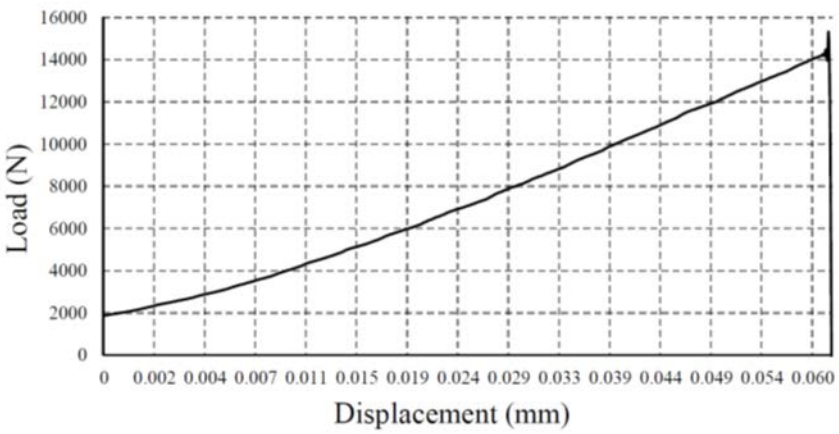


Fig. 4 The mid-length regions of the reference annealed glass specimens were undamaged

4.2 Reference Tempered Glass Test Specimens

Architectural fully-toughened glass is produced by heating up and then rapidly cooling (quenching) annealed glass. The rapid cooling causes sudden solidification of the surface and the subsequent cooling of inner core generates high tensile stresses in the middle region. The subsurface tensile stresses are then balanced by compressive stresses developed in the surface regions (Balan and Achintha, 2015). In Europe, typically the surface compressive stresses of commercially available thermally toughened glass are between 80 and 150 N/mm^2 (IStructE, 2014). Due to the surface compression and the resistance against the development of critical flaws on the surfaces means toughened glass are stronger than equivalent annealed glass specimens. However, unlike annealed glass, which fractures into large pieces due to the presence of tensile stress in the mid-thickness regions in fully-toughened glass, cracks progress rapidly causing complete fragmentation of fully-toughened glass specimens.

As expected, the reference tempered glass bolted joint test specimen shattered in to small dice as shown in Fig. 5a. The failure of the joint was instantaneous and caused complete fragmentation of the entire two glass specimens. This behaviour was different to the reference annealed glass test specimen where the failure was localised to the vicinity of the bolted joints (see Fig. 4). The applied load–axial displacement relationship shown in Fig. 5b suggests no post-fracture load resistance was existed in the reference tempered glass test specimens. Nevertheless, as expected, the reported load capacity of the joints were higher compared to that of the reference annealed glass bolted joints. For example, the reference tempered glass bolted joint test specimen shown in the Fig. 5a, failed at ~14300 N, ~275 % higher than the observed failure load of 3800 N of the reference annealed glass test specimen shown in Fig. 3a.



a) b)

Fig. 5a) Complete fragmentation of both two glass specimens in a reference fully-toughened bolted joint , b) Applied load–displacement relationship of a reference bolted joint in fully-toughened glass test specimen

4.3 GFRP Reinforced Annealed Glass Specimens

As expected, the reinforced bolted joints in annealed glass specimens also failed due to failure of glass in the vicinity of the bolted joint. However, unlike the reference test specimens, the reinforced joint did not fail instantaneously after the initiation of a critical crack in glass. For example, the applied load–axial displacement relationship of one of the reinforced test specimens shown in Fig. 3b suggests that the joint resisted the applied load after the formation of the first major crack in the test specimen. Fig. 6 shows this reinforced annealed glass test specimen after removing from the testing machine. The figure shows that unlike in the reference annealed glass test specimens where complete fractures occurred across the bolted joints, or the references fully-toughened test specimens where entire glass shattered into small pieces, no complete fracture occurred in the reinforced annealed glass bolted joint test specimen.

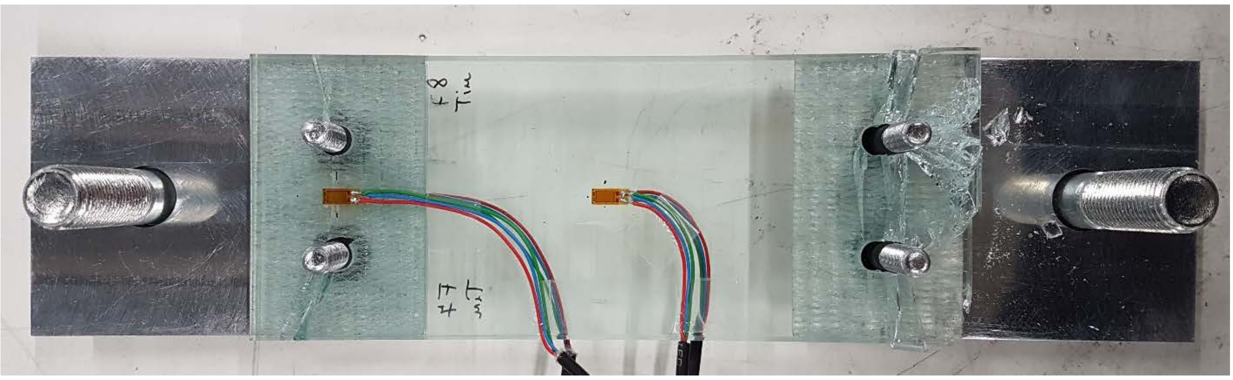
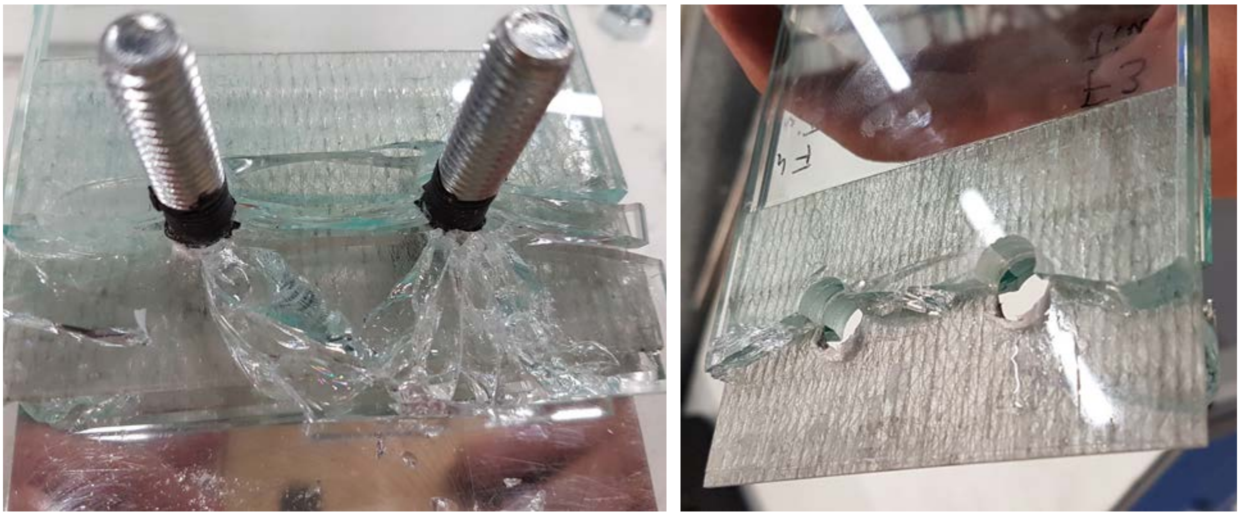


Fig. 6 Failure pattern of a reinforced annealed glass test specimen

Although the reinforced joint still failed in the vicinity of the bolted joints, the GFRP strip prevented a complete failure of the test specimen by holding the broken glass pieces together. Fig. 7a shows a close-up view of a reinforced bolted joint where the most damaged in glass occurred among all the test specimens tested in the present study. As can be seen from Fig. 7b, despite the glass was damaged very significantly in the joint shown in Fig. 7a, the GFRP strip remained intact. It is anticipated that the GFRP strip will have potential to contribute to the resisting the applied load even after a complete failure of the glass in the vicinity of the joint.



(a) (b)

Fig. 7: Failure of glass in a reinforced annealed glass joint configuration, a) Glass fractured in the vicinity of the bolts , b) The GFRP strip remains intact although the glass has fractured

The applied load–axial displacement relationships of the reinforced annealed glass bolted joint and the reference annealed glass joint shown in Fig. 3b suggest the behaviour of the two joints were very similar at lower loads (i.e. prior to the failure of glass in the reference specimen). However, the strengthened specimen carried a higher load than the reference specimen. The load capacity of the strengthened joint was ~9360 N, ~150% higher compared to that of the reference specimen (~3800 N). The figure also shows the reinforced joint showed an ability to resist the applied load after the peak load – i.e. even after the glass failed in the vicinity of the bolt. Although, the load capacity of the strengthened joint (~9360 N) was still lower than that of an equivalent joint in fully-toughened glass (~14300 N), a safe failure behaviour of the former after the attainment of the peak load is very commendable. The results suggest the use of a GFRP reinforcement strip increased the load resistance of the bolted joint in annealed glass, and it also ensured a notable ductility compared to brittle failure observed in conventional bolted joints in annealed and fully-toughened glass.

5. Conclusions

- The experimental results presented in this paper show that despite the higher load capacity of the bolted joints in fully-toughened glass compared to an equivalent joint configuration in annealed glass, fully-toughened glass shattered into small dice, consequently resulting in no post-fracture resistance.
- The results showed that the peak load of the reinforced joints in annealed glass increased up to 250% compared to reference annealed glass joints.
- Reinforced annealed glass bolted joints showed a notable ductility before the final failure compared to the brittle failure observed in conventional unreinforced joints in annealed and fully-toughened glass.

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