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GLASS–GFRP HYBRIDS: FROM BRITTLE GLASS TO DUCTILE AND HIGH STRENGTH STRUCTURAL GLASS

M. Achintha [1*], B. Balan [1], M. Bessonov [1], T. Zirbo [1] and J. Kanvar [1]

[1] *Faculty of Engineering and the Environment, University of Southampton, Southampton, SO17 1BJ, UK*

[*]*Email: Mithila.Achintha@soton.ac.uk*

ABSTRACT

This paper presents selected findings from a research programme that aimed to exploit the use of adhesively-bonded Glass Fibre Reinforced Polymer (GFRP) laminates as a mean of improving strength and ductility of glass structural elements. In the first half of the paper, using the results of an experimental investigation of the load response and failure behaviour of annealed glass beams reinforced with GFRP laminates, it is shown that the load resistance and the ductility of the glass beams can be enhanced. In the latter half of the paper, it is shown that the stress concentration geometries and bolted joints in annealed glass can sustain greater loads with greater ductility, even after microcracks formed, if the glass is reinforced with adhesively-bonded GFRP laminates.

KEYWORDS

Bending, Ductility, GFRP, Glass, Joints, Reinforcement, Strength.

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 have an increased and central role in future energy-efficient buildings. In order to make buildings more energy efficient using glass, it will be required to use glass as a load bearing construction material (e.g. facades, beams, columns, floors). The exploitation of full potential of glass for delivering energy efficient buildings is currently being held back by brittle material behaviour and the relatively low tensile strength (compared to metals). The tensile strength of basic float glass (also known as annealed glass) is about 40 MPa (IStructE, 2014). The presence of surface flaws and other stress concentration features can further reduce the actual tensile strength of glass. Tempered glass (also known as toughened glass), which is produced by heating up annealed glass up to a high temperature and then rapidly cooled, has a surface compressive pre-stress (i.e. residual stress) of magnitude of 80–150 MPa (IStructE, 2014). Owing to the higher apparent tensile strength, tempered glass can be potentially used in load bearing structures. However, tempered glass display a poor failure behaviour, similar to that in annealed glass, with no residual load capacity after the initiation of a critical crack/defect.

The brittle material behaviour of glass means the design and construction of connections in glass pose major challenges. Mechanical fixings such as clamps and bolted joints are used in contemporary glass designs in order to fix glass panels together or to fix them into a sub-frame support structure. Surface flaws and the consequent stress concentrations cause by drilling holes and the inevitably present localised stress concentrations in the vicinities of mechanical joints significantly weaken glass exactly at locations where glass is subjected to greater stresses. Despite isolating hard materials from glass via the use of softer materials such as plastic and rubber, all of which redistribute stresses to a certain extent, the mechanical fixings methods are not effective in transferring loads through glass. Usually, only the toughened glass can be used with mechanical fixings. Despite the higher cost and additional difficulties due to improper surfaces, toughened glass has poor failure behaviour and low degrees of toughening around bolt holes (Nielsen, et al. 2009). Although adhesive bonding offers the potential to be an attractive alternative to mechanical joints, 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.

This paper shows a few selected applications of the use of Glass Fibre Reinforced Polymer (GFRP) as a mean of overcoming inherent structural deficiencies in annealed glass when used as a construction material. Four applications are discussed: (1) as a mean of improving ductility of annealed glass beams; (2) use of a prestressed GFRP interlayer as a mean of improving the strength of annealed glass beams; (3) as a mean of improving strength and ductility of stress concentration features in glass; and (4) as a reinforcement in bolted joints in annealed glass.

The results show that bonded GFRPs can potentially be used to increase the apparent tensile strength of glass as well as to increase the ductility of glass structures.

REINFORCED GLASS BEAMS

The use of reinforcing materials has potential to improve the post-fracture behaviour of glass structures. For example, commercially available laminated glass where one or more thin PolyVinylButyral (PVB) or ionomer interlayers are bonded in-between laminated glass sheets has relatively safer failure characteristics compared to monolithic annealed/tempered glass. When a laminated glass sheet fails, the interlayer absorbs the energy, and the interlayer also has potential to hold broken glass pieces. This behaviour ensures some post-breakage load resistance, and eliminates a complete failure of the glass sheets. Despite the potential of laminated glass ensuring a safe failure behaviour, the low stiffness and the low strength of the thin interlayers mean careful designs are required in order to ensure an adequate ductility. Cutting, drilling holes etc. on sites without damaging the original laminated glass is difficult. This limitation together with the higher cost compared to monolithic glass hamper the exploitation of full potential of laminated glass in complex building geometries. On the other hand, the use of relatively stronger (in tension) and stiffer reinforcing materials in glass, similar to the concept of using of steel reinforcement bars in concrete beams, has potential develop a new form of reinforced glass which will have greater post-breakage resistance and ductility.

Adhesively-bonded or mechanically-connected additional material, such as steel (e.g. Louter et al., 2012), timber (e.g. Blyberg et al., 2014), and Fibre Reinforced Polymer (FRP) (Achintha and Balan, 2017) have been investigated in the literature as a mean of reinforcing glass beams. The results reported in the literature suggest, after glass has failed in tension, the reinforcement and the compressive stresses can keep the broken glass pieces locked in place whilst the reinforcement resisting the tension in the post-cracked regime of the glass beams. This behaviour ensured an ability to resist load beyond the peak load, thereby enabling a notable post-fracture resistance and stability in the beams. Research investigations show a better ductility in reinforced annealed glass beams compared to that in reinforced tempered glass beams (Louter et al., 2012). This is because annealed glass shatters into large pieces, unlike in tempered glass, in which cracks progress rapidly causing complete fragmentation of small dice. Detailed reviews of types of reinforced glass beams investigated in the literature can be found in Martens et al. (2014), Bos (2009) and Correia et al. (2011).

ANNEALED GLASS BEAMS REINFORCED WITH GFRP INTERLAYER

Owing to high strength, lightweight and semi-transparent characteristics of GFRPs are attractive for reinforcing glass. In most GFRP reinforced glass beams reported in the literature, the GFRP was embed in composites sections of 'I', 'T', 'H' and box profiles. Various forms of GFRP were used in these studies; for example, adhesively bonded GFRP rods (e.g. Louter, 2010) and GFRP pultruded profiles (e.g. Correia et al., 2011, Speranzini and Agnetti, 2014) were the most commonly used GFRP systems. The GFRP reinforced beams demonstrated significant post-fracture resistance and ductility compared to unreinforced annealed and tempered glass beams (Martens et al., 2014). However, despite the favourable post-breakage load resistance, the final failure of the beams were still sudden and explosive due to debonding of the adhesively bonded GFRP from the glass and/or due to glass failure. Some of the GFRP reinforced glass beams also failed due to instability in the lateral direction.

In the present study, a simple arrangement of double layer annealed glass beams reinforced with an adhesively bonded GFRP interlayer (Figure 1) subject to minor axis bending was investigated. This arrangement provides the flexibility required to use GFRP reinforced glass in a range of geometries, including areas around joints and fixtures where greater strengths and ductility are required. As can be noted from the results presented in this paper, the minor axis bending arrangement also eliminated lateral instability failure commonly observed in the beams tested in the studies reported in the literature.

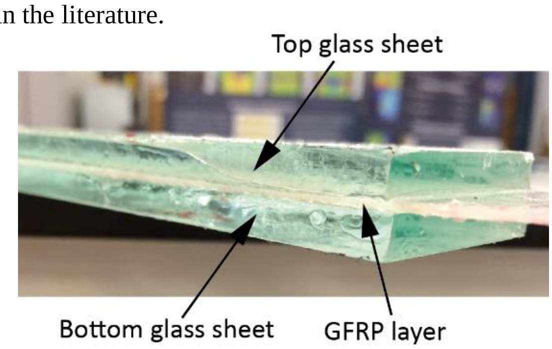


Figure 1: Two-layer annealed glass beam with an adhesively bonded GFRP interlayer

Fabrication of GFRP Reinforced Annealed Glass Beams

10 mm thick annealed glass sheets purchased from a commercial supplier and cut in to dimensions of 600 mm x 40 mm were used in the present study to make glass beams. The GFRP laminate that used to reinforce the glass beams 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 length and the width of the GFRP reinforcement layer was taken to be the same as that of the glass beams. The GFRP was bonded as an interlayer between two glass beams by using structural epoxy adhesive, "Araldite2020" (Araldite2020, 2015). In order to bond the GFRP onto glass sheets, an adhesive layer of ~0.1 mm thick was uniformly spread over one surface of each glass sheet, and then placed the GFRP strip on the top of one glass surface. The second glass sheet was then placed on the top of the GFRP, and a good bond was ensured by applying a small pressure on glass sheets. The beams were then first cured inside an autoclave at temperature of 40^{o}C and atmospheric pressure for 24 hours, followed by further six days of curing under ambient conditions.

Beam Tests, Load Response and Failure Behaviour

The beams were tested in four-point bending with a constant moment zone of 400 mm long and two equal shear spans of 50 mm (Figure 2), displacement controlled and at a slow displacement rate representing a static loading scenario. For brevity, only the results of one beam specimen are presented in this paper. Detailed results of other beams tested in the present study, including beams made from glass sheets of different thickness are presented in Achintha and Balan (2017).

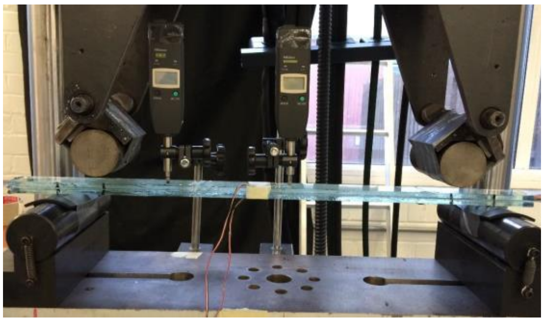


Figure 2: Four-point bending test of glass beams

Figure 3a shows the load–midspan deflection relationship of the GFRP reinforced double layer annealed glass beam. In order to compare the load response and the failure behaviour of the reinforced glass beam, the results of a single-layer and an adhesively-bonded double-layer (i.e. without GFRP reinforcement) glass beams are also shown in the figure. As can be seen from the figure, until the formation of the first major crack, the reinforced beams showed linear behaviour, similar to other types of beams. Although the other beams failed in a brittle manner at the peak load, the reinforced glass beam continued to carry the load after the peak load where a major crack caused a fracture of the bottom (i.e. tension) glass sheet. After the attainment of the maximum load (5600 N), the load resistance of the reinforced beam dropped by ~65%, to1960 N due to the failure of the bottom glass sheet. However, the presence of the GFRP layer prevented a complete failure.

Figure 3b shows the final crack pattern of the reinforced beam: a distributed cracks throughout the top (i.e. compression) glass layer. The figure also shows that the GFRP held the cracked glass pieces together despite the continuous cracking during the post-breakage regime. This behaviour contributed to maintain a notable bending stiffness in the beam in the post-breakage regime. The 'ductility index', may be defined as the ratio of the additional midspan deflection after the peak load to that at the peak load. This suggests the ductility index of reinforced beams is over 500%, and this can be compared with the zero ductility index of single and unreinforced double-layer beams.

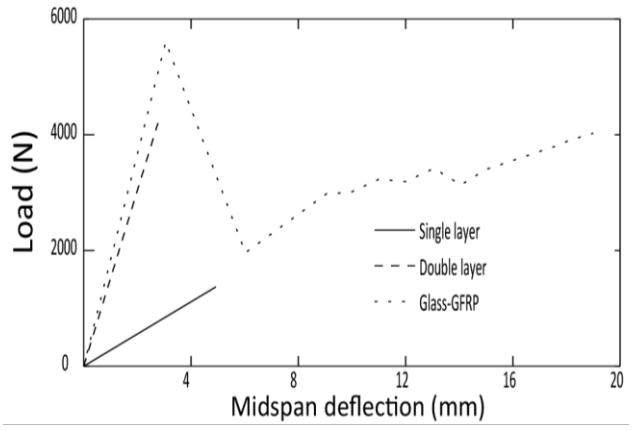


Figure 3a: Load–midspan deflection relationships of the beams

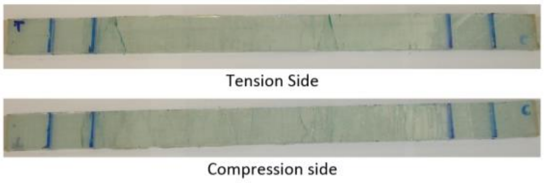


Figure 3b: Final cracking state of the GFRP reinforced glass beam

PRESTRESSED GLASS BEAMS

The results presented in the previous section suggest that the use of GFRP as a reinforcement has potential to ensure a safe post-breakage behaviour in annealed glass beams. However, despite the notable ductility showed by GFRP reinforced annealed glass beams, the GFRP reinforcement cannot increase the tensile strength of glass where fracture initiated due to a critical surface flaw in the tension side (i.e. bottom glass sheet). Since glass is strong in compression, a surface compressive prestress has potential to improve the apparent tensile strength. However, although commercially available toughened glass possess a compressive prestress in the surface regions, the balancing tensile stress in the mid-thickness region (Balan and Achintha, 2015) mean they will break in to small pieces - a behaviour which is not desirable from a structural point of view.

The potential for extending the previous work of reinforcing annealed glass beams with GFRP interlayer by introducing an adhesively bonded pre-tensioned GFRP interlayer was explored in the present study. Unlike in tempered glass where the prestress level cannot be chosen at the sites, by choosing the right force, a desirable compressive prestress in the glass beams which is tailored for the design requirements of the beam can be achieved.

Fabrication of Prestressed GFRP Reinforced Annealed Glass Beams

6 mm thick annealed glass and the GFRP laminate and the adhesive used in the earlier study of GFRP reinforced annealed beams were used here. However, prior to bonding the GFRP onto the glass sheets, the GFRP sheet was tensioned using a hydraulic test machine. Once the tension force in the GFRP had reached a prescribed value, the load was hold until the glass beams were bonded to the either side of the prestressed GFRP. The beams were then cured in the same way as that of previous glass beams with unprestressed GFRP interlayer. End-clamps connections were used to maintain the prestress force in the GFRP until the full curing of the glass–GFRP adhesive bond. A schematic representation of the fabrication process is depicted in Figure 4.

Initial Compressive Prestress in Glass Beams

Once the end clamps were released after the full curing of the glass–GFRP adhesive bond, the stresses present in the glass sheets were measured using a polariscope, SCALP-05 (SCALP, 2015). SCALP-05 instrument uses glass birefringence that changes the polarisation of an input laser beam, and the consequent variation in the intensity (optical retardation) of the scattered light to determine the stress in glass. The use of SCALP-05 to measure initial stresses in glass is presented in Achintha and Balan (2015). The results suggests that the prestressed GFRP interlayer caused a largely uniform (along the thickness of the beam) compressive stress of ~7 MPa in the glass.

Load Response and Failure Behaviour

The prestressed glass beams were tested in the same way as earlier GFRP reinforced beams. Figure 5 presents the load–midspan deflection relationships of the pre-stressed beam and that of an equivalent unprestressed GFRP reinforced glass beam. Similar to the unprestressed beam, the prestressed beam showed a largely linear behaviour until the formation of the first major crack, and followed by a notable post-breakage load carrying behaviour. The peak load of the prestressed beam was determined to be 2200 N. This suggest ~18% increase compared to that of the unprestressed beam (1870 N). The results suggest an increase in the apparent tensile strength resulted in an increase in the peak load of the prestressed beam compared to the unprestressed beam. The prestressed beam displayed a notable ductility, similar to that of the unprestressed reinforced glass beam. The relatively high flexural stiffness of the prestressed beam just after the peak load may be attributed to less cracking occurred in the beam owing to the compression caused by the GFRP. However, as can be seen from Figure 5, with the increase of the damage the flexural stiffness of the prestressed beams approached that of the unprestressed beam.

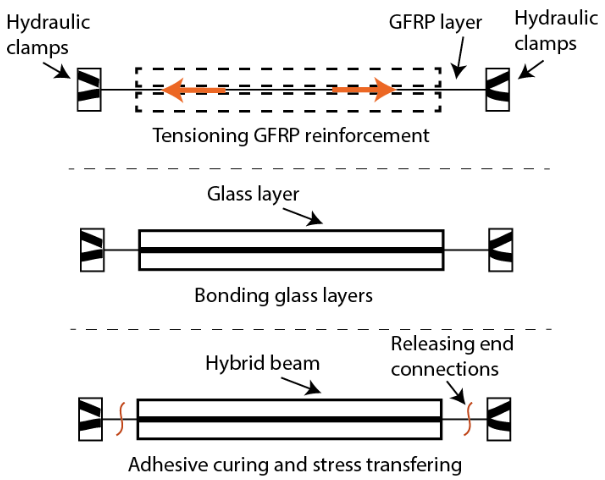


Figure 4: A schematic representation of the fabrication of GFRP prestressed glass beams

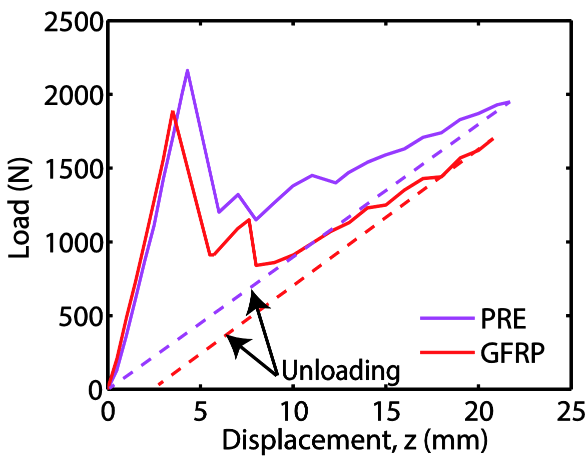


Figure 5: Load–midspan deflection relationships of the reinforced and prestressed glass beams

STRENEGTHENING STRESS CONCENTRATIONS FEATURES IN ANNEALED GLASS

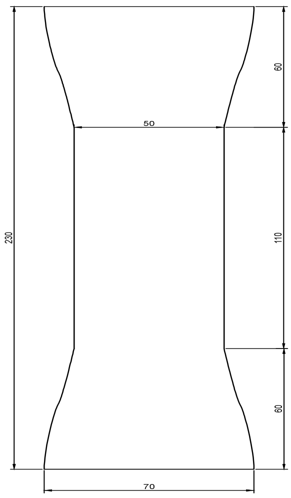
Due to the brittle material behaviour of glass, the stress concentration features pose a major challenge when designing and constructing glass structures. The potential for using adhesively bonded GFRP laminates to strengthen stress concentration zones in glass was experimentally investigated using open-hole annealed glass tensile test specimens.

Test Specimens

A dogbone shape was chosen as the test specimen geometry of the tensile test specimens (Figure 5a). The thickness of the glass was 4 mm and the width and the length of the central part of the test specimen was 50 mm and 110 mm respectively. A 10 mm diameter central hole was drilled using a diamond drilling tool. The efficacy of strengthening was investigated by strengthening the test specimen using GFRP strips. The same GFRP laminate used in the earlier works of the present study was used to strengthen the vicinity of the hole. Two GFRP strips of 50 mm x 20 mm were bonded on each surface of the glass adjacent to the edge of the hole along the loading direction using “Araldite2020”. The reinforced test specimens and the reference unstrengthened specimens were tested in uniaxial tension representing a static loading scenario.

Results

Details of the full experimental programme, including the results of all test specimens tested in the present study can be found in Bessonov (2016). For brevity, only the load–displacement relationships of one strengthened and one reference specimens are shown in Figure 5b. The reference unreinforced specimen failed in a brittle manner across the hole at applied load 2960 kN. In the reinforced specimen, the GFRP strips bridged the cracks those developed around the hole. The results shown in Figure 5b suggest the formation of multiple cracks, consequently resulting in a notable ductility before the final failure. The failure load of 5260 N of this test specimen is 78% higher than that of the reference specimen.



(all dimensions in millimetres)

Figure 5a: Dimensions of the test specimen

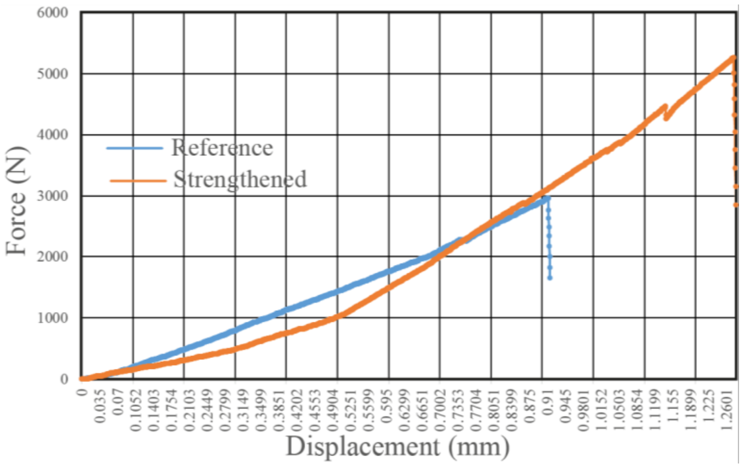


Figure 5b: Applied load–displacement relationship of the reinforced and the reference tensile test specimens

GFRP REINFORCED BOLTED JOINTS IN ANNEALED GLASS

The potential of adhesively bonded GFRP for enhancing strength and ductility of stress concentration features in annealed glass was extended in order to experimentally investigate the efficacy of strengthening bolted joints.

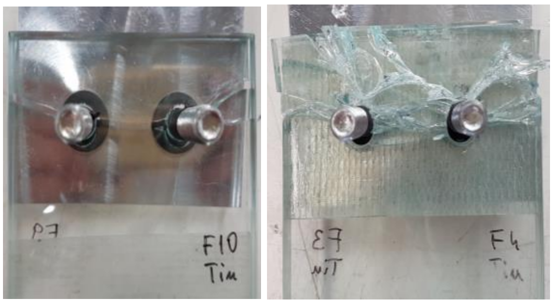
Test Specimens

100 mm x 250 mm pieces of 6 mm thick annealed glass was used in the experimental investigation (Figure 6). Two 11 mm diameter holes were drilled at each end of the test specimen. Cutting the glass specimens in to the required size and drilling of the holes were done by a commercial supplier. All edges, including inside of the bolt holes were polished. At each end of the glass piece, a 100 mm x 60 mm GFRP strip, made from the same GFRP laminate used in the earlier works of the present study was bonded to two glass pieces using "Araldite2020". 11 mm diameter holes were also drilled on the GFRP and ensured that the holes in the GFRP and the glass were perfectly aligned. The specimens were cured in the same way as the reinforced glass beams described in the first half of this paper. After curing, the GFRP reinforced glass test specimen was connected to aluminium plates using M10 bolts (Figure 6). EPDM rubber was used to avoid direct contact between the glass and the bolts. The aluminium sheets were then connected to a thicker aluminium sheet, which was then used as the fixing grip to the test machine (Figure 6). The test specimens were tested in tension under a displacement rate representative of a static load scenario. The load response and the failure behaviour of the reinforced bolted joints were compared with that of an equivalent glass assembly, but without GFRP reinforcement.

Results

Figure 7 shows the typical failure observed in the GFRP strengthened and reference (i.e. unreinforced) test specimens. As expected, in all test specimens the failure occurred in glass in the vicinity of the bolted joint. The applied load–axial displacement (measured at the mid-length region of the test specimen) relationships of one reinforced and one reference test specimen are shown in Figure 8. As can be noted from the figure, both specimens showed a largely linear response. In the reference test specimen, one glass sheet was failed first causing a little drop in the load resistance. Although the other glass sheet then started to carry the load, it also failed soon after the failure of the first one. The specimen was failed in a brittle manner where glass failed completely throughout the cross section of the joint (Figure 7a) at applied load 3800 N. The strengthened joint did not fail instantaneously, and as can be seen in Figure 7b, also no complete failure occurred across the joint. The GFRP held the broken glass pieces together and also contributed to carry the after the glass started to crack. The peak load of the strengthened joint was 9360 N, ~150% higher compared to the reference specimen. The figure also shows the strengthened joint resisted some load beyond the peak load. The results suggest the GFRP interlayer prevented complete failure of the glass in the vicinity of the bolts and also contributed to carrying the load in the post-cracked regime.

Figure 6: Test arrangement of bolted joints in glass



(a) (b)

Figure 7: Failure of the: (a) unreinforced; reinforced joints

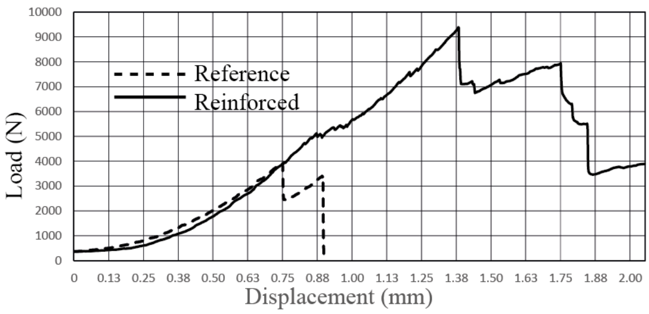


Figure 8: Load–midspan displacement of the reinforced and unreinforced bolted joints

CONCLUSIONS

The experimental results presented in this papers show that:

- the use of an adhesively-bonded GFRP interlayer can improve the ductility of annealed glass beams;
- the mechanical prestressing using a pretensioned GFRP reinforcement has potential to improve the apparent tensile strength of annealed glass beams;
- externally-bonded GFRP laminates has potential to strengthen stress concentration features in annealed glass;
- the use of an adhesively bonded GFRP laminate improved the strength and ductility of bolted joints in annealed glass.

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