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Characterisation of the mechanical behaviour of annealed glass–GFRP hybrid beams

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HIGHLIGHTS

- Glass–GFRP hybrid beams are stronger and ductile than annealed glass beams.
- In hybrid beams, once the tension glass has cracked, the GFRP carries the tension.
- A large part of the deflection of the hybrid beams was recovered in unloading.
- Finite element analyses can predict the load response of the hybrid beams.
- Incorporation of the residual stress in glass ensured accurate predictions from FE models.

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ABSTRACT

This paper presents the results of a combined experimental and numerical investigation on the mechanical behaviour of annealed glass–Glass Fibre Reinforced Polymer (GFRP) hybrid beams. The experimental results showed that an adhesively-bonded GFRP interlayer significantly improved the strength and ductility of annealed glass beams. The paper also presents the post-breakage behaviour and the response of damaged beams in unloading. The paper numerically investigates the degree to which the strength and stiffness of the hybrid beams can be modelled by using finite element (FE) analyses. The novelty of work also includes numerical modelling and validating the through-thickness stress profiles in the hybrid beams.

1. Introduction

Owing to the fascinating physical, optical, chemical, and thermal properties of glass together with its potential to deliver energy efficient building envelopes, glass has become one of the most preferred construction materials in modern buildings. However, despite the great potential of glass as a construction material, its brittle material behaviour pose major challenges when constructing load-bearing structural members, such as large glass panels, roofs, floors, staircases and partitions. Poor post-breakage strength, lack of ductility and inefficient connections are the main inherent challenges compared to other construction materials, such as concrete, steel and timber. The usual industrial practice is to over-design glass structural elements and/or to use sacrificial layers [1]. However, neither approach will eliminate brittle failure of glass.

Annealed float glass has a low tensile strength (<40 MPa) [2] compared to steel, and hence, the structures made from annealed glass have modest load bearing capacities. The compressive strength of glass is much higher than the tensile strength, but the compressive strength is largely irrelevant in practical structural designs because compression members will most likely fail prematurely due to buckling or the tensile stresses developed due to Poisson's ratio effects. 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 [2]. Tempered glass is often used in load bearing structural elements. Heat-strengthened glass, which is also used in con-

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struction industry, is produced in the same as way as fully-toughened glass, but the heated annealed glass is quenched at a slower cooling rate. Heat-strengthened glass has a low surface pre-compression, compared to toughened glass, of magnitude 40–80 MPa [2]. Residual stresses – i.e. the stresses generated in glass owing to the thermal misfit strains generated due to the differential cooling takes place during the manufacturing of float glass and during the quenching of tempered glass - has an influence on how glass breaks during a failure; annealed glass shatters into large pieces of sharp shards, whereas in tempered glass, cracks progress rapidly causing complete fragmentation of small dice of about 100 mm^2 [3].

One efficient way to ensure a notable post-breakage strength and ductility in glass is the use of reinforcing materials. Commercially available laminated glass, which is produced by combining two or more sheets of annealed/tempered glass with one or more thin PolyVinylButyral polymer interlayers, has relatively safe failure characteristics compared to single layer annealed/tempered glass. The recent developments of lighter and stronger laminated glass include the use of ionomer interlayers; laminated glass with ionomer interlayers are lighter and stronger than conventional laminated glass [4]. However, the low stiffness and strength of the thin interlayers mean careful designs are required to ensure an adequate post-breakage strength for laminated glass. At present, laminated glass cannot be made at constructions sites, and it is difficult to make alterations (e.g. cutting, drilling, etc.) in laminated glass. Therefore, all the processing steps are carried out before lamination.

The use of relatively strong reinforcing materials enables the development of glass hybrids that possess high pre-crack and post-breakage strengths, and ductilities [5]. A number of materials, such as timber, steel, reinforced concrete, fibre reinforced polymer (FRP), steel, etc. have been used in combination with glass [1]. The post-breakage strength and the ductility of glass hybrids have been mostly studied using experiments of beams. In most hybrid beams, the second material was used to make composites sections of 'I', 'T', 'H' and box profiles, and in other cases, small amounts of the second material was used to reinforce the glass without significantly altering the original rectangular shape. Detailed reviews of types of hybrid glass beams investigated in the literature can be found in [1,6,7]. Adhesive bonding of the reinforcement material to glass sheets has been preferred over mechanical connections (e.g. bolts), since the mechanical joining systems are largely structurally ineffective. Commonly available adhesives, such as polyurethane, epoxy and acrylic were used to make glass hybrid beams [6]; epoxy adhesives were found to be more effective in enhancing post-breakage strength and ultimate load capacity of the hybrid beams owing to the high strength and stiffness of the adhesive [6]. Although tempered and heat-strengthened glass hybrid beams provided higher load capacities compared to equivalent annealed glass hybrid beams, the latter provided better post-breakage behaviour [5].

Timber [8] and steel [5,9] composite glass beams are already well developed and tested, largely resulting optimal designs for beams. Typically, 'T' – or – 'I' sections, in which the web is glass and the flanges are steel/timber were found to be structurally efficient. However, durability is a concern in timber/steel glass hybrids. Different shapes and forms of steel reinforcements, bars/strips [10] and steel reinforced polymer sheets along the tension edge of the glass beams [11] were also used in laminated glass beams. In these hybrid beams, the bonding surfaces were usually parallel to the direction of the applied load. The efficiency of redistributing the load upon failure of subsequent glass sheets and the resistance against lateral buckling of individual glass panes were critical to achieving improved post-breakage behaviour.

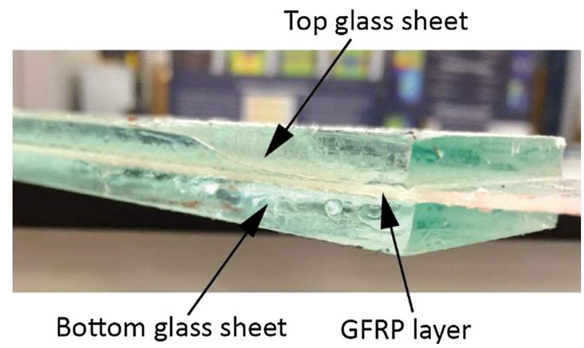

Fig. 1. Glass–GFRP hybrid beams.

High strength, lightweight and non-corrosive characteristics of Carbon (CFRP) and Glass (GFRP) Fibre Reinforced Polymers make them attractive for reinforcing glass beams [12]. Mostly, CFRP/GFRP rods were used in the experiments reported in the literature [12]. As expected, the glass–FRP hybrid beams showed good structural performances, in particular, flat reinforcement rods were more effective compared to rounded reinforcement rods [10]. Glass–CFRP hybrid beams mostly failed prematurely in brittle manner due to debonding of the CFRP from the glass, whereas glass–GFRP hybrid beams showed higher deformation capacities. Laminated glass beams with embedded GFRP rods showed enhanced peak load and improved ductility at failure [13]. Recent studies (e.g. [6], [14], [15]) demonstrated the potentials of GFRP pultruded profiles in glass hybrid beams, either as a tension reinforcement unit in a stack of glass sheets bonded in the vertical direction, or as a web of composite section with glass sheets as flanges. GFRPs are cheaper than CFRP, and have translucent properties. Despite the potentials of annealed glass–GFRP hybrids have been noted in the literature, the existing knowledge is limited to the specific parameters chosen in each experimental programme, and prediction of the structural behaviour for a different set of load parameters or a different structural geometry requires a new experimental/numerical analysis. There is a need for a more detailed investigation which represents the basic mechanics of simple geometries and load cases.

The authors have previously presented [16] the preliminary results of a combined experimental and numerical investigation of annealed glass–GFRP hybrid beams. In the hybrid beam, a GFRP strip was adhesively bonded in between two horizontal glass sheets (Fig. 1). The work presented in that conference presentation is limited to a single thickness of glass sheets and simple comparisons between the experimental results and the predictions from finite element (FE) analyses. The current paper extends the previous work [16] and shows the results of mechanical behaviour of a much larger matrix of hybrid beams made from glass of two different thicknesses. The paper also presents the post-breakage behaviour and the response of the damaged beams in unloading. The novelty of work also includes modelling and validating the through-thickness stress profiles in the hybrid beams.

2. Glass–GFRP hybrid beams

The system of an adhesively-bonded GFRP strip in between two annealed glass sheets (Fig. 1) provides the flexibility required to use glass–GFRP hybrids in a range of geometries, including areas around joints and fixtures where a greater strength and a ductility are important. From an experimental investigation of hybrid glass beams made from plies of chemically toughened glass (as outer layers), conventional polymer interlayers and a heat treated/