Glass reinforced glass

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Abstract

Laminated glass units are traditionally used to provide a degree of post-fracture strength, but the residual strength is often limited to relatively low levels sufficient for holding the glass fragments together for a predetermined amount of time. It is possible to achieve a higher level of residual strength, but this requires specific boundary conditions and/or opaque reinforcing materials. This paper describes the experimental investigations on laminated glass units that can provide a significant degree of post-fracture resistance, without the need of boundary restraints or opaque reinforcing materials. The glass units are composed entirely of combinations of conventional transparent interlayers and commercially available glass (annealed, heat treated and chemically strengthened). The paper also describes an empirical energy-based interpretation of the mechanical response of the laminated units.

Introduction

Laminated glass units are used in building, automotive and aerospace applications where a degree of structural integrity after first fracture is required. The units consist of plies of monolithic glass, typically annealed or heat treated soda-lime silica glass, bonded together by polymer interlayers typically Polyvinyl Butyral (PVB), Ethylene Vinyl Acetate (EVA) or SentryGlas ionomer (SGP). The interlayers provide shear coupling between the glass layers and upon glass fracture the interlayer adheres to the glass fragments thereby offering a degree of post-fracture (residual) capacity. Furthermore, it generally advisable to use different types of monolithic glass in a laminated unit (e.g. combining heat strengthened glass and fully toughened glass) as this provides a good balance between strength to first fracture of fully toughened glass and post-fracture stiffness of heat strengthened glass [1,2].

There has been extensive research on the mechanical response of laminated glass in its unfractured state. These date back to the 1970's and are beyond the scope of this paper, but a detailed review is provided by Asik & Tezcan [3] and Galuppi & Royer-Carfagni [4].

In contrast, the post-fracture response of laminated glass is a relatively recent area of research that has come to the fore in the last 10 years. There is general agreement that the post-fracture strength and stiffness are a function of: bulk material properties of glass and polymer interlayer; adhesion at the interlayer-glass interface; fragmentation pattern; and boundary conditions. There are two distinct approaches that are used to account for these characteristics:

1. A bottom-up approach, where the focus is on characterising the mechanics of failure at a typical crack in laminated glass. Most of this research has been on interfacial adhesion at the polymer-glass interface [5-8]. This research involves carefully controlled small-scale experiments such as through-crack-tension and peel tests, but the underlying assumption that underpins this work is that the fractured laminated glass can be represented by a collection of stiff glass fragments connected by elastomeric bridging ligaments. As such, this approach requires an a-priori knowledge of the fracture pattern and assumptions on the energy dissipated in the glass from first fracture up to failure. It is possible that this approach will eventually provide a complete analytical solution to post-fracture response, but this is not yet possible.

2. A top-down approach, where larger glass elements such as plates and beams are tested to destruction and a cracked section analysis (similar to that used in reinforced concrete) is subsequently performed to derive some semi-empirical relationships on the post-fracture response [9,10]. This is an effective approach but it does not decompose the response into its constituent parts and it is therefore difficult to extrapolate these semi-empirical rules beyond the glass element that is tested.

From the research to-date it is therefore evident that there are two significant challenges when developing laminated units. Firstly, determining the unfractured, and particularly the post-fracture, response of laminated glass is not a trivial task and secondly it is difficult to provide a significant degree of post-fracture capacity without adding opaque materials such as metallic reinforcing elements, meshes etc.

A useful development in the glass industry is the growing availability of chemically strengthened glass in the building industry. It consist of glass that is immersed in a bath of potassium salts at approximately 400°C which causes the smaller sodium ions in the glass to be replaced by larger potassium ions from the salt bath, thereby creating a thin compressive layer (20µm to 50µm thick). Residual surface stresses in excess of 250 MPa may be achieved with soda-lime-silica-glass, however the most effective ion exchange occurs in alakli-alumino-silicate glass where residual surface stresses of up to 981MPa have been obtained [11]. This glass together with the wide range of transparent polymer interlayers available on the market provide an opportunity to develop multi-layered laminated glass units that exhibit high strength to first fracture and significant post-fracture strength and stiffness.

This paper describes the experimental investigations on the multi-layered laminated units where the chemically strengthened glass is used as reinforcement layer for other glasses. The paper also provides an empirical energy-based interpretation of the mechanical response of the glass units during the various stages ranging from unfractured state to collapse.

Method

A series of 5-layer (3-glass-ply) laminated units incorporating combinations of different glasses and ineterlayers were assembled in a commercial autoclave. All laminated units were 900 mm long by 300 mm wide (Figure 1). The glass faces consisted of either 1mm thick or 0.7mm thick Corning Gorilla © Glass which is an alkali alumino-silicate glass that is chemically strengthened using an ion exchange process. The glass cores consisted of annealed, heat strengthened or fully toughened soda-lime-silica float glass manufactured to BS EN 572-2 [12] which for the heat strengthened and the fully toughened glass were heat treated to BS EN 12150-2 [13]. The interlayer was either an architectural grade Polyvinyl butyral interlayer or Sentryglas © Plus (an ionoplast interlayer manufactured by DuPont). Three nominally identical samples of each of the units listed in Table 1 were tested giving a total of 24 laminated units.

Unit reference	Glass faces	Interlayers	Glass core
1CS_0.76PVB_6AN	1mm CS	0.76mm PVB	6mm AN
1CS_0.76PVB_6HS	1mm CS	0.76mm PVB	6mm HS
0.7CS_0.76PVB_6HS	0.7mm CS	0.76mm PVB	6mm HS
1CS_0.76PVB_6FT	1mm CS	0.76mm PVB	6mm FT
1CS_0.76SGP_6AN	1mm CS	0.76mm SGP	6mm AN
1CS_0.76SGP_6HS	1mm CS	0.76mm SGP	6mm HS
0.7CS_0.76SGP_6HS	0.7mm CS	0.76mm SGP	6mm HS
1CS_0.76SGP_6FT	1mm CS	0.76mm SGP	6mm FT

Glass: Chemically strengthened (CS); Annealed (AN); Heat strengthened (HS); Fully toughened (FT)
Interlayers: Polyvinyl butyral (PVB); Sentryglas plus (SGP)

Table 1 Laminated unit samples

Systematic destructive four point bending (4PB) tests were performed on the laminated units to investigate the mechanical performance of the units in the unfractured and post-fractured states. The 4PB test rig was identical that described in BS EN 1228-3 [14] with the exception of sample dimensions that are indicated in Figure.1. The vertical deflection at mid-span and at the load points were measured by linear variable differential transformers (LVDTs) and recorded on a Solartron SI 3535D Scorpio data logging system. The vertical load was monitored with a 150kN load cell. Load was applied by means of a computer-controlled Instron 5500R electromechanical testing machine at a cross-head displacement of 20 mm/min., which equates to a surface stress on the glass faces of approximately 2 MPa/s. The tests were performed at 23±1°C and a relative humidity of 50±5%.

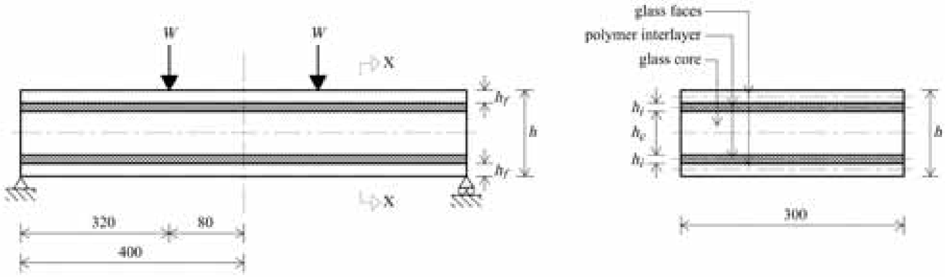

Figure 1. Laminated glass unit in four point bending (4PB) test set-up. Side view shown on the right and cross-section XX shown on the left.

Test results

The experimental test results are summarised in Table 2 and representative load-displacement results are shown in Figure 2 and Figure 3.

Unit reference	First fracture		Collapse		Relative residual stiffnes (%)
	Mean load 2W kN)	Coefficient of variation	Mean load 2W kN)	Coefficient of variation	
1CS_0.76PVB_6AN	0.50	0.93	2.97	0.24	61
1CS_0.76PVB_6HS	2.40	0.07	3.39	0.39	58
0.7CS_0.76PVB_6HS	2.14	0.08	1.81	0.30	43
1CS_0.76PVB_6FT	3.09	0.13	2.53	0.19	51
1CS_0.76SGP_6AN	1.74	0.11	5.21	0.30	89* (76†)
1CS_0.76SGP_6HS	4.07	0.06	3.58	0.12	82
0.7CS_0.76SGP_6HS	3.21	0.02	3.47	0.25	74
1CS_0.76SGP_6FT	5.22	0.06	5.41	0.15	83

* Residual stiffness immediately after first fracture
† Residual stiffness on further loading and further core fragmentation

Table 2 Mean test results

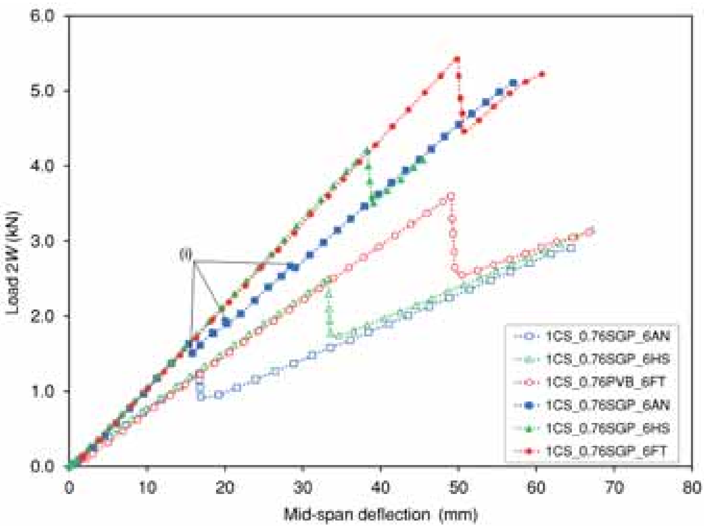

Figure. 2. Load vs. mid-span deflection test results for laminated units with 1mm thick chemically strengthened glass faces

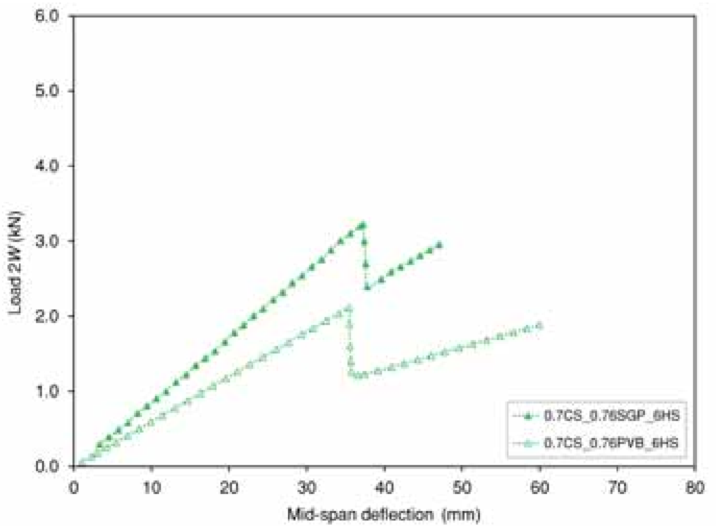

Figure. 3 Load vs. mid-span deflection test results for laminated units with 0.7mm thick chemically strengthened glass faces

Twenty-two out of twenty-four units exhibited a similar sequence of fracture, consisting of initial fracture of the core glass, followed by fracture of the tension and compression faces that fail simultaneously or in very quick succession. The fracture patterns could be grouped as follows:

1. Units with annealed glass core: the initial fracture propagates suddenly from one free edge to another and braches once or twice as it travels across the width of the specimen. As the load increases, further fractures, similar to the initial fracture, occur in the mid-span region of the core. Fractures in the faces occur on further loading and seem to propagate from one free edge to another. In each case the initial fractures in both the core and the faces originate from the free edges in the mid-span region.

2. Units with fully toughened glass core: both the fracture of the core and the faces are sudden and fragmentation extends along the entire length of the unit, with smaller fragments in the mid-span region. The core glass fails first into the characteristic small 'dice', resulting in a grid-like fracture pattern. The faces fail subsequently, into fragments smaller than those observed in specimens with annealed glass core. The origin of failure was generally located at the free edges but the dense fragmentation made it difficult to locate the fracture origin.

3. Units with heat strengthened glass core: these behaved in a similar way to those with the fully toughened glass core. The sudden fragmentation of the core extended along the length of the unit in a grid-like fractures pattern. In some of the specimens whose core failed at relatively low load, a fracture pattern similar to the annealed glass core was initially observed, but this was followed by the formation of fractures in grid-like pattern as the load increased further.

The fragment sizes of the core observed after the test was completed and ranged from 6mm to 12mm. There was no discernible difference in fragment length (in the direction of the span) between the different core glasses used or between the different interlayers. On the other hand the fragment width (perpendicular to the span) was between 6mm and 12mm for the units with fully toughened glass core, but was considerably larger (> 20mm) for the heat strengthened glass core and larger still for the (> 50mm) annealed glass core.

After testing it became evident that there was significant delamination between the PVB and the core glass to the extent that several small glass fragments became loose and fell out of the unit. On the other hand, there was no observable delamination in the units with SGP interlayer.

Discussion

From Table 2 it is evident that the units with an annealed core provide the largest post-fracture reserve. This is because the relatively weak core fails at low loads, which is unlikely to suit practical applications. The SGP laminated units with either a heat strengthened core or a fully toughened core consistently provided a high load to first fracture followed by a significant residual; stiffness and a collapse load which exceeded the load at fist fracture. As such these are the most promising combinations for practical applications.

Furthermore Figure 2 and Figure 3 show that the residual stiffness (after first fracture) intersects at the origin. This suggests that it is possible to determine the stiffness of the unit in its fractured state by analytical means. The stepped reduction in stiffness labelled as (i) in Figure 2 correspond to the further cracking of the annealed core. This suggests that the stiffness of the unit after first fracture is a function of the fragment size for the units with PVB interlayer, but not for units with SGP interlayer. Therefore any analytical solution must capture this phenomenon. This analytical solution is the subject of further work and is not discussed further here.

It is also possible to explain the explain the mechanical response of the units in terms of the energy stored and dissipated as shown in Figure 4.

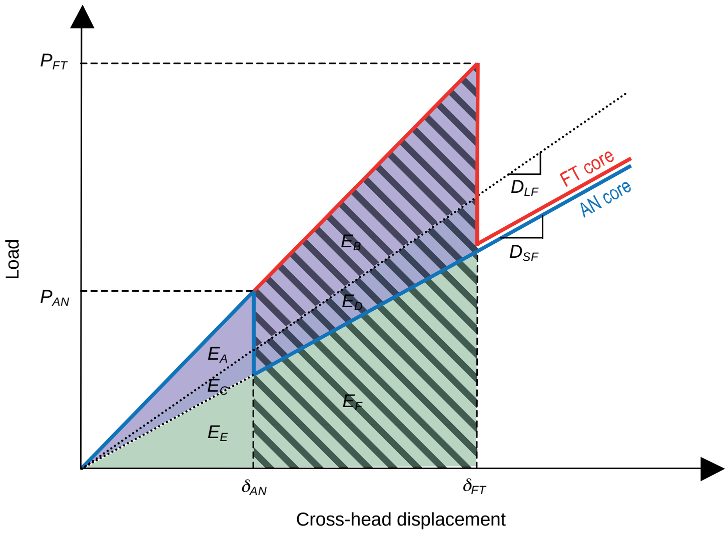

Figure. 4. Schematic load vs. cross-head displacement.

The interpretation of figure 4 is as follows:

P_{AN}	= Load at first fracture in annealed core
δ_{AN}	= Cross-head displacement at first fracture in annealed core
P_{FT}	= Load at first fracture in fully toughened core
δ_{FT}	= Cross-head displacement at first fracture in annealed core
D_{SF}	= Stiffness of unit with core fractured in small fragments
D_{LF}	= Stiffness of unit with core fractured in large fragments
E_A	= Strain energy released on first fracture of annealed core
$E_C + E_D$	= Energy released during subsequent core fragmentation after first fracture
$E_A + E_B + E_C + E_D$	= Strain energy released upon fracture of fully toughened core
$E_B + E_D$	= Strain energy due to fully toughened stress profile
E_E , E_F	= Strain energy stored in unit after core fractures (predominantly in unfractured faces)

This empirical approach could be used for predicting the state of the laminated units for a given load or for determining the amount of kinetic energy that the laminated units can safely absorb.

Conclusion

The laminated hybrid-glass units described in this paper achieved significant levels of post-fracture strength and stiffness. In some of the units, the post-fracture load bearing capacity exceeded the load at first fracture. As expected, the largest relative post-fracture capacity was observed in the units with annealed glass cores and the largest post-fracture stiffness was observed in the units with SGP interlayer. The SGP laminated units with either heat strengthened or fully toughened cores are the best candidates for practical applications. The post-fracture stiffness was largely unaffected by the type of glass used in the core and the fragment length tended to converge to between 6mm and 12mm irrespective of the glass type. The empirical energy-based interpretation of the mechanical response provides a useful means of estimating the energy stored in units in the unfractured and fractured states.

The stiffness of the laminated units after first fracture suggests that the post-fracture response of these units this may be predicted by analytically. Such a solution would have to account for the influence of fragment size on the post-fracture stiffness that was observed in these tests. This is the subject of on-going work.

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