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On the blast resistance of laminated glass

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ABSTRACT

Blast resistant glazing systems typically use laminated glass to reduce the risk of flying glass debris in the event of an explosion. Laminated glass has one or more bonded polymer interlayers to retain glass fragments upon fracture. With good design, the flexibility of the interlayer and the adhesion between layers enable laminated glass to continue to resist blast after the glass layers fracture. This gives protection from significantly higher blast loads when compared to a monolithic pane. Full-scale open-air blast tests were performed on laminated glass containing a polyvinyl butyral (PVB) interlayer. Test windows of size 1.5 m × 1.2 m were secured to robust frames using structural silicone sealant. Blast loads were produced using charge masses of 15 kg and 30 kg (TNT equivalent) at distances of 10–16 m. Deflection and shape measurements of deforming laminated glass were obtained using high-speed digital image correlation. Measurements of loading at the joint, between the laminated glass and the frame, were obtained using strain gauges. The main failure mechanisms observed were the cohesive failure of the bonded silicone joint and delamination between the glass and interlayer at the pane edge. A new finite element model of laminated glass is developed and calibrated using laboratory based tests. Predictions from this model are compared against the experimental results.

1. Introduction

Annealed float glass is often used in windows but is a brittle material that offers little resistance to the blast waves produced by explosions. When it fails it breaks into very sharp fragments that can travel at high velocity. Historically, the majority of injuries from bomb blasts have been from flying glass fragments Smith (2001). Laminated glass has been found to be effective at mitigating these risks and is now often used to protect building occupants by retaining glass fragments on a polyvinyl butyral (PVB) interlayer upon fracture (Fig. 1). Significant resistance to blast loading is seen in laminated glass even after the glass layers have fractured. It is important to understand the conditions for and types of failure mechanism in laminated glass in order to optimise the design of facade structures.

Whilst there are some analytical and finite-element (FE) based approaches to predicting the response of laminated glass to blast loading, there is little experimental data available for validation of these models. Furthermore current FE models deal only with the uncracked phase of the laminated glass response. This phase only makes up a small portion of the total resistance offered to a blast wave. There is a therefore a need to develop models that predict the laminated glass response after the glass fractures. This paper aims to address these gaps by describing experimental results from four well instrumented full-scale open-air blast tests on lamented glass. The paper also details a FE based approach to modelling the post-fracture laminated glass response and compares it with the experimental data acquired.

2. Background

The behaviour of uncracked laminated glass has been studied by several researchers including Norville et al. (1998), Behr et al. (1993), Hooper (1973). The flexural stiffness of laminated glass is dependent on the fraction of horizontal shear force transferred between the glass layers by the PVB interlayer. At one extreme the PVB transfers no horizontal shear stress and its only function is to maintain the separation distance between the glass layers. In this case, each glass layer bends independently and the total laminate flexural stiffness is the sum of the flexural stiffness of the individual glass layers. At the other extreme, significant flexural stresses exist within the interlayer in addition to the transfer of all the horizontal shear stress between the glass layers. The limiting case occurs when the stress distribution varies linearly through the thickness and would only be obtained when the elastic modulus of the PVB interlayer equals that of the glass layers.

The analysis by Norville et al. (1998) showed that for most laminates the PVB interlayer only needs to transfer a fraction of horizontal shear stress between the glass layers to give a section modulus

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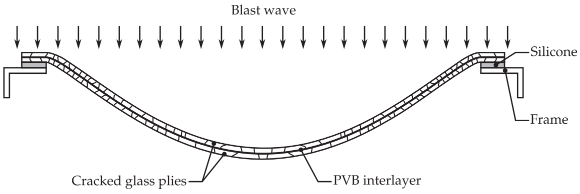

Fig. 1. Example of postcrack deformation in laminated glass due to blast loading.

exceeding that of the equivalent monolithic pane. The equivalent monolithic pane was defined as a monolithic pane of the same thickness as the total thickness of the glass layers in a laminate. For example, a 6 mm monolithic pane would be equivalent to a 7.52 mm laminated pane consisting of two 3 mm glass layers and 1.52 mm PVB interlayer. Since PVB is a viscoelastic material, the amount of horizontal shear stress transferred between the glass layers is dependent on the rate of applied loading and temperature. It was found that under short duration loads that laminated glass has a higher section modulus than the equivalent monolithic pane. The increase in section modulus also reduces the peak tensile stress on the outer surface of the glass layers for a given load and accounts for an apparent increase in fracture strength for a given load when compared to an equivalent monolithic pane.

Bennison et al. (1999) and van Duser et al. (1999) used a Generalized Maxwell Series model to account for the time dependent modulus of PVB interlayers. Terms in the Maxwell model were determined experimentally using dynamic mechanical analysis. The time dependent PVB material model was used in finite element models of a plate subjected to uniform pressure loading and biaxial flexure. It was found that for most laminates the peak tensile stress on the outer surface of the glass layers was lower than that for an equivalent monolithic pane. The advantage of this approach is that the PVB shear modulus is calculated during the analysis and therefore accounts for time dependent effects. Variation in shear modulus at different temperatures was also taken into account by using the Williams–Landel–Ferry (WLF) equation (Williams et al., 1955) to shift the time dependent shear modulus curve to a different temperature.

The strength of annealed glass has a wide statistical variation. Test data gathered in the development of the glazing standard prEN 13474-3 (CEN/TC129, 2008) includes tensile strength results from over 700 annealed glass samples from different manufacturers using the ring-on-ring test method. As expected, a wide variation in breaking strength was found, from 30 MPa to 120 MPa at a loading rate of 2 MPa/s. The data can be characterised statistically using a Weibull distribution. For normal design purposes a breaking strength of 45 MPa is given based on 95% of samples not failing below this stress. Cormie et al. (2009) extrapolated this strength data to the higher strain rates experienced in blast loading using a relationship proposed by Charles (1958) and arrived at a dynamic breaking strength for annealed glass in the region of 80 MPa.

The mechanical behaviour of laminated glass after cracking has been investigated by Muralidhar et al. (2000). In this study, laminated glass with an aligned crack in each glass layer was subjected to constant rate tensile loading (a displacement rate of 1 mm/s was used). Under these conditions, PVB delaminates from the glass at the crack edge and deforms to bridge the crack. It was found that under constantly increasing displacement, the tensile force rises to a steady state value. They also used different hyperelastic material models to calculate the fracture energy associated with the delamination process. However, no viscous energy dissipation was accounted for in the analysis. The calculated fracture energy values include this dissipation energy and therefore overestimate the actual energy involved in the fracture process. The loading rates investigated were also too slow relative to those experienced during blast loading.

Static loading of fractured laminated glass plates was studied theoretically and experimentally by Seshadri et al. (2002). Plates constructed from a single glass and a single PVB layer were loaded centrally by a spherical steel surface at a constant rate of displacement. The glass layer was indented before loading to create a known flaw and a simple regular fracture pattern. Post breakage behaviour of the laminate was modelled using the work on PVB delamination described previously. Good agreement between experimental results and predictions was found. However, only a single glass layer was studied so the restraining effects of a second glass layer were not taken into account. Their approach is also difficult to apply to practical situations where there may be many thousands of cracks and where the crack pattern is not known in advance.

2.1. Glazing materials for blast protection

For increased protection from blast, modern glazing systems use laminated glass bonded to robust framing with structural silicone adhesives. Laminated glass consists of one or more polymer layers sandwiched between layers of glass. Polyvinyl butyral (PVB) is the most common interlayer and is bonded between the glass layers by the application of pressure and heat. It is commercially manufactured in sheets 0.38 mm thick for the architectural glazing market. More than one PVB sheet can be used in an interlayer, increasing the overall interlayer thickness in multiples of 0.38. Current recommendations for blast resistance advise a minimum interlayer thickness of 1.52 mm (Home Office Scientific Development Branch, 2008). Annealed float glass is the most common material used for the glass layers due its low cost. However, tempered glass can also be used where increased initial strength is required, although slight undulations from the tempering process can make laminating difficult. For situations where impact and ballistic strength is a consideration, additional layers of polycarbonate are used in the laminate.

Under blast loading a laminated glass pane initially deflects in a manner similar to a monolithic pane, that is as an elastic plate. This is termed the precrack phase of the laminated glass response. Fracture of the glass layers again occurs when the tensile stress at a flaw anywhere on the glass surface is high enough to cause crack propagation. After the glass layers fracture, the laminate is said to be in the postcrack phase of the response. In this phase the glass fragments are held bonded to the PVB interlayer, giving continued resistance to the blast wave. The cracked laminate behaves similarly to a membrane and is able to undergo large deflections without further damage (Fig. 1). Failure of the laminate occurs by PVB tearing and the conditions for this are not well understood. To be effective the laminated glass needs to be strongly fixed to a supporting structure. If the joint or framing structure is not strong enough, the pane could detach and enter a building at high velocity, injuring occupants.

Structural silicone sealant is commonly used to bond the laminate to a framing structure. In commercial buildings the framing is often constructed from extruded aluminium alloy sections. The laminate is restrained at two or four edges of the pane with a silicone bonded joint on one or both faces of the laminate. Securing all four edges on both sides is the recommended practice for blast resistance. However, single-sided joints are increasingly preferred by architects for aesthetic reasons. Minimum joint dimensions are calculated with reference to the dead-weight of the pane, the wind loading and thermal expansion. Current recommendations for blast resistance advise a double-sided silicone joint of at least 35 mm in depth (Home Office Scientific Development Branch, 2008). Other methods of restraining laminated glass exist such as rubber gaskets, glazing tape and mechanical point fixings. These systems are generally considered to give inferior blast protection to silicone bonded edges.