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Influence of interlayer properties on the blast performance of laminated glass panels

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HIGHLIGHTS

- Blast response of laminated glass (LG) has been numerically investigated.
- Influence of interlayer thickness and Young's modulus (E) were studied.
- Constant adhesion between glass and interlayer was maintained.
- Design target should be critical interlayer thickness or Young's Modulus (E).
- The safer failure mode enhances energy absorption and reduces support reaction.

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ABSTRACT

This paper investigates the influence of interlayer properties on the blast performance of laminated glass (LG) panels. A parametric study is carried out by varying the thickness and Young's modulus (E) of the interlayer under two different blast loads. Results indicate the existence of a critical interlayer thickness (or E) that causes the onset of interlayer failure. This should be achieved in the design to enhance energy absorption, reduce support reactions and initiate a safer failure mode. Present findings provide information to achieve such design targets and enable safe and efficient performance of LGs under credible blast loads.

1. Introduction

Glazed facades with monolithic annealed glass are often used in buildings for visual exposure, aesthetics, opacity and environmental compatibility. These glazed facades could be 4–10 m height at the lower levels of the buildings which will have the most detrimental effects form explosions occurring at the ground level. It is evident from previous terrorist attacks that more than 80–90% of the blast related injuries occurred directly and indirectly from window glass failure [1]. Blast related injuries caused by glass breakage include ear drum damage, lung collapse and penetration or laceration type injuries. On the other hand, if building facades disintegrate, direct blast pressure entering the building can cause injuries to occupants and even structural collapse. Fig. 1(a and b) illustrate the internal damage to buildings based on the façade performance [2]. Fig. 1(a) shows complete and catastrophic internal devastation to the interior of a building which did not have any measures for blast mitigation. However, according to Fig. 1(b) the interior of the building is completely protected from the blast pressure by using blast resistant glazing fabricated with laminated glass (LG) panels. It is therefore evident that building facades fabricated with LG provide significant blast resistance compared to monolithic annealed glass used in most buildings. The design of building facades for a credible blast event using a safety glass such as LG, will minimise if not eliminate the hazard from the effects of uncontrolled explosions.

LG consists of two or more glass plies permanently bonded with one or more polymer interlayers. Annealed and heat strengthened glass types are usually used in LG, instead of tempered glass, as they break into larger fragments which adhere well to the interlayer. Different interlayer materials such as polyvinyl butyral (PVB), ethylene vinyl acetate (EVA), ionoplasts and thermoplastic polyurethanes (TPU) are used in practice [3,4]. However, PVB is

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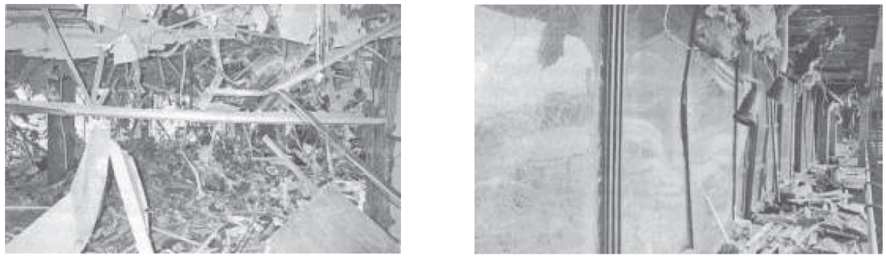

(a) Catastrophic devastation without having any measures for blast mitigation

(b) Complete protection from blast pressures by using LG

Fig. 1. Internal damage to buildings based on the facade performance [2].

the most common interlayer material, which is mostly used in blast resistant glazing [5]. LG panels are fixed to the window frames using structural sealant joints where silicone sealants are mostly used in blast resistant glazing. LG has two major advantages over monolithic annealed glass used in most buildings. When LG fractures, glass fragments adhere to the interlayer avoiding free flying shards which have been the major cause of injuries with monolithic annealed glass. Furthermore, LG has higher load carrying capacity than monolithic annealed glass due to its post-crack behaviour. After glass cracks, the interlayer deforms by absorbing blast energy where the post-crack load carrying capacity of LG is considerably higher than that at the pre-crack phase.

The post-crack behaviour of a LG is considerably influenced by the interlayer properties [6]. This has been shown in a previous paper [7], where the interlayer properties had a significant influence on the blast response of a LG panel under a stronger blast load. LG should be designed for a credible blast load, where the failure is initiated by tearing of the interlayer rather than any failure at the supports. The interlayer properties should therefore be analysed carefully, when designing LG under blast loads. The design standard ASTM F 2248-09 [8] incorporates the charts given in the ASTM E 1300-09a [9] to determine the required glass pane thickness for designing LG under blast loads. However, the charts available in ASTM E 1300-09a [9] were developed only for LG panels having PVB as the interlayer material, without accounting for the thickness of the interlayer. This standard therefore does not account for the effects due to the variations of the thickness of the interlayer and also the effects of different interlayer materials with varied material properties on the blast response of LG panels. According to the UFC 4-010-01 [10], LG used in blast resistant glazing should have an interlayer with at least 0.76 mm thickness. Overall, it is evident that the current design standards provide limited information on the effects of geometric and material properties of the interlayer on the blast performance of LG panels [11].

This paper presents a comprehensive numerical procedure to study the blast response of LG panels using the LS-DYNA explicit finite element (FE) code. A parametric study has been carried out with the developed FE models by varying the thickness and Young's modulus (E) of the interlayer to investigate their influence on the blast performance of the LG panel. Results from this study show that both the thickness and Young's modulus of the interlayer should be carefully treated, as they have a noticeable influence on the energy absorption, support reactions and failure behaviour of a LG panel. This paper provides useful design information to determine the interlayer thickness or to select a proper interlayer material for a credible blast load. The critical interlayer thickness (or E) which causes the onset of interlayer failure should be achieved in the design as it enhances the energy absorption and reduces support reactions while initiating the safer failure mode. The interlayer thickness should not be increased unnecessarily as it will increase the total thickness of the LG panel and hence the size of the framing members. This paper will therefore enhance the capabilities of engineers towards the efficient and economical design of LG for a credible blast load.

2. Background

The most challenging part of designing blast resistant structures is to estimate the credible blast load, as the type, magnitude and location of the explosions caused by terrorist attacks will be unknown. It is important to use a realistic or a credible blast load in the design, where the blast resistant design is achievable. This section provides the background information on the blast phenomenon and the post-crack behaviour of LG as explained below.

2.1. Blast phenomenon

A blast or an explosion is a sudden release and transformation of potential energy into kinetic energy with the production of gas under high pressure and temperature. This potential energy can be mechanical, chemical, electrical or nuclear based on the origin of the explosive device. The high pressure gas generated from the explosion travels at a high velocity away from the explosion source by creating shock waves [12]. Initially, the pressure of the shock front increases to a maximum value and then it decays when the shock wave expands away from the explosion source. After a short time, pressure behind the shock front drops below the ambient pressure by creating a partial vacuum. It creates high suction winds capable of carrying debris for long distances away from the explosion source.

Blast overpressure variation with time at a point away from the explosive source is illustrated in Fig. 2 [13]. Initially, the blast over-

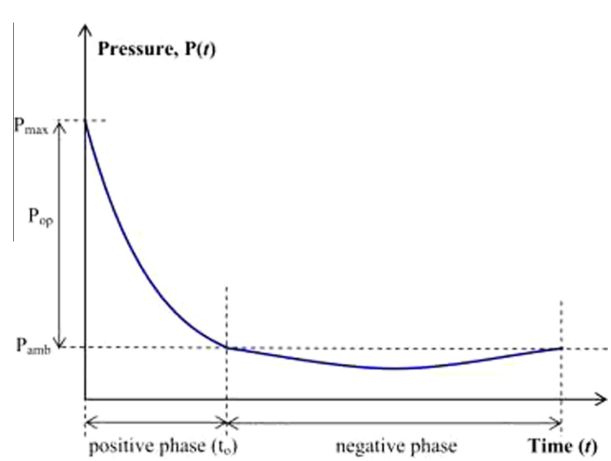

Fig. 2. Blast overpressure variation with time for a typical blast load [13].