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Dynamic response of a novel laminated glass panel using a transparent glass fiber-reinforced composite interlayer under blast loading

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ABSTRACT

The novel laminated glass-composite panel consists of a transparent glass fiber-reinforced polymer composite interlayer bonded to glass sheets. A numerical model has been developed to simulate the dynamic response of the laminated glass-composite panel under blast loading. The simulated dynamic response, in terms of the midpoint deflection, correlates well with the experiments conducted in a blast load simulator. Stress analysis of the laminated glass shows that it can survive under both medium intensity (peak pressure ≈ 4 psi) and high intensity (peak pressure ≈ 10 psi or higher) blast.

1. Introduction

Terrorist bomb attacks and threats are on the rise all over the world [1–3]. One of the significant effects of a blast is to damage glass-based windows in nearby buildings. The sharp glass fragments produced from the damaged windows can lead to large casualties [4]. And blast pressure entering the buildings through the damaged windows can cause additional injuries to the occupants [5,6]. Hence, the need for mitigating the hazards caused by windows failure is urgent [7–10]. One way to mitigate the damage is to use laminated glass, which is conventionally made of one polyvinyl butyral (PVB) interlayer sandwiched between two glass sheets [5,11–13], for windows. Several experimental and analytical investigations have been carried out on studying the response of the laminated glass with PVB interlayer under blast loading. Zhang et al. [10] reported that PVB interlayer thickness can affect impact-resistant performance of laminated glass window under impact loading. Increasing interlayer thickness can be effective in decreasing the laminated glass penetration vulnerability. Hidallana-Gamage et al. [14] found that the interlayer of laminated glass has a major impact on the blast response of the laminated glass under severe blast loads. Wei and Dharani [11] studied the behavior of laminated glass panels under simulated blast loading. They found that bending stress mainly controls the response of a laminated plate under blast loading and square panel is less blast resistant than a rectangular panel. Duser et al. [15] analyzed the dynamic response of rectangular laminated glass panels under uniform lateral pressure. Their analysis results showed that the loaded laminated glass panels responded in a complex manner due to the large mismatch in stiffness of the two materials (glass/PVB). Hooper et al. [16] studied the failure of laminated glasses under blast loading. Results showed that the deflection profile of a laminated glass during a blast test could differ significantly from its static deflection profile.

Although laminated glass with PVB interlayer is widely used in the world [11,15–19], it still has some disadvantages, such as large thickness requirement for blast resistance, which increases the production cost and installation cost. The thickness and weight can be potentially reduced by replacing the PVB interlayer with a glass fiber-reinforced polymer composite interlayer, because glass fiber-reinforced polymer composites have high strength to weight ratio [20–22].

In this paper, a novel laminated glass using a transparent glass fiber-reinforced composite interlayer has been successfully fabricated [23]. The transparency of the composite interlayer was achieved by chemically matching the refractive index of the polyester matrix to that of glass fibers. The optical property of the novel laminated glass was investigated using an ultraviolet-visible (UV-VIS) spectrometer. The mechanical properties of the composite interlayer were studied using an Instron universal testing machine. Field blast testing of the laminated glass was done at the Engineering Research and Development Center (ERDC, US Army Corps of Engineers Lab, Vicksburg, Mississippi) using a Blast Load Simulator (BLS). Real time

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loading pressure and midpoint deflection of the laminated glass were recorded. A numerical model is proposed to characterize the dynamic response of the fabricated laminated glass under blast loading. The validity of the proposed numerical model has been proven by experimental results. Laminated glass's failure analysis is also performed in this study using the stress analysis approach.

2. Experimental methods

2.1. Transparent glass fiber-reinforced composite interlayer fabrication

Polyester resin (Ashland Chemicals Co., USA) was mixed with 1.2% by weight of methyl ethyl ketone peroxide (MEKP, Sigma-Aldrich Co., USA), an initiator; 4% by weight of divinyl benzene (DV, Sigma-Aldrich Co., USA), a crosslinker; and 0.03% by weight of cobalt (II) 2-ethylhexanoate (CE, Sigma-Aldrich Co., USA), an accelerator. By using this formulation, the refractive index of the polyester matrix was chemically modified more closely to that of glass fibers. All the above mentioned components were thoroughly mixed for 3-4 min by hand in a plastic bucket. The mixture was set in a vacuum degassing chamber so as to allow air bubbles inside it to escape by creating vacuum inside the chamber. After degassing, a small amount of the mixture was first poured into a 3.2 mm deep mold so as to wet the base surface of the mold which was made by placing aluminum frames on top of a polyvinyl chloride (PVC) plate with Mylar sheet (Fig. 1). Then a layer of glass fiber cloth (Aerospace Composite Products Co., USA) was placed in the mold and some more mixture was poured on top of the cloth. This procedure was repeated 4 times, producing a composite of 3.2 mm thick with 5 layers of glass fiber cloth. Finally, another PVC plate with Mylar sheet was laid on top of the frame, the top and bottom plates were clamped with C-clamps. The clamped plates were erected sideways to let entrapped air escape from the mold. The setup was left at room temperature (~ 20 °C) for two days to ensure the complete curing of the composite.

2.2. Laminated glass panel fabrication

The novel laminated glass panel was fabricated by sandwiching the glass fiber-reinforced composite interlayer between two glass sheets (each of 3.2 mm or 0.125 in thick). The composite interlayer and glass sheets were bonded using a two part polyurethane resin (SP&S Co., USA). The procedure for fabricating a laminated glass is as follows: firstly, a tempered glass sheet was placed on a table and a very thin layer of polyurethane resin was uniformly spread on the glass sheet. Secondly, the composite interlayer was placed on top of the glass sheet. Pressure was applied to spread the resin and remove any entrapped air bubbles. Finally, a very thin layer of polyurethane resin was uniformly spread on the composite interlayer and the second glass sheet was placed on top of the composite interlayer. The setup was left at room temperature for at least two days to ensure complete curing of the polyurethane adhesive. This process produced a laminated panel of nominal thickness of about 10 mm or 0.375 in.

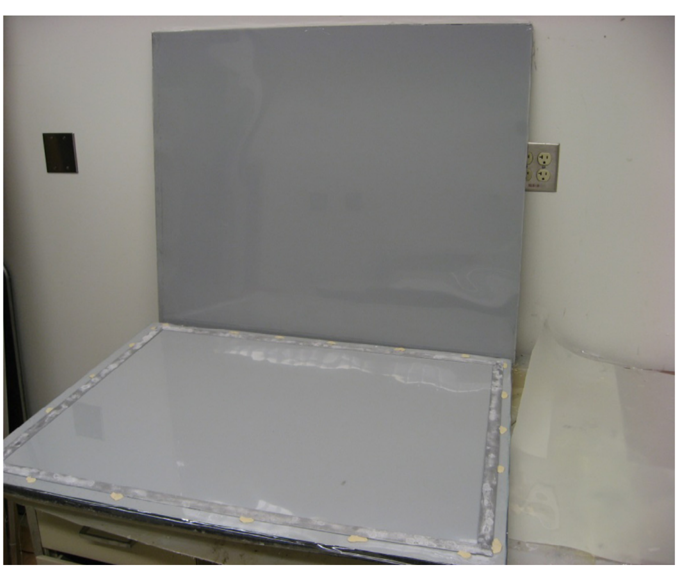

Fig. 1. Mold for fabricating glass fiber-reinforced composite interlayer.

2.3. Composite interlayer's mechanical properties testing

Since the interlayer is of a new transparent glass fiber reinforced polymer composite, its mechanical properties were determined and used in modeling the mechanical response of the panel to blast loading.

2.3.1. Young's modulus and Poisson's ratio

Strips of 250 mm long and 25 mm wide were cut from the fabricated composite sheets. The strips were machined to ensure that they were straight and had smooth edges. Tensile tests were performed at room temperature by using a servo-hydraulic Instron 8800 universal testing machine with a fast track digital controller and a 10 kN load cell, at a crosshead speed of 2mm/min. For the measurement of strains, strain gages (Vishary Precision Inc., USA) were attached on the specimens in both longitudinal and lateral directions. During the test, loads and strains were recorded by computer. These data were used to find Young's modulus (E) and Poisson's ratio (ν_{12}) of the composite based on ASTM standard D3039 [24].

2.3.2. Shear modulus

Strips of 250 mm long and 25 mm wide ±45° were cut from the fabricated composite sheets. Strain gages were also attached on the specimens in both longitudinal and lateral directions. The ±45° specimens were loaded in tension while recording load and strain data. These data were used to calculate shear modulus of the composite based on ASTM standard D3518 [25].

2.4. Optical property testing

The light transmittance of the fabricated laminated glass in the thickness direction was measured over a wavelength range of 190 to 900 nm by using a UV-VIS (ultraviolet-visible) spectrometer (UV 240PC, Shimadzu Co., Japan). The resolution of the equipment is 1 nm within the measured wavelength range. All the measurements were done at room temperature (~ 20°C).

2.5. Blast resistance testing

A blast is a sudden release of stored energy. When a blast happens, rapid expansion of energy resulting from the blast gives rise to a wave of compressed air which is called shock front. The shock front travels radially in air in all directions. As the shock front moves, the shock front releases energy to surrounding air and the overpressure of the shock front decreases. When the pressure of the shock front drops below the atmospheric pressure, surrounding air gives energy to the shock front and the pressure of the shock front finally returns to the atmospheric pressure [26]. The whole process is shown schematically in Fig. 2 [11].

The pressure–time curve shown in Fig. 2 can be described using the following equation [27]