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 it can survive under both medium intensity (peak pressure ≈ 4 psi) and high intensity (peak pressure ≈ 10 psi or higher) blast.

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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 of 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 the interlayer of laminated glass has a major impact on the blast response of the laminated glass under severe blast loads. Wei et al. [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 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.

Figure 1 Mold for fabricating glass fiber-reinforced composite interlayer

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.

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

250 mm long and 25 mm wide strips 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

250 mm long and 25 mm wide $\pm 45^\circ$ strips were cut from the fabricated composite sheets. Strain gages were also attached on the specimens in both longitudinal and lateral directions. The $\pm 45^\circ$ 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 the 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].

Figure 2 Shock front expansion process

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

$$P(t) = P_o \left(1 - t/t_p\right) e^{-\alpha t/t_p} \quad (1)$$

where $P(t)$ is the blast pressure at time t , P_o is the peak pressure, α is a constant and t_p is the positive pressure duration time. According to references [27, 28], the key parameters of a blast are: peak pressure P_o , constant α and positive pressure duration time t_p .

Field blast loading experiments were done at the Engineering Research and Development Center (ERDC, US Army Corps of Engineers Lab, Vicksburg, Mississippi) using a Blast Load Simulator (BLS). The installation of the laminated glass inside the BLS is shown in Fig. 3. The

thickness of the laminated glass was around 9.5 mm (a 1/8 inch (3.2 mm) thick transparent composite interlayer laminated to two 1/8 inch (3.2 mm) thick tempered glass sheets). The length and width of the laminated glass were 0.89 m and 0.59 m, respectively. Sample gages were attached to the laminated glass to record the pressure loading history and the midpoint deflection history during the blast.

Figure 3 Laminated glass installation inside the BLS

3 Experimental results

3.1 Mechanical properties of the composite interlayer

All quasi-static mechanical properties of the composite interlayer are listed in Table 1. From Table 1, it can be seen that Young's modulus of the composite interlayer is 7.67 GPa which is much higher than that of the neat polyester (~ 3 GPa) [29]. Poisson's ratio and shear modulus of the composite are 0.33 and 2.14 GPa, respectively.

Table 1 Quasi-static mechanical properties of the glass fiber-reinforced composite

	Young's modulus (E , GPa)	Poisson's ratio (ν_{12})	Shear modulus (τ , GPa)
Fiber-reinforced composite	7.67	0.33	2.14

3.2 Optical property of the novel laminated glass

Fig. 4 shows the light transmittance of the fabricated laminated glass over a wavelength range of 190-900 nm. The light transmittance of the laminated glass is above 60% over a wavelength range of 482 to 900 nm. The highest transmittance is 84.4% when the wavelength is 577 nm. This result means the laminated glass has good transparency in the visible light range. Similar results have been reported by Olsen et al. [30] and Iba et al. [31].

Appearance of distant objects through the laminated glass is shown in Fig. 5. Through the laminated glass, the outside view can be clearly observed, which shows the fabricated laminated glass has good transparency though there is a slight haziness. This result coincides with the light transmittance spectra analysis result shown above.

Figure 4 Light transmittance spectrum of the novel laminated glass

Figure 5 Appearance of the new laminated glass panel

3.3 Blast resistance testing results

Both medium and high intensity blast loading tests were done at ERDC. The pressure-time curve of the medium intensity blast test conducted in a blast load simulator is shown in Fig. 6. The key parameters of the blast are obtained by curve fitting the initial pressure phase using equation (1). The result of fitting is: peak overpressure $P_o=5.14$ psi (35.4 kPa), constant $\alpha=0.1011$, and positive pressure duration time $t_p=11.3$ ms.

Figure 6 Pressure-time curve of the medium intensity blast

Fig. 7 shows the midpoint deflection of the laminated glass under the medium intensity blast shown in Fig. 6. It can be seen that the maximum deflection is about 0.415 inch (10.5 mm) and appears in the first deflection peak region.

Figure 7 Midpoint deflection of the laminated glass under the medium intensity blast

The pressure-time curve of the high intensity blast is shown in Fig. 8. The key parameters of the blast are: peak overpressure $P_o=13.22$ psi (91.1 kPa), constant $\alpha=0.2744$, positive pressure duration time $t_p=15.4$ ms.

Figure 8 Pressure-time curve of the high intensity blast

Fig. 9 shows the midpoint deflection of the laminated glass under the high intensity blast shown in Fig. 8. The maximum deflection is around 0.99 inch (25.1 mm) and also appears in the first deflection peak region.

Figure 9 Midpoint deflection of the laminated glass under the high intensity blast

Field experiments are important for understanding the dynamic response of the laminated glass under blast loading. Besides field testing, model-based analysis can also be used to study the dynamic response of the laminated glass under blast loading. In this study, a numerical model is proposed to characterize the dynamic response of the fabricated laminated glass under blast loading.

4 Numerical modeling of the dynamic response of the fabricated laminated glass panel under blast loading

The methodology used to solve for the deflections and stresses is shown in the flow chart in Fig. 10.

Figure 10 Flow chart for getting deflections and stresses of the laminated glass under blast loading

The detailed derivations are listed below.

According to Hamilton's principle [32]

$$\int_{t_1}^{t_2} (\delta T - \delta \Pi + \delta W) dt = 0 \quad (2)$$

where T is the kinetic energy of the laminated glass, Π is the strain energy of the laminated glass and W is the work done by external load(s).

For the laminated glass, kinetic energy T can be calculated using the following equation [33]

$$T = \frac{1}{2} M \int_0^a \int_0^b \left(\frac{\partial w}{\partial t} \right)^2 dx dy \quad (3)$$

260

261 where M is the unit area mass of the laminated glass and is equal to $\rho_o h_o + \rho_c h_c + \rho_i h_i$, and ρ_o ,
 262 ρ_c and ρ_i are the density of the outer glass sheet, the composite interlayer and the inner glass
 263 sheet, respectively. $\rho_o = \rho_i = 2600 \text{ kg/m}^3$ and $\rho_c = 1200 \text{ kg/m}^3$. h_o , h_c , and h_i are the thickness of
 264 the outer glass sheet, the composite interlayer and the inner glass sheet, respectively. In this
 265 study, $h_o = h_c = h_i = 3.2 \text{ mm}$, w is the transverse (thickness direction) deflection of the laminated
 266 glass.

267 Strain energy Π can be calculated using the following equation [33]

268

$$\Pi = \frac{1}{2} \iiint_V (\sigma_x \epsilon_x + \sigma_y \epsilon_y + \tau_{xy} \gamma_{xy}) dx dy dz \quad (4)$$

270

271 According to the classical plate theory [34], the strain components in the x-y plane (Fig. 11)
 272 can be expressed by the transverse deflection, w , as

273

$$\epsilon_x = -z \frac{\partial^2 w}{\partial x^2}, \quad \epsilon_y = -z \frac{\partial^2 w}{\partial y^2}, \quad \gamma_{xy} = -2z \frac{\partial^2 w}{\partial x \partial y} \quad (5)$$

274

Figure 11 Schematic diagram of the laminated glass

For the orthotropic composite interlayer, $\sigma_x = \frac{E_c}{1-\nu_c^2} \epsilon_x + \frac{\nu_c E_c}{1-\nu_c^2} \epsilon_y$, $\sigma_y = \frac{\nu_c E_c}{1-\nu_c^2} \epsilon_x + \frac{E_c}{1-\nu_c^2} \epsilon_y$

and $\tau_{xy} = G_c \gamma_{xy}$, where E_c , G_c and ν_c are Young's modulus, shear modulus and Poisson's ratio of the composite interlayer, respectively. It should be noted that the mechanical properties of the glass fiber-reinforced composite, such as Young's modulus and shear modulus, are influenced by strain rate [35]. However, in this analysis, since strain rate was not measured in field testing, the strain rate effect is not considered. So E_c , G_c and ν_c values used here are the values obtained from previous quasi-static mechanical tests (Table 1). Substituting σ_x , σ_y and τ_{xy} expressions into equation (4), the strain energy of the composite interlayer is

$$\Pi_{comp} = \frac{1}{2} \iiint_V \left(\frac{E_c \epsilon_x \epsilon_x}{1-\nu_c^2} + \frac{\nu_c E_c \epsilon_y \epsilon_x}{1-\nu_c^2} + \frac{\nu_c E_c \epsilon_x \epsilon_y}{1-\nu_c^2} + \frac{E_c \epsilon_y \epsilon_y}{1-\nu_c^2} + G_c \gamma_{xy} \gamma_{xy} \right) dx dy dz \quad (6)$$

Integrating equation (6) through the transverse direction (thickness direction, z direction) results in

$$\Pi_{comp} = \frac{1}{2} \int_0^a \int_0^b \left[\frac{E_c h_c^3}{12(1-\nu_c^2)} \left(\frac{\partial^2 w}{\partial x^2} \right)^2 + \frac{E_c h_c^3}{12(1-\nu_c^2)} \left(\frac{\partial^2 w}{\partial y^2} \right)^2 + \frac{2\nu_c E_c h_c^3}{12(1-\nu_c^2)} \left(\frac{\partial^2 w}{\partial x^2} \right) \left(\frac{\partial^2 w}{\partial y^2} \right) + \frac{4G_c h_c^3}{12} \left(\frac{\partial^2 w}{\partial x \partial y} \right)^2 \right] dx dy \quad (7)$$

where a is the length of the laminated glass, b is width of the laminated glass. In this study, $a = 0.89$ m and $b = 0.59$ m.

Similarly, the strain energy of the outer and inner glass sheets is

$$\Pi_{glass} = \frac{1}{2} \left\{ \frac{2E_g}{3(1-\nu_g^2)} \left[h_g^3 + \frac{3h_c^2 h_g}{4} + \frac{3h_g^2 h_c}{2} \right] + \int_0^a \int_0^b \left[\left(\frac{\partial^2 w}{\partial x^2} \right)^2 + \left(\frac{\partial^2 w}{\partial y^2} \right)^2 + 2\nu_g \frac{\partial^2 w}{\partial x^2} \frac{\partial^2 w}{\partial y^2} + 2(1-\nu_g) \left(\frac{\partial^2 w}{\partial x \partial y} \right)^2 \right] dx dy \right\} \quad (8)$$

where h_g is the thickness of one glass sheet (inner or outer layer glass sheet), E_g is Young's modulus of glass, ν_g is Poisson's ratio of glass, In this study, tempered glass is used, for which $E_g = 68$ GPa, $\nu_g = 0.2$. Summing the strain energy of the composite interlayer and glass sheets, the total strain energy of the laminated glass is

$$\Pi = \frac{1}{2} \int_0^a \int_0^b \left[A(w_{xx})^2 + A(w_{yy})^2 + Bw_{xx}w_{yy} + C(w_{xy})^2 \right] dx dy \quad (9)$$

$$A = \frac{2E_g}{3(1-\nu_g^2)} \left[h_g^3 + \frac{3h_c^2 h_g}{4} + \frac{3h_g^2 h_c}{2} \right] + \frac{E_c h_c^3}{12(1-\nu_c^2)}$$

$$B = 2\nu \left\{ \frac{2E_g}{3(1-\nu_g^2)} \left[h_g^3 + \frac{3h_c^2 h_g}{4} + \frac{3h_g^2 h_c}{2} \right] \right\} + \frac{2\nu_c E_c h_c^3}{12(1-\nu_c^2)}$$

$$C = 2(1-\nu) \left\{ \frac{2E_g}{3(1-\nu_g^2)} \left[h_g^3 + \frac{3h_c^2 h_g}{4} + \frac{3h_g^2 h_c}{2} \right] \right\} + \frac{4G_c h_c^3}{12}$$

309

310 where w_{kl} means a differentiation with respect to variable k and variable l .

311 For blast loading, the work done by external load is given by [33]

312

$$W = \int_0^a \int_0^b P(t) w dx dy \quad (10)$$

314

315 where $P(t)$ is the instantaneous blast pressure and can be described by equation (1).

316 Substituting T , Π , W into equation (2), it can be rewritten as

317

$$\int_0^{t_2} \int_0^a \int_0^b \left\{ -M\ddot{w}\delta w - \left(Aw_{xxxx} + Aw_{yyyy} + (B+C)w_{xxyy} \right) \delta w + P(t)\delta w \right\} dx dy dt = 0 \quad (11)$$

319

320 where $\ddot{w}$ means a differentiation with respect to time. From equation (11), the equation of

321 motion of the laminated glass is obtained as

322

$$M\ddot{w} + A(w_{xxxx} + w_{yyyy}) + (B + C)w_{xyy} = P(t) \quad (12)$$

324

325

326 The laminated glass in this study is considered as simply supported. So the boundary conditions
327 are

328

$$w = 0, \quad w_{xx} = 0, \quad \text{at } x = 0, a,$$

329

$$w = 0, \quad w_{yy} = 0, \quad \text{at } y = 0, b,$$

330

331 The initial condition is

332

$$w(x, y, 0) = 0, \quad \dot{w}(x, y, 0) = 0$$

334

335 In order to solve equation (12), an approximate function is chosen for w by considering the
336 simply supported boundary conditions [11, 33, 36, 37]

337

$$w(x, y, t) = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \psi \sin\left(\frac{m\pi x}{a}\right) \sin\left(\frac{n\pi y}{b}\right) \quad (13)$$

339

340 where ψ is a unknown time dependent function. Here, for calculation convenience, m and n are
341 both simplified to 1. Substituting equation (13) into equation (12) and applying Galerkin method,
342 the equation of motion of the laminated glass is changed to

$$\frac{\left(a \left(\frac{A\pi^6\psi}{4} - 4b^4 P_o (1-t/t_p) e^{-\alpha t/t_p} + \frac{M\pi^2\ddot{\psi}b^4}{4} \right) \right)}{\pi^2 b^3} + \frac{a^2 \left(\frac{B\pi^6\psi b^2}{4} + \frac{C\pi^6\psi b^2}{4} \right) + \frac{A\pi^6\psi b^4}{4}}{\pi^2 a^3 b^3} = 0 \quad (14)$$

Rearranging equation (14) and the following equation is obtained

$$\ddot{\psi} = \frac{4}{M\pi^2 b^4} \left(-\frac{A\pi^6\psi}{4} + 4b^4 P_o (1-t/t_p) e^{-\alpha t/t_p} - \frac{a^2 \left(\frac{B\pi^6\psi b^2}{4} + \frac{C\pi^6\psi b^2}{4} \right) + \frac{A\pi^6\psi b^4}{4}}{a^4} \right) \quad (15)$$

Equation (15) is a nonlinear ordinary differential equation and can be solved using Runge-Kutta method. After obtaining function ψ , the transverse deflection w can be calculated using equation (13).

5 Comparison between numerical and experimental results

Fig. 12 shows the predicted maximum deflection state of the laminated glass under the medium intensity blast loading. Fig. 13 shows the predicted maximum deflection state of the laminated glass under the high intensity blast loading. In Fig. 12 and 13, the laminated glass is simplified to a zero-thickness plate. From Fig. 12 and 13, it can be seen that the maximum deflection occurs at the midpoint. At the position close to the edge of the laminated glass, the deflection decreases. This prediction corresponds fairly well with the experimental results.

Figure 12 The maximum deflection state of the laminated glass under the medium intensity blast loading

Figure 13 The maximum deflection state of the laminated glass under the high intensity blast loading

From Fig. 7 and 9, it can be seen that the maximum deflection, which is an important criterion for evaluating the blast resistance of the fabricated laminated glass, occurs in the first deflection peak region. Therefore, the knowledge of the deflection history in the first peak region is important and is simulated by the developed numerical model. Fig. 14 shows the predicted midpoint deflection history in the first deflection peak region. The predicted maximum deflection is 0.42 inch (10.6 mm) and the predicted positive deflection duration time is 7.8 ms. The experimentally measured midpoint deflection history (the circled region in Fig. 7) is also plotted in Fig. 14. The experimentally measured maximum deflection value is 0.415 inch (10.5 mm) and the measured duration time is 8.3 ms. The discrepancy between the numerical result and the experimental result may be caused by the neglect of the composite interlayer's plastic deformation and the strain rate effect on mechanical properties in the modeling. It can be

observed from Fig. 14 that for the medium intensity blast loading, the predicted result matches well with the experimentally measured result.

Similarly, for the high intensity blast loading, the predicted midpoint deflection history in the first deflection peak region is compared in Fig. 15 with the experimentally measured result. The predicted maximum deflection is 1.03 inch (26.1 mm) and the predicted positive deflection duration time is 8.1 ms. The experimentally measured maximum deflection value is 0.99 inch (25.2 mm) and the measured duration time is 9.4 ms. Fig. 15 shows that for the high intensity blast loading, the predicted result also matches fairly well with the experimentally measured result. Considering the good match of the numerically predicted results and the experimentally measured results under medium and high intensity blast loading, it can be concluded that the developed numerical model is valid for predicting the dynamic response of the laminated glass under both medium and high intensity blast loading.

Figure 14 Midpoint deflection of the laminated glass under the medium intensity blast loading in the first deflection peak region

Figure 15 Midpoint deflection of the laminated glass under the high intensity blast loading in the first deflection peak region

6 Laminated glass failure analysis

Based on the stress-strain relationship, the stresses of the laminated glass under blast loading can be expressed as following equations

$$\sigma_x = \frac{E_{avg}}{1 - \nu_{avg}^2} (\epsilon_x + \nu_{avg} \epsilon_y) \quad (16)$$

$$\sigma_y = \frac{E_{avg}}{1 - \nu_{avg}^2} (\nu_{avg} \epsilon_x + \epsilon_y)$$

$$\tau_{xy} = G_{avg} \gamma_{xy}$$

Substituting equation (5) into equation (16) results in

416

$$\sigma_x = -\frac{E_{avg} z}{1-\nu_{avg}^2} \left(\frac{\partial^2 w}{\partial x^2} + \nu_{avg} \frac{\partial^2 w}{\partial y^2} \right) \quad (17)$$

417

$$\sigma_y = -\frac{E_{avg} z}{1-\nu_{avg}^2} \left(\nu_{avg} \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} \right)$$

$$\tau_{xy} = -2G_{avg} z \frac{\partial^2 w}{\partial x \partial y}$$

418

419 where E_{avg} , ν_{avg} and G_{avg} are the average Young's modulus, Poisson's ratio and shear modulus of
 420 the laminated glass, respectively. These parameters can be calculated using the following
 421 equations [11, 38]

422

$$E_{avg} = \frac{E_g h_g + E_c h_c + E_g h_g}{h_g + h_c + h_g}$$

423

$$\nu_{avg} = \frac{\nu_g h_g + \nu_c h_c + \nu_g h_g}{h_g + h_c + h_g}$$

$$G_{avg} = \frac{E_g h_g + 2(1+\nu_g) G_c h_c + E_g h_g}{2(1+\nu_g)(h_g + h_c + h_g)}$$

424

425 After obtaining the values of the deflection w , the stresses of the laminated glass can be
 426 calculated using equation (17). And then the principal stresses of the laminated glass can be
 427 calculated. According to the literature [33], the maximum principal stress always occurs at the
 428 midpoint of the laminated glass. So the midpoint maximum principal stress history in the first
 429 and second deflection peak regions (the first positive deflection peak region and the first negative

deflection peak region) is calculated and compared with the tensile strength of tempered glass to determine whether the laminated glass can survive when subjected to blast loading. This criterion is proposed by Wei et al. and used in their research [11]. The reason for studying the principal stress history in the first two deflection peak regions only is that according to equation (17), stresses varies directly with the deflection w . From Fig. 7 and 9, it can be observed that compared with the maximum deflection (the first deflection peak), the deflection after the first two deflection peak regions is small, which means corresponding stresses/principal stresses are small. Therefore, in this study, the principal stress history after the first two deflection peak regions is not discussed. When subjected to the medium intensity blast loading, the midpoint maximum principal stress histories of the inner glass surface (pressure impact surface) and the outer glass surface (pressure non-impact surface) in the first two deflection peak regions are calculated and plotted in Fig. 16, respectively.

Figure 16 Midpoint maximum principal stress history under the medium intensity blast loading

445

446 Fig. 16 illustrates that for the inner surface, the maximum compression stress is about 55
447 MPa and the maximum tensile stress is about 50 MPa; for the outer surface, the maximum
448 compression stress is about 31 MPa and the maximum tensile stress is about 85 MPa. The tensile
449 strength of tempered glass is usually above 175 MPa (sometimes above 200 MPa), and its
450 compressive strength is much higher than its tensile strength [39-42]. Therefore, according to the
451 stress analysis, the laminated glass will survive when subjected to the medium intensity blast
452 loading. This result has been proven by the experimental result.

453 When subjected to the high intensity blast loading, the midpoint maximum principal stress
454 histories of the inner surface and the outer surface in the first two deflection peak regions are
455 shown in Fig. 17. From Fig. 17, it can be observed that the outer glass layer first experiences its
456 maximum tensile stress of around 200 MPa, which is close to but not beyond the tensile strength
457 of tempered glass. Then, the inner glass layer experiences its maximum tensile stress of ~95
458 MPa, which is lower than the tensile strength of tempered glass. Thus, the laminated glass will
459 survive exposure to the high intensity blast loading. This result corresponds with the
460 experimentally observed result.

461

Figure 17 Midpoint maximum principal stress history
under the high intensity blast loading

3.7 Conclusions

A novel laminated glass using a transparent glass fiber-reinforced composite interlayer has been developed. The light transmittance of the laminated glass is above 60% over a wavelength range of 482 nm to 900 nm and the highest transmittance is 84.4% when the wavelength is 577 nm. The appearance of the laminated glass shows it has good transparency.

The dynamic response of the laminated glass under blast loading was investigated by field experiments and a model-based simulation. The predicted dynamic response, in terms of the midpoint deflection, agrees fairly well with the experimentally measured results under both medium and high intensity blast loading. Stress analysis and experimental results both show that the new laminated glass panel with a transparent glass fiber reinforced polymer interlayer can survive under medium and high intensity blast loading.

477

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