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Dynamic response of glass panels subjected to shock loading

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ABSTRACT

A controlled study has been performed to understand fracture and damage in glass panels subjected to air blast. A shock tube apparatus has been utilized to obtain the controlled blast loading. Five different panels, namely plain glass, sandwiched glass, wired glass, tempered glass and sandwiched glass with film on both the faces are used in the experiments. Fully clamped boundary conditions are applied to replicate the actual loading conditions in windows. Real-time measurements of the pressure pulses affecting the panels are recorded. A post-mortem study of the specimens was also performed to evaluate the effectiveness of the materials to withstand these shock loads. The real time full-field in-plane strain and out-of-plane deformation data on the back face of the glass panel is obtained using 3D Digital Image Correlation (DIC) technique. The experimental results show that the sandwich glass with two layers of glass joined with a polyvinyl butyral (PVB) interlayer and protective film on both the front and back faces maintains structural integrity and outperforms the other four types of glass tested.

1. Introduction

Accidental explosions or bomb blasts cause extreme loading on glass structures. This results in the shattering of glass panels into small pieces which have sharp edges and move at very high velocities. These high velocity glass fragments are the major cause of injuries to people. Apart from this, the blast pressure entering the building through the shattered window panels can also cause additional injuries to the occupants. Five different types of glass panels are subjected to blast loading using a shock tube to study their dynamic response. Post-mortem analysis has been conducted on the blast loaded panels to evaluate the effectiveness of the material to mitigate blast loading. Previously, the main focus of research in this area has been on the numerical/theoretical analysis of glass panels subjected to an explosion. Recently, experimental studies have been done on glass panels to analyze their blast mitigation properties. However, these experiments used either an indenter or an impactor to simulate the blast condition. The aim of this study is to analyze the damaged area, mid-point transient deflection, and other characteristics of the dynamic response of glass panels subjected to a controlled blast loading.

Saito et al. [1] modeled the blast process on glass using the indenting method. They discussed the mechanism of formation of residual stress in the indenting process, both analytically and experimentally, in order to optimize the processing conditions to produce the desired residual stress in a blast loading. Gogotsi et al. [2] used different shapes of indenters to analyze the fracture in rectangular shaped optical and technical glasses and showed that the fracture resistance of float glass was higher than that of fused silica and other optical glasses Bouzid et al. [3] studied glass material under impact conditions where stress waves and their interactions are dominant. They proposed a damage model characterized by the damage volume to evaluate the damage development and fragmentation. It was found that damage volume is a function of impact duration and critical stress.

Wei et al. [4] formulated a failure criterion based on the energy balance approach for a laminated glass panel subjected to a blast loading. They developed a damage factor to assess the failure of the laminated glass panel. According to them, the negative phase of the blast load will cause the breakage of the laminated glass if the positive phase of the blast load is not violent enough to cause failure. They also predicted the size of the glass shards using the surface energy based failure model. Wei et al. [5] developed a 3-D nonlinear dynamic finite element model to characterize the stress distribution in a laminated architectural glazing subjected to blast loading. They considered the viscoelastic parameter of the PVB interlayer on the dynamic response of the glass panel. The parametric study showed that the panel exhibited a non-linear response to the blast overpressure. At the same time they found that the through thickness stress and displacement distribution are nearly linear.

Karuthammer et al. [6] analyzed the effect of the negative phase of blast waves on glass panels. They developed an approximate numerical model for the dynamic response simulation of glass panels subjected to blast loading. This also included the stochastic considerations of the glass flaw characteristics. They also conducted a parametric study showing that the glass panels exhibit different responses at different scaled ranges, and for different charge sizes. In one of the other

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publications, Wei et al. [7] studied the response of a rectangular laminated glass panel based on the classical small deflection and large deflection theory. Their main conclusion was that the mid-span deflection and tensile stress due to the negative pressure are almost double of that in the case of positive pressure. They also showed that the tensile stress develops on the back face of the laminate panel whereas the compressive stress develops on the front face or the face which experiences the blast loading. Glasses have higher compressive strength, which is about ten times that of their tensile strength [8]. Hooper et al. [9] studied the post-fracture behavior of laminated glass under full scale blast loading. They used 3D digital image correlation for full-field deflection measurement. They studied the delamination between the interlayer to glass interface using high-speed photoelasticity and concluded that panels having interlayer thickness less than 1.52 mm fail prematurely and should not be used in blast resistant glass panels. Carson and Papanu [10] developed an aqueous-based solution which provides substantial increases in strength to the cut edges of planer glass. The application and then subsequent curing of this aqueous solution to the damaged glass surface showed a significant increase in fracture strength.

The present paper focuses on the response of five different types of glass panels subjected to a controlled blast loading applied by a shock tube. Real-time measurements of the pressure pulses affecting the panels are recorded. Post-mortem study is used to evaluate the effectiveness of the panels to withstand these shock loads. The real time deformation mapping is done using the Digital Image Correlation (DIC) technique [11]. In the following sections, the methods used to carry out these experiments are presented, and the experimental results are discussed in detail.

2. Experimental procedure

2.1. Material details

The five different panels used during these experiments include a clear glass panel, tempered glass panel, wired glass panel, sandwiched glass panel and laminated sandwiched glass panel with a protective film on both of its faces (Fig. 1). Each experiment is repeated three times. The specimens are 305 mm long × 305 mm wide × 6.5 mm thick. Laminated sandwiched glass panel has a thickness of 7.5 mm because of the protective film on both front and back faces of the sandwiched panel.

The panels are made out of soda–lime–silica glass which has a tensile strength in the range of 20–100 MPa and a compressive strength of approximately 10 times of that. The clear glass panel is the regular glass panel on which no additional treatment is performed. The tempered glass panel is made from the clear glass panel. Specimens of a specific size are cut out from the clear glass panel which is then heat treated to release the pre-stress and induce beneficial residual stresses. The wired glass panel is manufactured by building the whole panel on a wire frame such that the wire frame is imbedded within it. The sandwiched glass panel consists of two clear glass panels which are bonded by a polyvinyl butyral (PVB) interlayer. This bonding process takes place utilizing heat and pressure treatment. The PVB layer has good bonding strength, is optically clear and does not diminish the optical properties of the glass panel. The laminated sandwiched glass panel is made by adhering a protective film from XO ARMOR® on both of the outer faces of the sandwiched glass panel. The XO® protective film is 0.5 mm thick and a special adhesive XO® bond was used to adhere the protective film onto both of the faces of the sandwiched glass panel. According to the manufacturers, XO® bond penetrates the glass surface and forms a chemical bond between the glass and XO® film at the nano level. The protective film was used as a measure of retrofitting existing windows for possible improvement in blast mitigation properties.

2.2. Shock loading apparatus

The shock tube apparatus used in this study to obtain the controlled dynamic loading is shown in Fig. 2. A complete description of the shock tube and its calibration can be found in [12]. The shock tube consists of a long rigid cylinder, divided into a high-pressure driven section and a low pressure driven section, which are separated by a diaphragm. By pressurizing the high-pressure section a pressure difference across the diaphragm is created. When this pressure differential reaches a critical value, the diaphragm ruptures. The subsequent rapid release of gas creates a shock wave, which travels down the tube to impart a shock loading on the specimen.

When the shock wave impacts the test panel located at the end of the muzzle, the gas becomes superheated and the wave is reflected at a higher pressure than that of the incident shock pressure. The theoretical detail on the equations for shock tubes has been previously established in the literature and is briefly discussed in the following section [13]. There are four basic theoretical assumptions which are used to describe the gas flow in a shock tube:

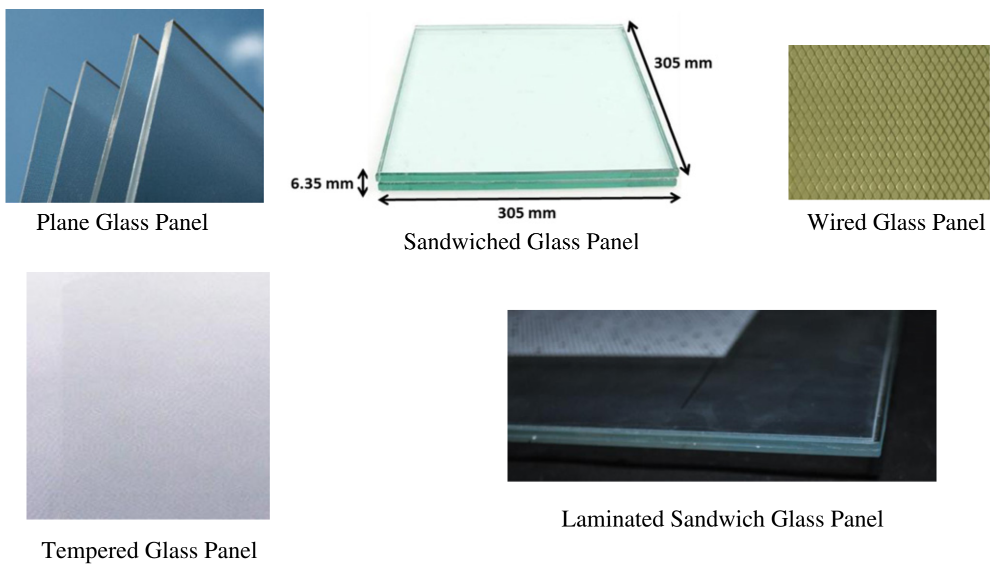

Fig. 1. Specimens.

Fig. 2. The URI shock tube facility.

1. The gas flow is one-dimensional.
2. The gas is ideal and has constant specific heats.
3. Heat transfer and viscosity effects are neglected.
4. Diaphragm rupture is instantaneous and does not disturb the subsequent gas flow.

The shock tube utilized in the present study has an overall length of 8 m, consisting of a driver, driven, converging and muzzle sections. The diameter of the driver and driven section is 0.15 m. The final muzzle diameter is 0.07 m. Two pressure transducers (Fig. 3), mounted at the end of the muzzle section measure the incident shock pressure and the reflected shock pressure during the experiment. All of the glass specimens are subjected to the same level of incident pressure in this experiment. A typical pressure profile obtained at the transducer location closer to the specimen is shown in Fig. 4. The reflected velocity for the plane glass panel is 450 m/s, for tempered glass is 330 m/s, for the wired glass panel is 400 m/s, for sandwich glass panel is 310 m/s and for laminated sandwich glass panel is 300 m/s.

2.3. Loading conditions

The square flat plate specimens utilized in this experimental study are held under fully clamped boundary conditions prior to blast loading. The size of the specimens is 305 mm × 305 mm × 6.5/7.5 mm. The dynamic loading is applied over a central circular area of 76.2 mm in diameter.

2.4. Digital image correlation (DIC) technique

The digital image correlation technique is one of the most recent non-contact techniques for analyzing full-field shape and deformation. The main process involves the capture and storage of high speed images in digital form and subsequent post-processing of these images using the commercially available software to get the full-field shape and deformation measurements. The full-field shape and deformation measurements are obtained by the mapping of predefined points on the specimen. Two cameras are required for capturing the three dimensional response of the plates. These cameras must also be calibrated and have synchronized image recording throughout the event. The calibration of the cameras is performed by placing a predefined grid of dots in the test space where the glass specimens are located during the test. This grid is then translated and rotated both in and out of plane while recording the images. As this grid pattern has predetermined distances between the dots, the coordinates of the center of each dot are extracted from each image. The coordinate locations of each dot extracted uniquely for each camera allow for a correspondence of the coordinate system for each camera. The DIC is then performed on the image pairs that are recorded during the shock event. Prior to testing the back face of the sample is painted white and then coated with a randomized speckle pattern (Fig. 5). The post processing is performed with the VIC-3D software package which matches common pixel subsets of the random speckle pattern between the deformed and undeformed images. The correlation of pixel subsets is used to calculate the three dimensional location of distinct points on the face of the panel throughout the duration of the experiment.

A speckle pattern is placed on the back face of the glass panel (as seen in Fig. 5). Two high speed digital cameras, Photron SA1s, are positioned behind the shock tube apparatus to capture the real time deformation and displacement of the glass panel, along with the speckle pattern. The high speed cameras are set to capture images at 20,000 frames per second (inter frame time of 50 μs). During the blast loading event, as the panel responds, the cameras track the individual speckles on the back face sheet. Once the event is over, the high speed images are analyzed using DIC software to correlate the images from the two cameras and generate real time in-plane strain and out-of-plane deflection histories. A schematic of the set-up is shown in Fig. 5.

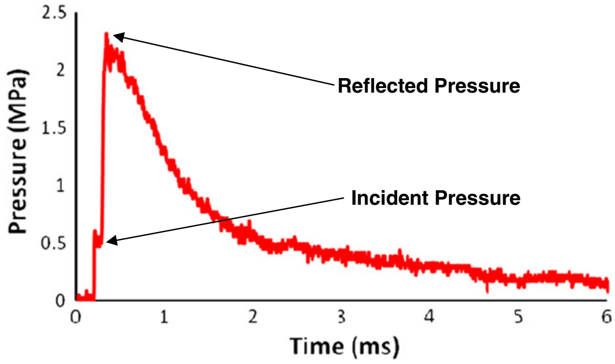

Fig. 4. A typical pressure profile.

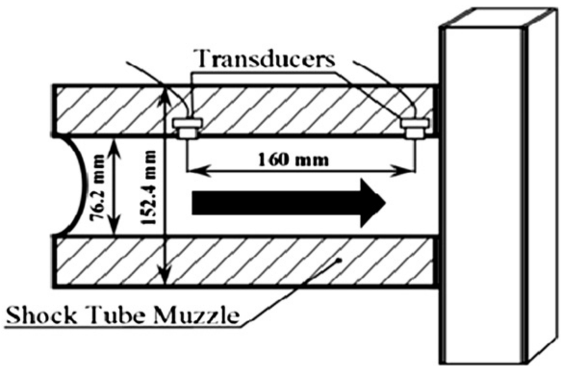

Fig. 3. Schematics of the muzzle of the shock tube and fixture.

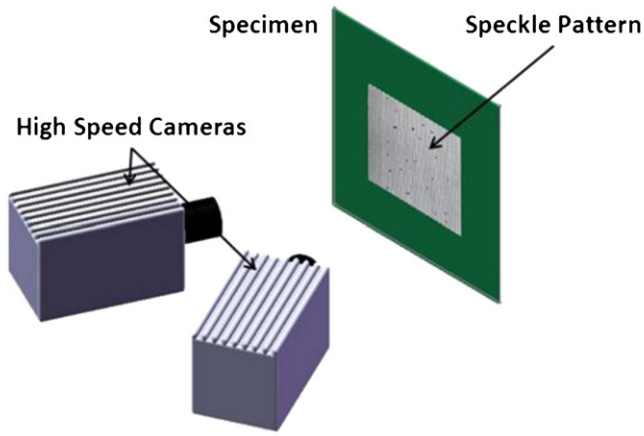

Fig. 5. Schematic of DIC system.

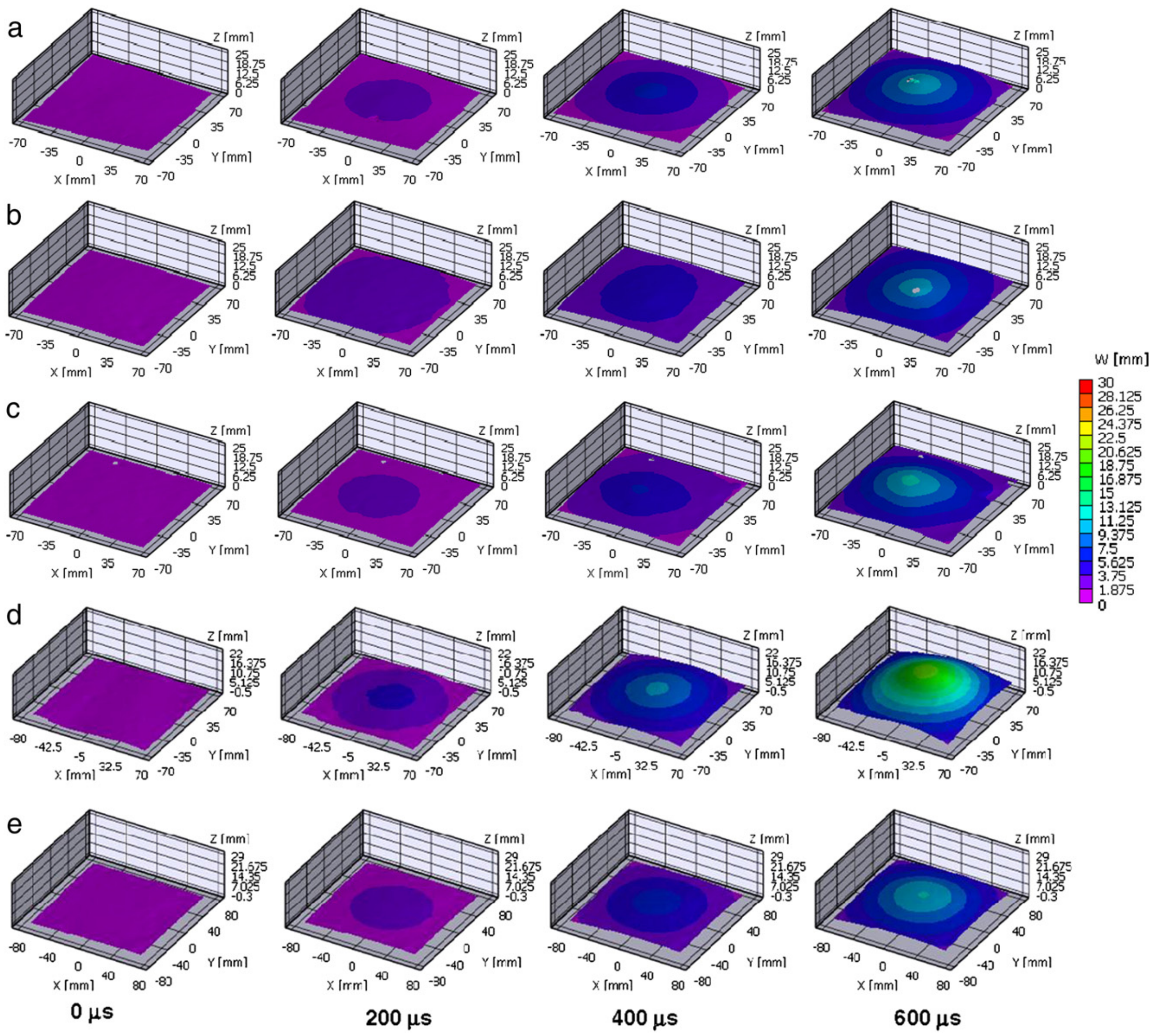

Fig. 6. Time-deflection history of the back face for: (a) plane glass, (b) tempered glass, (c) wired glass, (d) sandwiched glass, and (e) laminated sandwiched glass panels.

There are two key assumptions which are used in converting images to experimental measurements of object shape, deflection and strain. Firstly, it is assumed that there is a direct correspondence between the motion of the points in the image and that in the object. This will ensure that the displacement of points on the image has a correlation with the displacement of points on the object. Secondly, it is assumed that each sub-region has adequate contrast so that accurate matching can be preformed to define local image motion.

3. Experimental results

The DIC technique (as discussed in Section 2.4) is used to obtain the out-of-plane deflection and the in-plane strain on the back surface for all the five panels. The speckle pattern is applied onto the back face of the panels (Fig. 5) which are subjected to shock loading. The high speed images captured using two Photron SA1 cameras are analyzed to get the back face deflections from the DIC as shown in Fig. 6. Experiments have already been done to compare the back face deflection from the real time transient image and DIC to verify the accuracy of the DIC results. The error between the maximum deflection from DIC and real-time transient images is about 4% [14]. The DIC results are within the acceptable error limits and so the DIC results can be used to better understand the failure and damage mechanism in the panel.

The real-time full-field deflection of the different panels for the first 600 µs is shown in Fig. 6. For a better understanding of blast

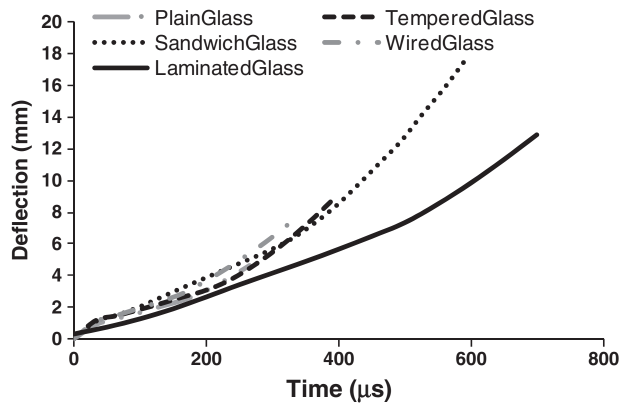

Fig. 7. Time-deflection history of the back face for five glass panels.

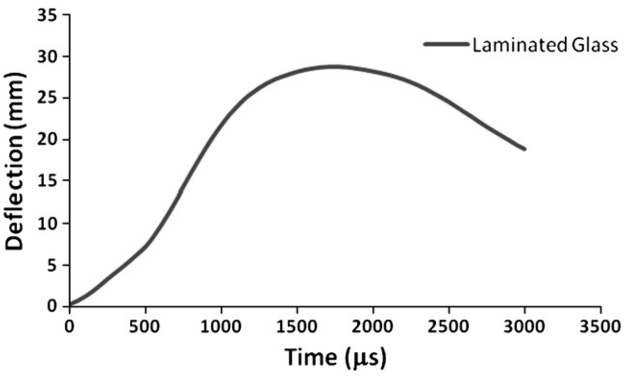

Fig. 8. Time-deflection history of the back face for laminated sandwich glass panel.

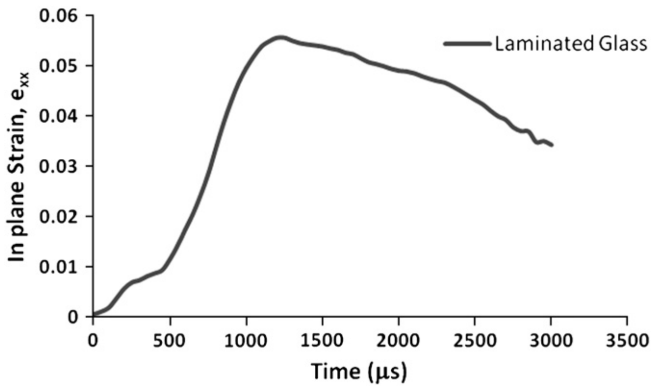

Fig. 10. Time-in-plane strain history of the back face for laminated sandwich glass panel.

mitigation properties, the center-point of this full-field analysis was chosen and out of plane deflection and in-plane strain data were extracted at this point. The center point deflections of all five panels are shown in Fig. 7. The sandwich glass panel has a maximum deflection of 18 mm prior to complete fracture, whereas at the same time, the laminated sandwich glass panel shows a deflection of 9 mm and no through hole formation. The tempered glass panel has a maximum deflection of 8 mm prior to fracture, the wired glass panel has a deflection of 6 mm and the plane glass panel shows a deflection of only 2 mm before shattering. The laminated sandwich glass panel did not fail catastrophically and had further deflection. The deflection history over an extended time for the laminated sandwich glass panel is shown in Fig. 8. Also, the in-plane strains on the back face of the five different glass panels tested are shown in Fig. 9. The sandwich glass panel has a strain of 5% before fracture initiates and at the same time the laminated sandwich glass panel only has a 1.7% strain (there was no through hole formation at this time), whereas in the case of the tempered glass panel it is 2%, 1% for the wired glass panel and 0.01% for the plane glass panel before fracture. The laminated sandwich glass panel did not fail catastrophically and deflected further which resulted in higher in-plane strain. The in-plane strain history for the laminated sandwich glass panel over an extended time is shown in Fig. 10.

4. Discussion

4.1. DIC analysis

The lamination of the sandwiched glass panel improved the blast mitigation properties of the laminate and also resulted in delayed deflection and damage propagation (Fig. 6). Also the laminated sandwich glass panel did not fail catastrophically. The deflection history over an extended time for the laminated sandwich glass panel (Fig. 8) shows that the laminated sandwich panel has a maximum deflection of 28 mm and recovers back to a final deflection of 16 mm. The other important point is that it experiences fragmentation and cracking in the glass panel, but the protective film is able to contain the shattered glass pieces from flying off. Also, the extended in-plane strain history for the laminated sandwich glass panel (Fig. 10) shows that the laminated sandwich panel has a maximum in-plane strain of 6% after which it recovers to 3%. Both, the time-deflection and in-plane strain history show that the laminated sandwiched glass panel behaves in a more ductile manner as compared to the other glass panels. In reality, glass is a brittle material, but adhering the protective film on both the

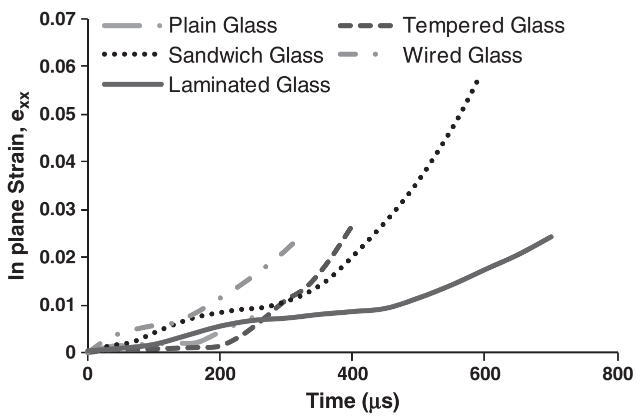

Fig. 9. Time-in-plane strain history of the back face for five glass panels.

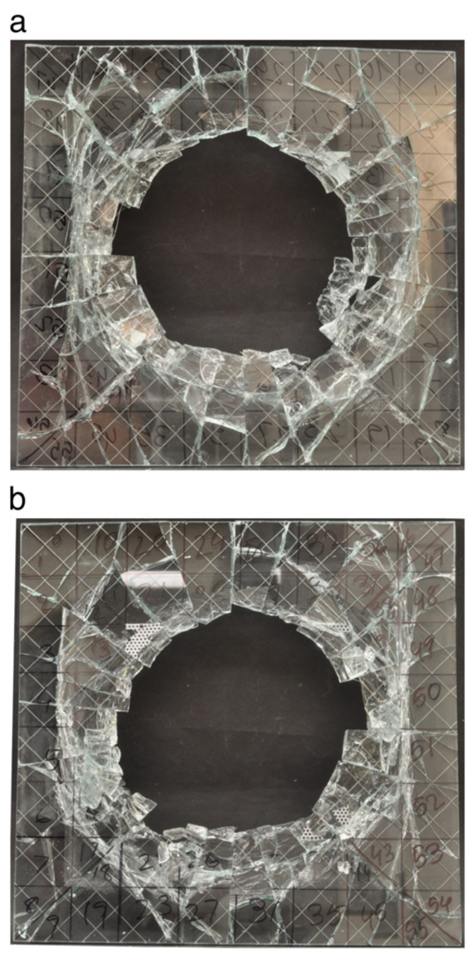

Fig. 11. Post-mortem evaluation of wired glass panel (a) front view; (b) back view.

front and back faces of the panel makes it more ductile as a structure and it helps in containing the shattered glass pieces. This avoids the catastrophic failure of laminated sandwich glass panel. The protective film also helps in dampening the incident shock wave as well as slowing the out of plane deflection of the glass which results in a lower strain rate.

4.2. Macroscopic post-mortem analysis

The result of post-mortem evaluation of the shock loaded glass panels is shown in Figs. 11–13. The post-mortem analysis of the clear glass and tempered glass panels have not been shown as they completely lost their structural integrity and shattered into pieces. The post-mortem analysis of a wired glass panel is shown in Fig. 11. The panel shows a large amount of fragmentation but in comparison to the clear and tempered glass panel, which shattered completely, it retained structural integrity. The post-mortem image of the sandwiched glass panel is shown in Fig. 12. There is heavy fragmentation on both the front and back faces as seen in Fig. 12(a)–(b). The PVB interlayer is able to withhold a substantial amount of these fragments. The post-mortem images of the laminated sandwich glass panel are shown in Fig. 13. It is evident from the post-mortem images that there is substantial fragmentation in the case of the laminated sandwich glass panel. However, the protective film is able to contain these pieces and prevent them from flying off. Also, there is no cracking in either of the layers (both on the front and back faces of the glass panel) of the protective film. The laminated sandwich glass panel is around 15% thicker than the other panels because of the protective film that had been adhered to both the front and back faces of the panel. The higher thickness also contributes to the improved performance of the laminated sandwich glass panel. The laminated sandwich glass panel was also tested at a higher incident pressure (1 MPa, which is twice that of the incident pressure at which the other panels were tested) and it was found that the panel survived the shock loading and that there was no catastrophic failure.

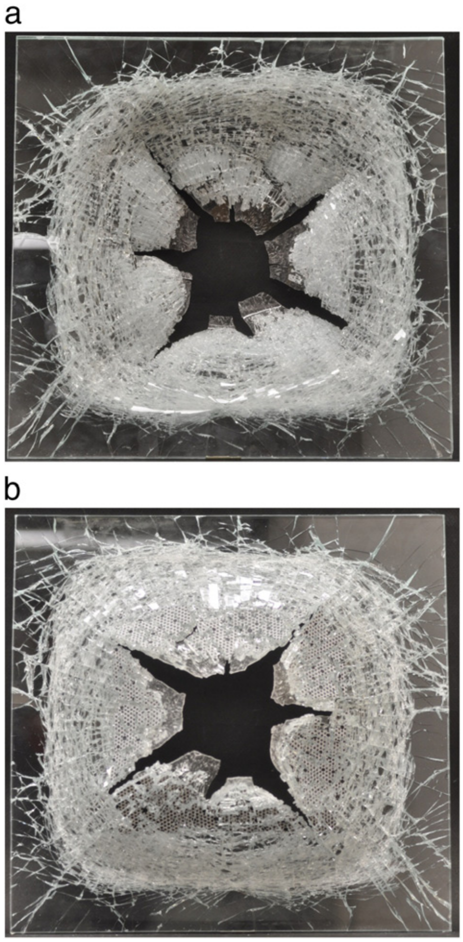

Fig. 12. Post-mortem evaluation of sandwich glass panel (a) front view; (b) back view.

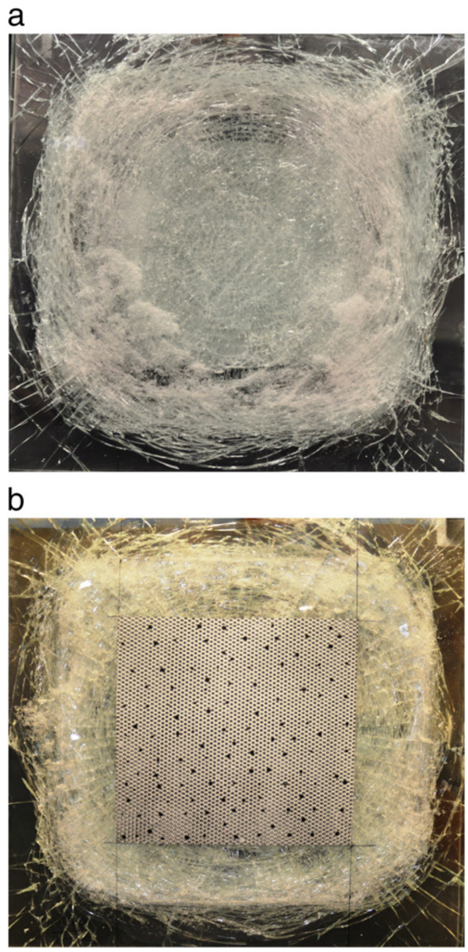

Fig. 13. Post-mortem evaluation of laminated sandwich glass panel (a) front view; (b) back view.

Overall, it can be concluded that the laminated sandwich glass panel has better blast mitigation properties than the other four panels. The clear glass panel and tempered glass panel have the worst blast mitigation properties and are shattered into pieces when subjected to the shock loading. The sandwiched glass performs better than the wired glass panel, but it still has fragmentation and shattered glass pieces flying around. The fragmentation in the case of the sandwich glass panel is lower as compared to that in the wired glass panel. Also, the diameter of the through hole formed in the wired glass panel is larger as compared to that in the sandwich glass panel. This improvement in the blast response of the sandwich glass panel can be attributed to the PVB interlayer which helps in withholding some of the shattered glass pieces.

5. Conclusions

Five different panels are subjected to a controlled air blast loading using a shock tube. The high speed photography and DIC analysis are applied to obtain the out-of-plane deflection and in-plane strain on the back face of all the five panels.

1. The macroscopic post-mortem analysis and DIC deflection analysis show that the sandwich glass panel has less damage due to blast loading as compared to the wired, tempered and clear glass panels.

The PVB interlayer increases the flexural rigidity of the panels, and results in less damage when subjected to the shock loading.

2. The area of the through hole formed in the case of the sandwich glass panel was smaller as compared to that in the case of the other three glass panels. This will minimize the blast overpressure entering in the buildings and thus lower the damage inflicted as compared to the wired, tempered and plain glass panels.
3. The application of the protective film (XO-ARMOR®) on the front and back faces of the sandwich panel further improves the blast mitigation property of the sandwich glass panel.
4. The laminated sandwich glass panel has fragmentation and cracking in the glass panel but the protective film is able to withhold the shattered glass pieces from flying off. Also, there is no through hole formation in the case of the laminated sandwich glass panel. This prevents the blast overpressure from entering the building and thus restricting the damage because of the overpressure.

Overall, the laminated sandwiched glass panels with PVB interlayer and protective film on both the faces have better blast mitigation properties as compared to the other four panels.

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