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Experimental and numerical study of boundary and anchorage effect on laminated glass windows under blast loading

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ABSTRACT

Over the years extensive studies have been conducted to analyze the response of laminated glass panes under blast loading for personnel and property protection. The failure modes of glass windows in most of those studies are related to flexural bending of the glass panel. The problems of laminated glass failure at boundaries along window frames, as well as the influences of window frame constrain effect and the interlayer anchorage on the overall response of laminated glass panels are less examined. In this paper, experimental and numerical studies are carried out to examine the boundary conditions and interlayer anchorages of laminated glass windows on their responses under blast loadings. Blast tests were designed and conducted on window specimens with different frame bite depths, fixed or sliding boundaries and different interlayer anchorages. Numerical model of laminated glass windows is also developed. The accuracy of the numerical model in prediction of glass window responses is verified by field blast testing results. The validated numerical model is used to perform intensive simulations to study the window boundary conditions and interlayer anchorage measures on glass window responses to blast loadings. The results demonstrate that properly designed window frame and interlayer anchorage will increase the survivability of laminated glass windows under blast loadings.

1. Introduction

Tragedies related to the hostile terrorist bombing attacks and accidental explosions are occasionally reported as news headlines throughout the world, e.g., the recent fuel tank explosion in Nanjing, China in June 2014, and the terrorist bombing attack in Oslo, Norway in 2011. Most post-event investigations of such incidents have cited the majority of human casualties and injuries were rather than by the air blast wave or the bomb container fragments themselves, but mainly by the shattered glass windows, fragments of walls and other objects which were not secured and were propelled towards the residents by the blast waves [1,2]. Due to its relatively weak strength, glass windows in such incidents are especially fragile, and consequentially lead to enormous casualties. For better human protection against blasting loads, the development of blast-resistant windows has been being research topics of many researchers, manufacturers, security personnel and government officials all over the world.

Different techniques and materials are available to provide blast resistant glass windows, which include replacing low strength annealed glass by high strength thermally tempered glass or by laminated glass. Lin et al. conducted an intensive review on available window strengthening solutions [3]. Recent field blasting tests on monolithic glass windows found that by using thermally tempered glass, the blast resistant capacity of the glass windows can be effectively improved [4]. However, under large magnitude blast loads monolithic tempered glass windows rupture into numerous jagged shards which impose significant threats to the residents [5]. Employing laminated glass panel for windows has proved itself through experiments and experiences of explosion incidents to effectively mitigate the risks of human injuries from ejecting glass fragments. Laminated glass consists of two or more glass plies bounded together by polymer interlayers such as Polyvinylbutyral (PVB) or SentryGlas® Plus (SGP, ionoplast produced by DuPont™) of different thicknesses. After glass crack under blast loading, the polymer interlayer will hold the glass splinters and continue to deform substantially as a membrane. In such a manner, the imposed blast energy will be dissipated by the laminated glass panel through large deformations.

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The failure process of a laminated glass pane under blast pressure can be divided into the following five steps: (1) the entire laminated pane deforms elastically; (2) cracks are formed on the outer glass ply under tension; (3) cracks extend and occur on the inner glass ply; (4) the interlayer retains the cracked glass plies and continues to deform; (5) Rupture is formed on the interlayer. Zhang et al. studied the failure modes of laminated glass panes through numerical simulations [6]. It was found that if the laminated glass pane is clamped firmly, shear failure occurs on the interlayer along the boundary when it is subjected to impulsive load with significant reflected pressure in short duration; flexural bending failure is expected when it is under relatively long duration loading; and a combined shear and flexural failure will be formed on the PVB interlayer if it is under intermediate dynamic loading. Parametric studies have been carried out to study the influence of glass thickness, interlayer thickness and glass strength, etc. on the failure modes of glass panes [6,7].

In analyzing the response of laminated glass windows to blast loads, the influence of boundary conditions is found to be significant. Larcher et al. [8] modeled a 1.0 m $\times$ 0.8 m laminated glass panel with different boundary conditions, i.e. fully fixed boundary, in-plane sliding boundary which restricted glass pane longitudinal movement in the direction of blast wave but allowed in-plane transitional sliding, and elastic boundary to model the supporting rubber strips between frame and glass. The numerical results showed the glass panes with different boundary conditions responded quite differently. A largest pane central deflection was found on the window with sliding boundary, while a smallest central deflection was resulted on the window with elastic boundary. A larger central deflection is more likely to cause interlayer rupture, which means the laminated pane with in-plane sliding boundary can be the most fragile. In Zhang et al.'s pressure-impulse analysis on 7.52 mm thick laminated glass panels, the ultimate load bearing capacity of the laminated pane with pinned boundary was found to be about 15% more than that with fully fixed boundary condition [7]. By reducing the rotational restraints along the window boundary, a more flexible window system was achieved which exhibited better blast resistant performance. These analyses on window boundary conditions lead to the possibility of adjusting the boundary conditions to further improve the blast resistant capacity of a laminated glass panel.

The ideal failure mode of laminated glass windows discussed above is not necessarily always achievable. In Hooper et al.'s full-scale field blasting tests on laminated glass windows [9], before tearing occurred on the PVB interlayer, the entire cracked laminated panes were pulled out of the window frame and pushed into the occupied area behind the windows. In other words, the failure of the window was mainly due to joint failure at the window boundary rather than the failure of the laminated glass pane itself. The bite depth, namely the embedment depth of the glass pane into the window frame, is believed to play an important role in the overall response of the laminated glass windows in face of blast loading. Morison mentioned that for laminated glass with 1.52 mm thick or more interlayer a 25–30 mm deep bite is required to achieve the better blast loading resistance [10]. Laboratory tests and field blasting tests on laminated glass panels reported recently provide more insights to the influence of window bite depth. For instance, Kranzer et al. [11] tested 7.52 mm thick laminated glass panels fully clamped in 1100 mm by 900 mm steel frames with 50 mm bite depth. No boundary failure was observed on any of the four tested panes. In the airbag pendulum impact tests by Zhang and Hao [12] carried out on 600 mm by 600 mm laminated glass (various thicknesses) with 30 mm bite depth all around, pane slipping out of the frame was not observed either. These tests on laminated glass windows indicate that a properly designed bite depth is needed to prevent premature failure of pulling the laminated pane out from the window frame before the interlayer ruptures so as to achieve the full blast loading resistance capacities of the laminated glass panes.

To prevent the potential slippage failure along window boundary, interlayer anchorages have been introduced to stop the laminated panes from being easily pulled out of the frame. For example, in manufacturing laminated glass panes tails of PVB interlayer are left perimetrally along the pane boundary, which are then clamped into the window frame to provide certain anchorage. Fixture bolts can also be applied along the frame at specific spacing, which further anchors the PVB tails to the window frame. Another measure introduced by US Air Force Research Laboratory is called mechanical fixture bar method [13]. This method uses a doubly laminated glass pane which consists of three glass plies and two PVB interlayers. The ends of the PVB interlayers wrap around steel rods which are firmly mounted into the wall. When the laminated pane is under lateral loading, the steel rods will hold the PVB interlayers and stop the laminated pane from being pulled out of the window frame. The efficiencies of all these strengthening techniques have been proved individually by their respective developers, mainly by field blast tests. However, performance of the respective strengthening techniques applied to windows other than those tested are not clear. The advantages and disadvantages of each individual measure over the other are not known either. Therefore, study and analysis on these anchoring measures for general window systems are needed.

In this study, full-scale field blast tests were carried out on 7.52 mm thick laminated glass panels fully clamped by two robust steel frames with 50 mm bite depth all around. The blast pressures and the responses of the laminated panes were recorded by pressure sensor and mechanical Linear Voltage Differential Transducers (LVDT). High-speed cameras were used to assist monitoring the response of the panes with pre-plotted tracking dot matrix. A doubly laminated glass panel installed in an innovative sliding boundary frame system was also tested in comparison with the one installed in the fully fixed boundary frame to examine the performance of the proposed sliding boundary system in mitigating the blast loading effect. Numerical models of laminated glass were developed and calibrated with field blast testing results. Numerical simulations were then conducted to investigate the influences of boundary conditions, namely the fully fixed or sliding, bite depth, and the interlayer anchoring methods on responses of laminated glass windows to blast loads.

2. Experimental investigation

2.1. Description of experiment setup

In the current work, laminated glass panes were tested with different weights of TNT at various stand-off distances in six shots. A reinforced concrete (RC) frame of approximately 3.4 m by 3.2 m by 2.0 m (width by length by height) as illustrated in Fig. 1 was constructed with deep rooted independent footings to support the glass window specimens for the test. The testing block consisted of two individual cells. The back wall of the block was left open for high-speed cameras to monitor the deformation of the glass panes. In each shot, two glass panes were tested with designed charge detonated in front of the RC block. The glass window specimens were installed on the openings of the front wall using steel frames. The laminated glass panes were 1.5 m $\times$ 1.2 m in dimension. For the first five tests, the laminated panes constructed with two plies of 3 mm thick annealed glass sandwiching a 1.52 mm thick PVB interlayer (Fig. 2a). These five 7.52 mm laminated glass panes were tested in pair with another five glass panes of the same sizes but different glass and interlayer thicknesses. The responses