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Experimental investigation of monolithic tempered glass fragment characteristics subjected to blast loads

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ABSTRACT

A series of field blasting tests of glass windows to blast loadings have been recently conducted. This is the second paper to report the testing data on monolithic tempered glass windows. While the first paper reports the glass panel response and failure modes, the current paper concentrates on the glass fragments induced by the blast loadings. Thermally tempered glass has been often adopted for monolithic windows to reduce ejecting fragment hazards after window fracture. However, previous blast tests conducted on monolithic tempered glass reported that in addition to small cubic fragments the shattered glass panes could break into large and jagged fragments similar to the cases in annealed glass which poses much more debris threats than expected. A thorough study on tempered glass fragments produced by air blast pressure is therefore necessary for better protection of human safety. In this paper, fragment characteristics of monolithic tempered glass windows observed in blasting tests are analyzed and presented. 1.5 m × 1.2 m monolithic panes of two commonly used thicknesses, i.e. 6 mm and 10 mm, fully clamped onto the opening of an enclosed RC frame were tested with 5–10 kg TNT charge detonated at 4.5–12.3 m stand-off distances. Glass fragment mass and splash distributions both in front of and behind the windows were evaluated with respect to reflected pressure and glass specification. Fragment size and shape were also analyzed. High-speed cameras were used to monitor glass window fracture processes. Fragment velocities were determined by post-processing the high-speed camera images. Fragment ejecting velocities were evaluated with respect to the reflected impulse. Negative pressure was found to significantly influence the fragment ejecting velocity and fragment splash distributions.

1. Introduction

Monolithic glass is ubiquitously used for windows in buildings. However, monolithic glass pane is very brittle and fragile which offers limited resistance to blast pressures from an explosion. The ejecting glass fragments as a result of fractured glass window often travel at very high velocity toward the residents, which therefore have always led to enormous injuries and casualties. Post event investigations have cited shattered glass windows as one of the major threats in the explosion events. For instance, after the Oklahoma City bombing incident, the investigation by Norville et al. [1] reported 198 people in buildings within a radius of 970 m suffered direct glass-related injuries including lacerations and abrasions. Similarly, in the 2011 Norway bombing attack 209 out of the total 325 injuries were associated with glass laceration [2]. Considering the increasing threats from accidental explosions and terrorist bombing attacks targeting at urban areas, it is important to understand the behavior of monolithic glass window under air blast waves and the characteristics of glass fragments from fractured windows for human protection.

Tempered glass has been adopted for monolithic windows to replace traditional annealed glass to improve window blast resistant performance. Thermally tempered glass, most commonly used for windows, is manufactured by heating and then cooling annealed glass in a tempering furnace, which results in compressive residual stress at the surface and tensile stress in the center of glass pane. The stress distribution can be represented by a parabola, with the magnitude of the surface compression stress equal to twice the center tension [3]. This prestress in the glass generally makes it four to five times stronger than annealed glass. Moreover, once a crack reaches the tensile zone of tempered glass,

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the entire glass sample breaks up due to the energy elastically stored in the sample during the tempering process [3]. Because tempered glass shatters into numerous small oval shaped fragments rather than jagged and sharp shards from annealed glass, it is entitled as safety glass and is widely installed to mitigate laceration hazards. However, the propagation of cracks within tempered glass may not necessarily reaches the surface but stay in the tensile zone [4]. In other words, only the central layer of the tempered glass would break into small cubicles, and the entire pane would remain intact until it further ruptures into large pieces. Field blast tests on monolithic tempered glass observed that tempered glass might break into large pieces of fragments with sharp edges [5,6], which impose significant threats to people in the surrounding area. The fragment mitigation effect of tempered glass is therefore not necessarily always achievable. It is necessary to study and understand the fragment characteristics of monolithic tempered glass panes for better protections of occupants.

Several design criteria are facilitated for blast resistant window design with fragment considerations. GSA standard [7] classifies glass fragment threat based on splash distances into the occupied space (Fig. 1). TNO defense of the Netherlands is in the process of designing a hazard assessment tool for glazing subjected to blast loading [8]. A fragment injury module is to be developed based on fragment velocity recorded in their continuous field tests. The US Army Technical Center and the US Army Corps of Engineers Protective Design Center are also developing injury-based glass hazard assessment tools. The primary challenge is the prediction of fragment size, shape and velocity, which will be derived from semi-empirical model based on shock tube tests. In general, all assessment criteria available or under development require the fundamental understanding about the glass fragmentation process and fragment characteristics such as fragment size, fragment shape, launching velocity and splash distance. Unfortunately, there is still a lack of knowledge in this sphere, and systematic study is badly needed.

Experimental investigations into glass fragmentation have been conducted over the decades. However, most of previous studies were primarily conducted on annealed glass windows. For instance, Doormaal et al. [8] tested 8 mm thick annealed glass windows under blast loads, and provided the relations of the maximum fragment velocity and blast reflected pressure and impulse. Locke and Unikowski [9] used pendulum with a steel rig to impact annealed glass. They investigated fragment distribution by collecting glass fragments splashed on the ground. More systematic experimental investigations on annealed glass windows were reported by Fletcher et al. [10] and Iverson [11], who respectively studied fragment characteristics and the related fragment velocity, mass, spatial density with blast reflected pressure, and also assessed biological impact from ejecting window fragments. The only literature available to public access on tempered glass fragmentation was by Beauchamp and Matalucci [6], who conducted two groups of blast tests on tempered glass windows. A block of backstop foam was used to capture glass fragments. However, the backstop foams were easily blown away by the blast air pressure entering the testing cell after the fracture of glass windows. To dig every single piece of the glass fragment cloud out of the stop foams and derive reliable results was found painstaking and not practical. The results provided were therefore limited. It was recommended that more field blast tests would be required with better methods to deal with ejecting glass fragments.

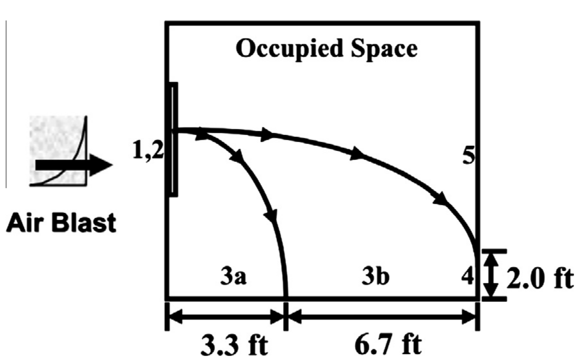

Fig. 1. GSA glass window performance levels [7].

Analytical solution and numerical simulations have also been employed in analyzing glass window response [12] and fragmentation process. Based on strain energy coupled with damage, Zhang et al. [13] formulated an analytical model for predicting fragment size and ejection velocity. The fragment ejection velocity was related to strain rate which was regarded suitable to investigate dynamic fragmentation process. Ge et al. [14] recently derived semi-analytical solutions to estimate glass fragment velocity and splash distance. The derivation was also based on energy principles, and the constants involved in the formula were determined by their field blast test on monolithic annealed glass. Numerical methods were widely used to simulate glass window responses to blast and impact loads [15–19]. However successful numerical models in simulating glass fragmentation are very limited. As pointed out by Hao et al. [20], the existing numerical approaches have inherited difficulties in predicting structural fragmentations. The popularized SDOF glass window models can only predict the overall window responses. The finite element method employs an erosion criterion to erode away elements to avoid element tangling, which results in loss of fractured mass and also violates the principle of energy conservation. The mesh-less method and discrete element method avoid erosion, but the particle sizes and weak sections that will lead to structure breakage are pre-determined. Therefore, all these methods not necessarily lead to reliable predictions of the fragment size, launching velocity and distance.

In this paper, field blast tests on monolithic tempered glass windows were carried out to examine glass fragment characteristics. Different combinations of TNT charge weights and stand-off distances were detonated in front of an enclosed RC frame built purposely to support the window specimens. Tempered glass panes of 6 mm and 10 mm thick were tested to check the influences of glass thickness on fragment characteristics. Glass fragment splash distributions in front of and behind the windows were collected and analyzed. Glass fragment size, and shape distribution were also evaluated. Fragment ejecting velocities, which were monitored by two high-speed cameras, were reported and analyzed.

2. Experiment setup

The aim of the current tests concentrates on investigating glass fragment characteristics, including fragment splash distribution, fragment size, fragment shape, and fragment velocity. In each test, fragment masses splashed at various distances, the amount of fragments of different sizes, fragment length ratio, and fragment velocity and trajectory were tracked and collected. The detailed experimental setup is described in this section.

2.1. Site plan and window installation

Fig. 2 depicts the experiment site for the current field blast test. A one storey reinforced concrete (RC) frame of 3.4 m × 3.2 m × 2.0 m (Width × Length × Height) in dimension was constructed to support the windows. The RC block was built with two individual testing cells. Both side walls and ceiling were fully covered to avoid blast wave refraction. The back wall of the frame was left