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# A theoretical study on the P-I diagram of framed monolithic glass window subjected to blast loading

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ABSTRACT

In this paper, an analytical model for determining the iso-damage curves for framed monolithic glass panels subjected to blast loading is proposed. Two typical damage levels corresponding to different conditions in GSA/ISC are classified, namely (a) the glass crack limit and (b) glass fragments invading with a certain velocity. The nonlinear dynamic responses and failure modes of framed monolithic glass under different blast loadings are firstly analysed numerically. Then critical states of glass panel in both impulsive region and quasi-static region of the pressure-impulse (P-I) diagram are defined. Based on the energy balance approach, an analytical method is proposed for determining the pressure asymptote and the impulse asymptote of framed monolithic glass for different damage levels. The proposed method is verified through comparison with published experimental data and numerical results. The method can be applied for any framed monolithic glazing with different dimension and thickness and provides a practical approach for engineering design and hazard level estimation of framed monolithic glass against blast loading.



## 1. Introduction

Glass curtain wall has become more and more popular in high-rise buildings nowadays for its artistic facade appearance and high clarity. However, its disadvantages are also very significant. Because glass is a brittle material with relatively weak strength compared with other structural members, glazing windows are more vulnerable to air blast waves caused by intentional or accidental explosions. Laminated glass has been proved to be very effective at mitigating the risk of fragment ejection, and therefore it is widely used and should be a priority choice in regions where high level of protection is required. However, due to the unpredictable nature of explosion occurrence, especially for concerns over malicious attacks, it is necessary to investigate monolithic glass as it is still the most commonly used glass type in the general building stock. According to the statistical data in literature [1], as listed in Table 1, over 40% of the injuries in an explosion incident have been glass-related injuries such as lacerations and abrasions from flying glass shards. Therefore, it is very important to strive for a proper design of glass windows with consideration of possible exposure to blast loading, and to this end a thorough understanding of the dynamic behaviour and failure mechanism of glass windows subjected to blast wave is crucial.

GSA/ISC [2] classifies the performance of window systems subjected to blast loads and the related hazard levels, as indicated in Fig. 1. These response conditions are classified based upon the post-test location of fragments and debris. Under condition 1 or 2 there will be little fragments invade and the glazing remains to be retained by the frame. Only dusting or very small fragments near the sill or on the floor may be acceptable. Condition 3a to 5 are specified according to the invasion distance and the corresponding hazard level. For example, condition 3a and 3 b correspond to invasion distances of no more than 1 m and 3 m respectively, while condition 4 or 5 represent fragments that can impact a target located 3 m away from the window at a height lower or higher than 0.6 m above the floor, respectively. Currently, for design of blast resistant glazing, ASTM-F2248 and ASTM-E1300 [3,4] specify an equivalent 3-second duration design loading and design charts for different types of glass windows. However, neither the dynamic characteristics of the blast loading nor the dynamic response of glazing has been considered in these ASTM standards [3,4]. Besides, it should be noted that the equivalent 3-second duration uniform load is associated with a probability of breakage less than or equal to 8 lites per 1000 for monolithic

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**Nomenclature**

| | |
|---|---|
| $a$, $b$ | length and width of the monolithic glass panel, with $a \geq b$ |
| $h$ | thickness of the monolithic glass panel |
| $E$ | elastic modulus of glass |
| $G$ | shear modulus of glass |
| $v$ | Poisson's ratio of glass |
| $\sigma_f$ | failure stress of glass material |
| $\psi$ | deflection function of glass panel |
| $w$ | deflection at the panel centre |
| $w_f$ | deflection at the panel centre at glass crack moment |
| $p$ | peak overpressure of a specific blast load |
| $i$ | impulse of positive phase of a specific blast load |
| $t_d$ | equivalent positive load duration of a specific blast load |
| $D_s$ | width of shear region |
| $C$ | length of shear region |
| $M_e$ | equivalent mass of the equivalent model |
| $K_b$, $K_s$ | flexural stiffness and shear stiffness of the equivalent model |
| $K_e$ | effective stiffness of the equivalent model |
| $P_e$ | equivalent load of the equivalent model |
| $W$ | the work done by the pressure |
| $\Delta_b$, $\Delta_s$ | flexural deflection and shear deflection of the equivalent model |
| $\Delta$ | effective deflection of the equivalent model |
| $\sigma_1$ | maximum principal stress within the glass panel |
| $E_{k0}$ | initial kinetic energy of glass panel |
| $E_k$ | total kinetic energy of glass panel |
| $E_{kr}$ | residual kinetic energy at glass failure moment |
| $v_0$ | initial velocity at the panel centre |
| $v_r$ | ejection velocity of the glass fragments |
| $U_i$ | internal strain energy of the panel |
| $U_f$ | dissipated energy due to glass fracture |
| $\gamma_s$ | surface energy per unit area |
| $\Delta a$ | side length of a representative square fragment |
| $A_f$ | area of new formed surfaces of fragments |
| $i_{cr}^k$, $p_{cr}^k$ | values of impulse asymptote and overpressure asymptote for damage level k, respectively. $k$ = I, II, III, ... |
| $\alpha$, $\beta$ | shape parameter for the dynamic region of P-I curve |
| $\xi$ | adjust coefficient to modify the impulse asymptote of damage level I |
| $i_c^1$ | modified impulse asymptote of damage level I |
| $T_s$ | natural period of glass panel |
| $\lambda$ | ratio of residual kinetic energy to total energy at glass failure moment |
| $\lambda_c$ | critical residual kinetic energy ratio for punching failure mode |
| $v_{rc}$ | critical ejection velocity for punching failure mode |
| $D_{sc}$ | shearing region width for critical damage level |

**Table 1**
Glass-related injuries by buildings in proximity to ground zero [1].

| Building number | Building name | Total bomb-related injuries | Glass-related injuries |
|---|---|---|---|
| 1 | Alfred P. Murrah Federal Building | N/A | N/A |
| 2 | Durham Post Office | 7 | 3 |
| 3 | Water Resources Board | 39 | 23 |
| 4 | Athenian Restaurant | 4 | 2 |
| 5 | YMCA | 81 | 33 |
| ... | ... | ... | ... |

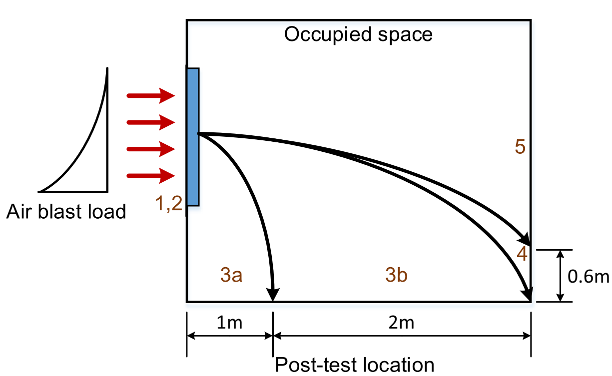


**Fig. 1.** Performance classification for window system response in GSA/ISC [2].

annealed glass, which cannot satisfy the demand of multi damage level based design.

This paper is concerned with the development of iso-damage curves for different damage levels of framed monolithic glass subjected to blast loading, which is to be used for practical applications in the blast resistant design of glazing as well as hazard estimation. A lot of research, including analytical derivation, field blast test and numerical simulation has been devoted to establish the iso-damage curves for glass windows. In particular, many studies have been conducted to predict the response of glass panel using a single-degree-of-freedom (SDOF) approach [5–7]. Cormie et al [7] developed a theoretical method to describe the behaviour of laminated glass, and proposed iso-damage curves for laminated glass under blast loading using a SDOF model. These iso-damage curves were compared with FEA results by Hooper [8] and Zhang [9], and the results revealed considerable errors in the values of impulse asymptote under different damage levels. The insufficient accuracy in the existing SDOF method for predicting blast resistant capacity of glass panels in different response regimes is believed to stem from the fact that the deformation shape function is inaccurate under impulsive loading.

On the other hand, experimental investigations including field blast tests and shock tube tests have also been conducted [10–16], most of which, however, were restricted to specific window sizes and material properties. As it is very expensive to conduct blast tests, it is not practical to rely on large numbers of blast tests to parametrically study the performance of glass panels or to obtain the detailed P-I curves. Numerical parametric study is another way to establish P-I curves. But the results based on numerical study and blast tests are only applicable to specific dimensions and thicknesses, therefore is not generally applicable. To achieve generality, developing a physics-based theoretical method for establishing P-I curves becomes of indispensable value.