Numerical Simulation of Blast Loads of Building with and without Glass Window

Xiaoqing Zhou , Licheng Xie and Junjie Yan

College of Civil and Transportation Engineering, Shenzhen University, Shenzhen, Guangdong, P.R. China
Email: xqzhou@szu.edu.cn

Abstract. A typical building model with and without glass windows has been constructed in the present paper using LS-DYNA to calculate the blast loading acting on it. For the without glass window case, the window is assumed to be an opening and there is no glass. Scaled distances of 0.5 m/kg$^{1/3}$, 1.0 m/kg$^{1/3}$ and 2.0 m/kg$^{1/3}$ are considered. The peak value of the overpressure at some typical positions inside the building are obtained and compared. The peak pressure distribution of each wall surface and the ceiling are obtained, and the influence of glass on the explosion load under different scaled distances is attained. It is found that the smaller the scaled distance, the less obvious the blocking effect of glass, and the glass can be ignored in the simulation. As the scale distance increases, the barrier effect of glass becomes more obvious. At this time, simply ignoring the glass may cause error.

1. Introduction

Once an explosion occurs, it will seriously threaten people's lives and property [1]. The main reasons for the explosion are terrorist attacks and accidental explosions. In recent years, the losses caused by explosion incidents have attracted widespread attention from the society. Research on anti-explosion and explosion-proof of building structures has become one of the hot topics for scientific research experts. Many effective anti-explosion measures and theories have been proposed. Previous research mainly focused on the calculation of blast loading, as well as the analysis of dynamic response and failure mode of structural components under explosion.

Based on the explosion similarity law and experimental data, the scholars such as Rogers [2], Henrych [3], Mills [4], and Brode [5], respectively proposed the formula for calculating the peak overpressure of the explosive shock wave in the air. These formulas are usually obtained by experiments in an open field or ignoring the interference of the surrounding environment on the explosion wave, assuming that the reflection surface of the building is infinite. However, the explosive environment where the actual building is located is different from the simple ideal environment, so the application of these empirical formulas has certain limitations.

Smith et al. [6] studied the propagation law of the explosion shock wave in the urban environment and considered the interaction of the surrounding building structures. The analysis results showed that the explosion shock wave was enhanced by the complex urban environment near the explosion point. Remennikov et al. [7] used Air3D software to numerically simulate the explosion shock wave of a building structure in a complex urban environment, and proposed that the impact of the surrounding building environment should be considered when determining the explosion shock wave parameters of the target structure.
In previous studies [6], the details of building rooms are usually not considered when simulating explosion waves. When considering room details, most of the doors and windows, even the infilled masonry walls, are directly regarded as openings. In the present study, for the first time, a glass window is constructed in a numerical building model to calculate its influence on the blast loading. LS-DYNA finite element analysis software is used to simulate the impact of explosion shock waves on rigid buildings under the action of close-range explosions. The overpressure time history curve of the target building has been obtained and the peak overpressure of the calculation results has been analyzed. Blast loading on building with and without glass window has been compared.

2. Finite Element Model

In this section, finite element model is constructed. Two different models, i.e., with and without glass window building models, are constructed. Material models for explosive, air and glass are given. The corresponding material parameters are provided.

2.1. Geometry Model and Boundary Conditions

The established geometric model is shown in Figure 1, where the size of the building model is 4.0 m × 4.0 m × 5.0 m (length × width × height), and the air domain is 6.0 m × 10.0 m × 6.25 m (length × width × height), the explosive is simplified into a cube with the standoff distance of 2m. It is assumed that the area of the glass window is 1.0 m×1.0 m and the thickness is 6 mm. Considering the symmetry of the model, in order to improve the calculation efficiency, half of the model is taken. The symmetrical boundary is adopted on the symmetry plane. For other air boundaries, the non-reflective boundary condition can be used to simulate the propagation of shock waves to the infinite air domain. That is, the energy of explosion waves is absorbed on the boundary of the model, so that stress wave reflection will not occur at the boundary. It is assumed that the glass is fixed to the rigid wall. The without glass model used for comparison does not consider the glass, and it is assumed that the window is an opening.

Four gauge-points are set (as shown in figure 1). Point A is in the middle of the building (2 m from the back wall, 1.5 m above the ground), B is on the left wall of the building (1.5 m above the ground), C is located above A (2 m from the back wall, 3.0 m above the ground), and D is on the back wall of the building (1.5 m above the ground).

Figure 1. Geometry model and boundary condition.

2.2. Material Model

The JWL equation of state [8] is used to model the detonation process of explosives. The equation describes the detonation process of explosives by reflecting the pressure-volume relationship of the explosive gas. The expression of the JWL equation of state is as follows:

\[ P = A(1 - \frac{\omega}{R_1 V})e^{-R_1 V} + B(1 - \frac{\omega}{R_2 V})e^{-R_2 V} + \frac{\omega E}{V} \]  

(1)
where $P = \text{hydrostatic pressure}; \ V = \text{specific volume}; \ E = \text{specific internal energy}; \ \text{and} \ A, B, R_1, R_2, \ \text{and} \ \omega$ are material constants. The values of the constants for many common explosives have been determined from dynamic experiments. In the present simulation, A, B, R_1, R_2, and $\omega$ are assumed as, $3.71 \times 10^5 \text{MPa}, 3.23 \times 10^5 \text{MPa}, 4.15, 0.95, 0.3$, respectively.

The equation of state of air is described by a linear polynomial,

$$P = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu + C_6\mu^2)E$$  \hspace{1cm} (2)

where $P = \text{hydrostatic pressure}; \ E = \text{specific internal energy}; \ C_0 \text{ to } C_6$ are material parameters, $C_0$ is assumed to be $-0.1 \times 10^6$, $C_1$, $C_2$, $C_3$ and $C_6$ are assumed to be 0, and $C_4$ and $C_5$ are 0.4, $\mu = \rho/\rho_0 - 1$, $\rho$ is air density and $\rho_0$ is air density under standard condition.

The JOHNSON_HOLMQUIST_CERAMICS (JH2) [9, 10] model is used to simulate glass, which can well simulate the strength and damage characteristics of brittle materials. The strength model of JH2 is to express the equivalent stress of the material as a function of intact strength, fracture strength, strain rate and damage. The dimensionless normalized equivalent material strength model is:

$$\sigma^* = \sigma_i^* - D(\sigma_f^* - \sigma_j^*)$$  \hspace{1cm} (3)

where $\sigma_i^*$ is the normalized intact strength, $\sigma_f^*$ is the normalized material strength at fracture, and $D$ is the damage scalar, ranging from 0 to 1. All the normalized stresses have the general form of $\sigma^* = \sigma/\sigma_{\text{HEL}}$, where $\sigma_{\text{HEL}}$ is the equivalent hydrostatic pressure at Hugoniot Elastic Limit (HEL), and $\sigma$ is the equivalent stress. When there is no damage ($D = 0$), the normalized intact equivalent stress, $\sigma_i^*$ is expressed as $\sigma_i^* = A(P^* + T^*)^N (1 + C \ln \dot{\varepsilon}^*)$; When the material is completely damaged ($D = 1$), the normalized material strength at fracture, $\sigma_f^*$, is expressed as $\sigma_f^* = B(P^*)^M (1 + C \ln \dot{\varepsilon}^*)$, where A, B, M, N, and C are material constants, are assumed to be 0.93, 0.2, 1, 0.77 and 0.003, respectively; $\dot{\varepsilon}^* = \dot{\varepsilon}/\dot{\varepsilon}_0$ is normalized strain rate, where $\dot{\varepsilon}$ is the actual strain rate, $\dot{\varepsilon}_0 = 1.0 \text{s}^{-1}$ is the reference strain rate; $P^*$ is the normalized hydrostatic pressure, $P^* = P/P_{\text{HEL}}$, where $P$ is the actual hydrostatic pressure, $P_{\text{HEL}}$ is the equivalent hydrostatic pressure at HEL; $T^*$ is the normalized maximum tensile hydrostatic pressure $T^* = T/P_{\text{HEL}}$, where $T$ is the maximum hydrostatic tensile stress that can withstand.

3. Numerical Results and Analysis

The above-mentioned typical building models with glass and without glass, considering the scaled distance $Z$ of 0.5 m/kg$^{1/3}$, 1.0 m/kg$^{1/3}$ and 2.0 m/kg$^{1/3}$, are modelled. Numerical results are presented and compared. The typical pressure time histories are given and the overpressure peak of the explosion shock wave on the building walls are compared.

3.1. Over-Pressure Time History and Peak Pressure Comparison

Typical pressure time histories at gauge point A of the scaled distances of 2 are shown in figure 2. It can be found that after the explosion wave reaches point A, the pressure quickly reaches its peak. The peak pressure in (b) is slightly larger than that in (a), which means that the glass has some barrier effect. After reaching the peak, the pressure drops rapidly, but due to the multiple reflections of the walls and the ground in the almost enclosed space, there are still many smaller peaks. After a long time of calculation, it still has not returned to atmospheric pressure. The distribution and the values of the subsequent smaller peak pressure for the two cases are totally different. The presence or absence of glass does change the distribution of explosion pressure.
Figure 2. Typical pressure time history (Gauge point A, scaled distance of $2 \text{m/kg}^{1/3}$).

Comparison of peak pressure at different gauge points of with and without glass buildings under different scaled distances are listed in Table 1. Whether a building has glass window or not, for the same point, the smaller the scaled distance, the greater the peak overpressure it experiences. In the case of the same scaled distance, the farther the gauge point is from the explosion source, the smaller the peak overpressure it receives, and the smaller it is affected by the explosion shock wave. From the data in the table, it can also be concluded that for the same point, under certain conditions, the smaller the scaled distance, the greater the peak overpressure, the greater the energy of the explosion shock wave, and the smaller the barrier effect of glass on it. On the other hand, the larger the scaled distance, the smaller the overpressure on the building, and the greater the barrier effect of the glass on the explosion load. Therefore, in analyzing the anti-explosion performance of the frame structure under the effect of near-explosion, whether the non-structural component glass can be ignored, the scaled distance is an important reference factor. The smaller the scaled distance, the smaller the barrier of the glass to the explosion load. This means that when the scaled distance is small, the glass window can be ignored because it has little effect on the calculation of overpressure. When the scaled distance is large, ignoring the influence of glass may cause larger errors. From the table, it can also be found that the peak pressure distribution on the walls and ceiling are different. For the scaled distance of $0.5 \text{m/kg}^{1/3}$, the peak pressure on the back wall are much larger.

Table 1. Comparison of peak pressure of two cases at different scaled distances.

| Position | Scale distance($\text{m/kg}^{1/3}$) | 0.5   | 1    | 2    |
|----------|-----------------------------------|-------|------|------|
|          | With glass                        | 0.144 MPa | 0.120 MPa | 0.091 MPa |
| A        | Without glass                     | 0.148 MPa | 0.125 MPa | 0.102 MPa |
|          | Error                             | 2.78%   | 4.17% | 12.1% |
|          | With glass                        | 0.163 MPa | 0.130 MPa | 0.111 MPa |
| B        | Without glass                     | 0.168 MPa | 0.140 MPa | 0.121 MPa |
|          | Error                             | 3.1%    | 7.7%  | 9.0%  |
|          | With glass                        | 0.122 MPa | 0.104 MPa | 0.088 MPa |
| C        | Without glass                     | 0.130 MPa | 0.112 MPa | 0.106 MPa |
|          | Error                             | 1.2%    | 7.7%  | 20%   |
|          | With glass                        | 0.561 MPa | 0.105 MPa | 0.081 MPa |
| D        | Without glass                     | 0.568 MPa | 0.112 MPa | 0.097 MPa |
|          | Error                             | 6.5%    | 6.7%  | 19.8% |

3.2. Distribution of Peak Overpressure on Building Wall
In order to study the difference in explosion loads, the contours of the overpressure peak value of each wall inside the building under different scaled distances are drawn in figures 3, 4 and 5. Figures 3, 4
and 5 show the distribution of peak pressure contour of the back wall, left wall and ceiling of the building at different scaled distances with and without glass. It can be seen found that: (1) The overpressure peaks at the four corners of each wall are much larger than those at other locations. The reason is that after the explosion shock wave propagates to the interior of the building, it passes through multiple reflections from the rigid wall and the rigid ground. Thus, the overpressure peak at each corner will be higher than other locations. (2) The overpressure peak of each wall with a scaled distance of 0.5 m/kg$^{1/3}$ is significantly higher than the overpressure peaks with a scaled distance of 1.0 m/kg$^{1/3}$ and 2.0 m/kg$^{1/3}$. The smaller the scaled distance, the greater is the explosive shock wave energy, and therefore the greater the peak overpressure acting on the building. (3) The smaller the scaled distance, the smaller is the barrier effect of the glass on the explosion load. The larger the scaled distance, the more obvious the barrier effect of the glass on the explosive load.

![Figure 3. Peak overpressure on the back wall at different scale distances.](image)

![Figure 4. Peak overpressure on the left wall at different scale distances.](image)
4. Conclusions
The LS-DYNA software is used to carry out numerical simulation analysis on typical buildings with and without glass subjected to explosion. The peak overpressure inside the building and the stress distribution of each wall under different conditions are comparatively analyzed. The study found that the peak pressure distribution is not proportional for different scaled distances. On the other hand, the smaller the scaled distance, the smaller the barrier effect of the glass on the explosive load.

Acknowledgments
This research was supported by the National Key R&D Program of China (2018YFB2100901).

References
[1] Ning J, Wang C and Ma T 2010 Explosion and Shock Dynamics Beijing National Defense Industry Press.
[2] Rogers G L 1959 Dynamics of Framed Structures John Wiley & Sons, Inc. New York pp80-91.
[3] Henrych J 1979 The Dynamics of Explosion and Its Use Amsterdam: Elsevier.
[4] Mills CA 1987 The design of concrete structure to resist explosions and weapon effects. Proceedings of 1st International Conference on Concrete for Hazard Protections Edinburgh UK p 61-73.
[5] Brode H L 1955 Numerical solution of spherical blast waves Journal of Applied Physics 26(6) 766-775.
[6] Smith P D and Rose T 2006 Blast wave propagation in city streets—an overview Progress in Structural Engineering and Materials 8(1) 16-28.
[7] Remennikov A M and Rose T A 2005 Modelling blast loads on buildings in complex city geometries Computers and Structures 83(27) 2197-2205.
[8] Lee E L, Hornig H C and Kury J W 1968 Adiabatic Expansion of High Explosive Detonation Products Report UCRL-50422 University of California Lawrence Radiation Laboratory Livermore CA USA.
[9] Holmquist T J, Johnson G R, Lopatin C, Grady D and Hertel E S 1995 High Strain Rate Properties and Constitutive Modeling of Glass Sandia National Labs Albuquerque USA.
[10] Hooper P A, Sukhram R A M, Blackman B R K and Dear J P 2012 On the blast resistance of laminated glass International Journal of Solids and Structures 49(6) 899-918.