Numerical Analysis and Theoretical Verification on the Dynamic Response of Typical Components under Explosion Load

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ABSTRACT: To analyze the response of float glass under explosion load, the model was developed by the method of FEM simulation combined with stress theory. The numerical simulation results show that the stress caused by the blast wave on the center of the glass panel is continuous, while the stress around the glass is instantaneous. The displacement on both sides of the glass is larger than that at the center and at the four corners of the glass. The effective stress at the center of the glass is 86.08 MPa by numerical simulation. However, the effective stress at the center of the glass is 87.75 MPa by theoretical calculation. The error rate between the simulation result and the theoretical result is only 1.90%. Therefore, it is proved that the theoretical expressions in this paper are reliable for calculating the effective stress of single float glass under explosion load.

1. INTRODUCTION

With more and more terrorist attacks in the city, the technology of explosion prevention and resistance is indispensable for building protection. During the terrorist attacks, destruction of structural components often occurs, such as wall failure, door failure, and window failure. Many researchers have studied failure behavior of the building. The window of a building is usually made of glass. Due to the brittle nature of glass, the damage of glass is much more serious than that of other two components. Thus, it is very important to study the limit of the stress of float glass under explosion load. Due to the high incidence of terrorist attacks in the city, the response and failure modes of the float glass under explosion load have attracted great attention.

For this reason, some scholars studied the dynamic response of the single glass window under explosion load. Blank et al. studied the influence of the loading mode, speed, and glass size on the static pressure resistance of glass by the four-point bending test. Veer et al. studied the tensile strength of float glass, semi-toughened glass, and toughened glass by the four-point bending test. The results show that the strength of semi-toughened glass is 1–2 times higher than that of float glass, and the strength of toughened glass is 3–4 times higher than that of float glass. Bedon et al. conducted full-size experiments and finite element numerical simulation on a glass column by a low-speed impact. By comparing the experimental results with the simulation results, it is found that although the data are different, they can represent the basic phenomenon, which has been verified by the simplified finite element model.

Pritchard and Weggel and Zapata studied the dynamic response of a single glass window under explosion load by the single-freedom simplified model in the form of triangular loads on glass panels. Weggel and Zapata also found that changing the boundary conditions can partly affect the dynamic performance of the components and that the explosion-proof of the glass panel supported by a rubber ring is much better than that of the glass panel supported by a simple support. Stewart and Netherton predicted the failure probability of single glass under explosion load by the single-freedom simplified model. The results show that the response of glass panels is different with different length/width ratios and different TNT equivalent weights. Makovicka and Lexa studied experimentally the dynamic response characteristics of the gas shock wave to a single glass plate, considering the influence of the pulse duration. Krauthammer and Altenberg evaluated the negative phase effect of the explosion wave on a single glass panel by the approximate numerical model. The results show that in the case of small packets exploding near or a large packet exploding far from the building, the negative phase effect of the blast wave can cause a large displacement of the glass back to the explosion. The authenticity of theoretical calculation can not only be verified by experiments, but numerical simulation based on theoretical

Received: September 7, 2020
Accepted: October 6, 2020
Published: October 20, 2020
derivation has also become an important means.\textsuperscript{10} Wang et al.\textsuperscript{11} proposed a new model and method, that is, “Separation of Nodes”, to analyze the fracture of brittle materials such as glass. The results show that this method does not cause the material quality loss and make the calculated value more exact. Yang et al.\textsuperscript{12} found that the rupture and dispersion of float glass are affected by the glass thickness and the methane concentration. In addition, the initial ejection speed of the shards is affected mainly by the glass thickness.

Some scholars have studied the damage of glass by the gas shock wave.\textsuperscript{13} For instance, Liu et al.\textsuperscript{14} experimentally investigated the dynamic response of laminated glass during a gas explosion. The results indicate that the PVB interlayer can bond the glass fragments together to restrain the flying effect. Furthermore, increasing the thickness of the glass and PVB layer helps the glass resist gas explosion. Amabili et al.\textsuperscript{15} investigated the nonlinear dynamic response of a laminated glass under explosion load by Friedlander’s model. Chen\textsuperscript{16} and Li and Yang\textsuperscript{17} simulated the dynamic response of a single tempered glass panel and laminated tempered glass panel by finite element analysis software. The results show that this software is reliable to simulate the problem related to explosion mechanics. Li and Ge et al.\textsuperscript{18,19} simulated the dynamic response of single glass under explosion load by LS-DYNA. Based on this, the explosion-proof design method of the glass curtain wall was determined.

From the above research studies, there are few research studies on the theoretical calculation of single glass under explosion load. In our research, the finite element method was used combined with stress theory to study the distribution of stress and displacement of building glass under explosion load. Therefore, a calculating system for calculating the dynamic stress value of single glass under explosion load is developed.

2. RESULTS AND DISCUSSION

To study the damage effect of high-energy explosives on the glass windows of buildings, the explosion-proof performance of single float glass at a short distance was studied by numerical simulation and theoretical calculation. At the center and on the side of the glass panel, seven panel units of 219,164 (measuring point 1), 182,680 (measuring point 2), 220,078 (measuring point 3), 202,794 (measuring point 4), 183,594 (measuring point 5), 221,038 (measuring point 6), and 184,554 (measuring point 7) are selected as measuring points, as shown in Figure 1. Through Ansys Autodyn, the stress values of seven measuring points with time were extracted, as shown in Figure 2. The maximum stress values of each measuring point are shown in Table 1.

![Figure 1. Measuring points on the front face of single float glass.](https://example.com/figure1.png)

![Figure 2. Effective stress curves of the float glass panel.](https://example.com/figure2.png)

Table 1. Maximum Effective Stress of Each Measuring Point of the Glass Panel

| Measuring point | Location of Measuring Point | Simulation Results |
|-----------------|----------------------------|--------------------|
| no. 1           | upper left                 | 59.71              |
| no. 2           | upper right                | 69.68              |
| no. 3           | left                       | 46.49              |
| no. 4           | center                     | 86.08              |
| no. 5           | right                      | 46.43              |
| no. 6           | lower left                 | 91.08              |
| no. 7           | lower right                | 75.68              |

![Displacement curve of the float glass panel.](https://example.com/figure3.png)

2.1. Effective Stress Law of Single Float Glass. Through the stress values of seven measuring points with time were extracted, as shown in Figure 2. The maximum effective stress values of each measuring point are shown in Table 1.

It can be seen from Figure 2 that the effective stress values of nos.1–3 and nos.5–7 measuring points reached the maximum value before $t = 0.8$ ms. Also, the effective stress decreased gradually with the increase in time. However, the effective stress

28352  
ACS Omega 2020, 5, 28351−28359  
https://dx.doi.org/10.1021/acsomega.0c04355  
ACS Omega http://pubs.acs.org/journal/acsonf  
Article
of no. 4 measuring point at the center fluctuated from 0 to 1.6 ms and reached the maximum value at $t = 1.1$ ms. This shows that the explosion pressure was continuously loaded at the center of the glass panel, but it was immediately loaded on the side of the
glass panel. It can be seen from Table 1 that the maximum effective stress values of no.1 measuring point to no.7 measuring point calculated by simulation were 59.71, 69.68, 46.49, 86.08, 46.43, 91.08, and 75.68 MPa, respectively.

2.2. Displacement of Single Float Glass. The displacements of seven measuring points were extracted, as shown in Figure 3.

It can be seen from Figure 3 that the displacement curve of seven measuring points increased linearly with time. The displacements of the measuring points on the sides of the glass were 12 and 18 cm. However, the displacements of the measuring points at the center and at the four corners were all less than 3 cm. Therefore, the deformation on two sides of the glass was greater than that at the center and at the corner of the glass. This is because the structure at the four corners and at the center of the square panel is more stable than that at the two sides. Thus, the deformation will start from the weak position on both sides and then gradually spread to the center.

2.3. Crushing Process of Single Float Glass. The crushing processes of float glass at different times are shown in Figure 4.

When \( t = 10 \) ms, the single float glass started to break from two sides. When the time was between 10 and 20 ms, the damage spread from both sides to the center of the glass. When \( t = 50 \) ms, the glass was broken seriously and it started to fall off the frame. When \( t = 125 \) ms, the glass broke into small pieces and flew outward.

### Table 2. Moment Coefficient

| \( l_i/l_h \) | \( J \) | \( l_i/l_h \) | \( J \) |
|----------------|--------|----------------|--------|
| 0.00           | 0.1250 | 0.70           | 0.0742 |
| 0.25           | 0.1230 | 0.75           | 0.0683 |
| 0.33           | 0.1180 | 0.80           | 0.0628 |
| 0.40           | 0.1115 | 0.85           | 0.0576 |
| 0.50           | 0.1000 | 0.90           | 0.0528 |
| 0.55           | 0.0934 | 0.95           | 0.0483 |
| 0.60           | 0.0868 | 1.00           | 0.0442 |
| 0.65           | 0.0804 |                |        |

### Table 3. Reduction Coefficient

| \( a_i \) | \( \eta \) | \( a_i \) | \( \eta \) |
|---------|--------|---------|--------|
| \( \leq 5.0 \) | 1.00   | 120.0   | 0.65   |
| 10.0    | 0.96   | 150.0   | 0.61   |
| 20.0    | 0.92   | 200.0   | 0.57   |
| 40.0    | 0.84   | 250.0   | 0.54   |
| 60.0    | 0.78   | 300.0   | 0.52   |
| 80.0    | 0.73   | 350.0   | 0.51   |
| 100.0   | 0.68   | \( \geq 400.0 \) | 0.50   |

3. VERIFICATION OF DYNAMIC STRESS THEORY FOR SINGLE FLOAT GLASS

3.1. Theoretical Calculation for Single Glass Panel under Explosion Load. The air explosion load is calculated as follows:

\[
P_{\text{in}} = 0.72 \left( \frac{\sqrt{Q_k}}{r_{bx}} \right)^3 + 0.30 \left( \frac{\sqrt{Q_k}}{r_{bx}} \right)^{1.5}
\]

where \( P_{\text{in}} \) is the peak overpressure of the incident shock wave in the air blast (MPa), \( Q_k \) is the TNT equivalent weight (kg), and \( r_{bx} \) is the distance between the calculated point and explosive core (m).

\[
0.014 \leq P_{\text{in}} \leq 0.50
\]

\[
t_i^+ = 1.01 \times 10^{-3} P_{\text{in}}^{0.313} \times Q_k^{1/3}
\]

\[
0.50 \leq P_{\text{in}} \leq 7.03
\]

\[
t_i^+ = 1.29 \times 10^{-3} P_{\text{in}}^{0.0536} \times Q_k^{1/3}
\]

\[
0.473 \leq \frac{r_{bx}}{\sqrt{Q_k}} \leq 7.60
\]

\[
i_{kr} = 1.65 \times 10^{-4} \left( \frac{\sqrt{Q_k}}{r_{bx}} \right)^{1.23} \times Q_k^{1/3}
\]

\[
0.210 \leq \frac{r_{bx}}{\sqrt{Q_k}} \leq 0.473
\]

\[
i_{kr} = 1.88 \times 10^{-4} \left( \frac{\sqrt{Q_k}}{r_{bx}} \right)^{1.06} \times Q_k^{1/3}
\]

\[
0.024 \leq \frac{r_{bx}}{\sqrt{Q_k}} \leq 0.210
\]

\[
i_{kr} = 2.79 \times 10^{-4} \left( \frac{\sqrt{Q_k}}{r_{bx}} \right)^{0.80} \times Q_k^{1/3}
\]

\[
0.0 \leq \frac{r_{bx}}{\sqrt{Q_k}} \leq 0.024
\]

\[
i_{kr} = 5.51 \times 10^{-3} \times Q_k^{1/3}
\]

\[
\tau_k = 3.15 \times 10^{-4} p_m^{-0.5} \times Q_k^{1/3}
\]

where \( t_i^+ \) is the positive pressure time of the incident shock wave in the air blast (s), \( i_{kr} \) is the impulse of the incident shock wave (N·s/mm²), \( \tau_k \) is the equal impulse equivalent action time of the impulse of the incident wave (s), \( P_{\text{in}} \) is the peak overpressure of the incident wave (MPa), \( Q_k \) is the TNT equivalent weight (kg), and \( r_{bx} \) is the distance between the calculated point and explosive core (m).
For convenience of calculating the stress of the components under explosion load, the dynamic load waveform, the explosion wave, is simplified as triangular load without boost time. 

\[ t_{sp} = \left( \frac{1 + 0.86 P_m^{1.63}}{1 + 1.58 P_m^{1.63}} \right) \times \tau \]  

(9)

where \( t_{sp} \) is the equivalent time of dynamic load (s), \( \tau \) is the equal impulse equivalent time of the impulse of the incident wave, \( \tau_i \) or \( \tau_d \) is selected according to the explosive position (s), and \( P_{mk} \) is the peak overpressure of the incident shock wave in the air blast (MPa).

\[ P_m \leq 2 \text{ MPa} \]

\[ n_{pm} = 2 + \frac{6 P_{pm}}{0.7 + P_{pm}} \]  

(10)

\[ 2 \text{ MPa} \leq P_m \leq 20 \text{ MPa} \]

\[ n_{pm} = 5.57 \times P_m^{0.216} \]  

(11)

\[ 20 \text{ MPa} \leq P_m \leq 100 \text{ MPa} \]

\[ n_{pm} = 7.47 \times P_m^{0.118} \]  

(12)

where \( n_{pm} \) is the reflection coefficient of the incident shock wave.

\[ P_f = P_m \times n_{pm} \]  

(13)

where \( P_f \) is the reflection overpressure of the explosion shock wave on the glass (MPa), \( n_{pm} \) is the reflection coefficient of the incident shock wave, and \( P_{mk} \) is the peak overpressure of the incident shock wave in the air blast (MPa).

The dynamic stress of the single float glass panel under explosion load was calculated as follows:

\[ \sigma_d = \frac{6 q_i l_s^2}{h_{bd}^2} \times \eta \]  

(14)

where \( \sigma_d \) is the center stress on the single float glass panel under explosion load (MPa); \( l_s \) is the length of the short side (m); \( l_l \) is the length of the long side (m); \( h_{bd} \) is the thickness of the glass panel (mm); \( f \) is the moment coefficient, which is selected by the ratio of \( l_s \) to \( l_l \); \( q_i \) is the equivalent static load perpendicularly to the glass, which is obtained from eq 16 (N/m^2); \( \eta \) is the reduction coefficient, which is selected in Table 3 according to \( \theta_f \) and \( \theta_{fi} \) is the calculation parameters of the reduction coefficient, which is obtained from eq 15.

\[ \theta_f = \frac{q_i l_s^2}{q_i h_{bd}^2} \times \frac{l_i}{l_l} \times \frac{\Omega \gamma}{(1 - \mu_i^2) P_f} \]  

(15)

where \( \theta_f \) is the calculation parameters of the reduction coefficient and \( q_i \) is the elastic modulus of the glass material (\( e_{bd} = 7.2 \times 10^5 \text{ kg/m}^2 \)).

\[ q_i = \frac{1}{\sqrt{d_i^2 - 1} \times w_{eq} + \frac{2a - 1}{2a} \times \frac{q_{i}}{w_{eq}} + 1} \]  

(16)

where \( q_{i} \) is the equivalent static load perpendicularly to the glass, which is obtained from eq 16 (N/m^2); \( P_f \) is the reflection overpressure of the explosion shock wave on the glass (MPa); \( u \) is the allowable ductility ratio of single float glass (\( u = 11 \)); \( w_{di} \) is the self-vibratory frequency of single float glass, which is obtained from eq 17 (1/s); and \( t_{sp} \) is the equivalent time of dynamic load (s).

\[ w_{di} = \frac{\Omega \gamma}{12(1 - \mu_i^2)} \times \frac{g}{\eta h_{bd}} \]  

(17)

where \( w_{di} \) is the self-vibratory frequency of single float glass (1/s); \( \Omega \) is the self-vibratory frequency coefficient, which is selected by the ratio of \( l_s \) to \( l_l \) in Table 4; \( \mu_i \) is Poisson’s ratio (\( \mu_i = 0.2 \)); \( \gamma \) is the bulk density of glass (\( \gamma = 2500 \text{ kg/m}^3 \)); and \( g \) is the acceleration of gravity (m/s^2).

When the explosive quantity is 0.5 kg, \( Q_i \) is taken as 0.5 kg. When the explosion distance is 0.5 m and the explosion height is 0.5 m, \( r_{ax} \) is taken as 500 mm. According to eq 1–13, the reflection overpressure of the explosion shock wave on the glass is 4.46 MPa.

When the length of the short side is 0.5 m and the length of the long side is 1 m, \( l_s \) and \( l_l \) are taken as 500 and 1000 mm, respectively. When the thickness of the glass panel is 5 mm, \( h_{bd} \) is taken as 5 mm. According to eqs 14–17, the center stress on the single float glass panel under explosion load is 87.75 MPa.

### 3.2. Comparison of Theoretical Calculation and Simulation Results

The comparison results of simulation calculation and theoretical calculation are shown in Table 5. The error rate was calculated from eq 18, seen in Table 5.

\[ \alpha = \frac{\sigma_{di} - \sigma_{dm}}{\sigma_{di}} \times 100\% \]  

(18)

where \( \alpha \) is the error rate, \( \sigma_{di} \) is the stress by theoretical calculation (MPa), and \( \sigma_{dm} \) is the stress by simulation calculation (MPa).

As can be seen from Table 5, the maximum effective stresses calculated by simulation at measuring points were 69.68, 46.43, 75.68, 86.08, 59.71, 46.49, and 91.08 MPa. In addition, the effective stress calculated by theory was 87.75 MPa. The location of the theoretical calculation point was at the center of the panel, which is the same as that at the measuring point 4. Therefore, the error rate of these two is 1.90%. In conclusion, this theoretical calculation result can reliably analyze the dynamic characteristics of single float glass under explosion load.

### 4. CONCLUSIONS

In this paper, the dynamic characteristics of single float glass under explosion shock waves were studied by finite element numerical simulation and theoretical analysis of explosion mechanics.

1. The effective stresses of seven different measuring points were calculated by FEM simulation. The maximum value is 91.08 MPa and the minimum value is 46.43 MPa.

2. The displacements of the measuring points on both sides of the glass were 12 and 18 cm. However, the displacements of the measuring points at the center and at the four corners were all less than 3 cm. It is proved that the glass started to warp from both sides under explosion shock waves consistent with the reality.
(3) The stress calculated by simulation of the point at the center was 86.08 MPa. Also, the stress calculated by theory was 87.75 MPa. Thus, the error rate between two values is 1.90%. It is proved that this theoretical calculation is reliable.

5. MODELS, MATERIAL PARAMETERS, AND VERIFICATION

5.1. Physical Model. The explosive is TNT with 1630 kg/m³. It is spherical in shape with a radius of 24.47 mm and a mass of 0.1 kg. The explosive is initiated at the central point. The material parameters are shown in Table 6. The size of the float glass model is 1000 mm high, 500 mm wide, and 5 mm thick, and its material parameters are shown in Table 8. The explosive is located at the central axis of the glass plate. Also, the horizontal distance between float glass and TNT is 500 mm, shown in Figure 5.

In order to improve the computational efficiency and to ensure the rationality of the results, the mesh size is increased as much as possible and the mapping grid is divided. The mesh size of the glass model is 5 mm. The air domain is divided by a progressive mesh with 5 mm.

The damage of glass under explosion load is affected by many factors, but for numerical simulation, it is impossible to fully consider all the influencing factors. In order to facilitate the simulation, the basic assumptions are as follows.

The nonreflecting boundary conditions were used around the air domain. The influence factors of temperature and humidity on explosion were not taken into account. Numerical simulation was carried out under ideal conditions.

5.2. Material Models. 5.2.1. Material Model and Parameters of Explosive. TNT explosive was used. The parameters are shown in Table 6.

The flow behaviors of gas products after explosion will lead to the change of pressure and volume. The JWL (Jones–Wilkins–Lee) state equation was used to describe the relationship between pressure, volume, and internal energy after the detonation C-J state. The JWL state equation is as follows

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

where \( P \) is the pressure (GPa); \( E \) is initial specific internal energy (GPa); \( V \) is the relative volume of detonation products; \( A, B, R_1, R_2, \) and \( \omega \) are the explosive parameters. The parameters of TNT explosive used during the simulation are shown in Table 6.

5.2.2. Material Model and Parameters of Air. The air is calculated as Euler 3D with a linear polynomial equation of state as follows

\[ P = (\gamma - 1) \rho E + P_{\text{shift}} \]  

where \( P \) is the pressure on the air (GPa); \( E \) is the initial internal energy per volume; \( \gamma \) is the adiabatic constant for air considered an ideal gas and equal to 1.4; and \( P_{\text{shift}} \) is the pressure offset. The parameters of air used during the simulation are shown in Table 7.

5.2.3. Material Model and Parameters of Glass. The float glass was calculated by the JH-2 model as follows

\[ P = K \mu + K_2 \mu^2 + K_3 \mu^3 \]  

where \( K_1 \) is the bulk moduli of float glass (MPa), \( K_2 \) and \( K_3 \) are the material constants, \( P \) is the hydrostatic pressure (GPa), and \( \mu \) is the volumetric strain.

The dimensionless strength model is as follows

\[ \sigma^* = \sigma^* - D (\sigma^* - \sigma_0^*) \]  

Table 7. Physical and EOS Parameters of Air

| material | \( \rho \) (kg/m³) | \( \gamma \) | \( E_0 \) (MPa) |
|----------|------------------|---------------|----------------|
| air      | 1.225            | 1.4           | 2.068 \times 10^5 |

Table 8. Material Parameters of Float Glass

| material | \( \rho \) (kg/m³) | G (GPa) | A | B  | C  | M  | N  | EPSI | T (GPa) | SFMAX | HEL (GPa) | \( P_{\text{HEL}} \) (GPa) | B |
|----------|------------------|---------|----|----|----|----|----|------|---------|-------|------------|-----------------------|---|
| glass    | 2530             | 30.4    | 0.93 | 0.088 | 0.003 | 0.35 | 0.77 | 1.0   | 0.065   | 0.5   | 5.95       | 2.92                  | 1.0 |
When \( D = 0 \), the material is not damaged, and the dimensionless equivalent stress is as follows

\[
\sigma^* = \alpha (p^* + \sigma_{\text{eq}}) + \left[ 1 + C \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right] \quad (23)
\]

When \( D = 1 \), the material is pretty smashed, and the dimensionless equivalent stress is as follows

\[
\sigma^* = \beta (p^*)^M + \left[ 1 + C \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right] \quad (24)
\]

where \( \sigma_{\text{eq}}^\text{max} \) is the maximum breaking strength of the material (MPa); \( \alpha, \beta, C, M, \) and \( N \) are the material constants; \( p^* \) is the dimensionless hydrostatic pressure \( (p^* = P/P_{\text{HEL}}) \). \( \dot{\varepsilon} \) is the real strain rate, \( \dot{\varepsilon}_0 \) is the reference strain rate, \( \dot{\varepsilon}/\dot{\varepsilon}_0 \) is the dimensionless strain rate. The parameters of glass used during the simulation are shown in Table 8.

### 5.3. Model Validation and Feasibility

Wu \(^21\) obtained the peak overpressure generated by explosion by numerical simulation and by the experiment. The specific steps of the experiment are as follows. TNT (1 kg) was placed in the air domain. Thirteen measuring points were set at the level of the explosive. The distance between measuring points (1–5 m from the explosive) is 0.5 m. The distance between measuring points (6–10 m from the explosive) is 1 m. The specific steps of the simulation are as follows. A 1D wedge model was established in the air domain. TNT was filled at the apex of the air model and initiated at the central point. Sixteen measuring points were set in the simulation.

In this paper, the comparative numerical simulation was carried out according to the conditions in the literature. A 1D wedge model with a bus length of 16,000 mm was established in the air domain. The length of the grid is 8 mm in the X direction. In order to ensure the accuracy of the verification results, the explosive and its near field are meshed refining. To ensure the simulation results not affected by the reflected wave, the boundary condition is set to outflow. The time—history curves of overpressure are shown in Figures 6 and 7.

The simulation results in this paper were compared with those in the literature, as shown in Table 9.

Curves obtained from data in Table 9 are shown in Figure 8 to observe its fitting. It can be seen from Figure 8 that the trend of the peak overpressure curve of the experiment in Wu’s literature and the simulation in Wu’s literature is exactly the same as that of the simulation in this paper. In addition, most of the errors are less than 1%, and the error rate decreases with the increase in distance. It can be proved that the simulation results are in good agreement with the actual overpressure results. Therefore, the calculation and simulation methods in this paper are correct.

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### Table 9. Comparison of Overpressure between Simulation and Experiment

| distance (m) | experimental data of Wu (kPa) | simulated data of Wu (kPa) | theoretical data (kPa) | simulated data of this paper (kPa) | error rate (compared with the experiment) | error rate (compared with the simulation) |
|--------------|--------------------------------|----------------------------|------------------------|------------------------------------|------------------------------------------|------------------------------------------|
| 1.0          | 1054.0                         | 728.7                      | 1029.0                 | 801.1                              | 24.0%                                    | 9.9%                                     |
| 1.5          | 383.0                          | 285.7                      | 376.6                  | 285.2                              | 25.5%                                    | 0.2%                                     |
| 2.0          | 197.0                          | 154.9                      | 196.1                  | 145.8                              | 25.9%                                    | 5.8%                                     |
| 2.5          | 122.0                          | 98.7                       | 122.0                  | 98.9                               | 18.9%                                    | 0.2%                                     |
| 3.0          | 84.0                           | 69.7                       | 84.4                   | 70.6                               | 15.9%                                    | 1.3%                                     |
| 3.5          | 62.3                           | 53.4                       | 62.6                   | 53.3                               | 14.4%                                    | 0.2%                                     |
| 4.0          | 48.5                           | 42.3                       | 48.8                   | 39.0                               | 19.5%                                    | 7.8%                                     |
| 4.5          | 39.7                           | 34.7                       | 39.3                   | 33.9                               | 14.6%                                    | 2.3%                                     |
| 5.0          | 33.2                           | 29.2                       | 32.6                   | 28.9                               | 12.9%                                    | 1.0%                                     |
| 5.5          | 25.1                           | 21.7                       | 27.6                   | 24.1                               | 11.7%                                    | 3.9%                                     |
| 6.0          | 24.7                           | 21.8                       | 23.7                   | 21.8                               | 11.7%                                    | 0.0%                                     |
| 6.5          | 19.3                           | 17.3                       | 20.7                   | 18.7                               | 12.2%                                    | 3.1%                                     |
| 7.0          | 19.6                           | 17.3                       | 18.3                   | 17.2                               | 12.2%                                    | 0.6%                                     |
| 7.5          | 15.6                           | 15.6                       | 16.3                   | 15.5                               | 13.0%                                    | 0.7%                                     |
| 8.0          | 16.1                           | 14.1                       | 14.7                   | 14.0                               | 13.0%                                    | 0.7%                                     |
| 9.0          | 12.1                           | 12.1                       | 11.8                   | 11.8                               | 0.9%                                     | 0.9%                                     |
| 10.0         | 11.8                           | 10.2                       | 10.2                   | 10.1                               | 14.4%                                    | 0.9%                                     |

Figure 7. Time—history curves of overpressure (measuring points 9–17).
Figure 8. Contrast between overpressure curves by simulation and experiment.

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Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

We would like to thank Dr. X. Wang and Dr. Y. Sun for informative discussion.

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