The analysis of the equivalent bare charge of aluminum cased charge exploding in confined space

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Abstract: The blast loadings from a cased charge, which include a cluster of fragments and shock waves, would cause severe damage to the structures, especially in the scenario of a confined space. In this paper, experiments of the dynamic response of steel plates subjected to the confined blast loading from a cased charge were performed, in which two set warhead models of aluminum cased TNT charge were employed. By using the explicit dynamic code AUTODYN and the Smoothed Particle Hydrodynamic (SPH) method, the rapture process of the aluminum shell was reproduced and the equivalent bare charge was determined by analyzing the results from numerical simulations. In addition, the dynamic response of steel plates subjected to confined blast loadings from cased charges were calculated numerically. Then, the method for calculating the equivalent bare charge that related to the deflection of blast loaded plates was proposed. In addition, this method was further used to determine the approximate mass of TNT charge that contributing to the blast loading of shock wave and subsequent quasi-static pressure in the confined space, in which the energy released by the burning of the detonation products and aluminum shell were taken into account. The present paper presented a reliable method to analyze the response of steel plates under confined blast loadings from a cased charge, which would be useful in the design of the protective structures.

1. Introduction

The damage to the structure is mainly caused by the blast wave and fragments when the cased charge explodes in a confined space [1, 2]. For the structures close to the warhead, the coupling of shock wave and fragments would lead to more severe damage effect. For the loads from warhead explosion, the following three aspects are concerned, (1) fragment velocity [3-6], (2) spatial and mass distribution of fragments [7-11] and (3) shock wave effect [12, 13]. However, few researches on the shock wave effect from equivalent bare charge of warhead in the confined space were reported, in which the damage effect on surrounding structures caused by the cased charge is more complex and severe. Generally, in order to evaluate the shock wave effect from a cased charge, the equivalent bare charge, which is defined as that quantity of the explosive that yields the same value of the free air blast...
parameter of interest as the cased charge at the same distance from the detonation point, should be firstly determined [14]. Some empirical formulas [14-16] for determining the equivalent bare charge from a cased charge were proposed, which were based on the energy or momentum method. However, these formulas are usually appropriate for the free air blast conditions. Their applicability in confined explosions should be further verified, before used in practice.

When it comes to the blast loadings in a confined space, there are many factors that affect the load characteristics should be taken into consideration [17, 18], such as the type of explosive, the dimension of the confined space and the influence of afterburning effect, etc., which make the evaluation of confined blast loading more complicated than blast loadings from free air explosions. However, in the design stage of the protective structure, it is essential to provide an accurate input load for evaluating the structural integrity and damage degree when subjected to blast loadings from a cased charge exploding in the confined space.

In this paper, the experiments of two warhead models of aluminum cased TNT charge detonating in a fully confined chamber were performed. In addition, the numerical simulations of the rapture process of the shell and the formation of fragments were conducted, to determine the initial energy transferred from TNT charge to the aluminum shell. Then, by comparing the deflection changes of plates subjected to the blast loadings from cased charge and bare charge, the influence of the energy releases from the afterburning of the detonation products and aluminum on the confined blast loadings were analyzed. Then, the calculation method of the equivalent bare charge contributed to the deflection of blast loaded plates was proposed.

2. Experimental tests and results

2.1. Experimental setup and loading conditions

An experimental setup was employed to detonate an aluminum shell warhead model in a fully confined chamber, which was a hollow box with both ends uncovered, and the test plates were clamped at both ends, as shown in figure1. The inner dimensions of the chamber were 1800 mm × 800 mm × 800 mm. In each test, a cylindrical explosive charge of TNT shelled by aluminum was hung in the center of the chamber and detonated to generate blast loading on the specimen. Specimens of steel plates were peripherally clamped along four edges between the clamping frames and supported by 36 M16 bolts at each end of the chamber. The target plate was square with dimensions of 1100 mm × 1100 mm × 4.7 mm, and the area exposed to the explosion after clamping was 800 mm × 800 mm. The hollow box of the chamber was tightly bolted to the ground base to limit the global displacement. In this series of tests, steel plates were made from Q235 mild steel. The mechanical properties were obtained by in-house quasi-static tensile tests using standard tensile specimens and procedures, as listed in table 1.
Figure 1. Schematic of confined chamber and test specimen.

Table 1. Mechanical properties of the steel plates.

| Density / (kg/m$^3$) | Young's Modulus/GPa | Poisson's ratio | Yield strength/MPa | Hardening Modulus/MPa |
|----------------------|---------------------|----------------|-------------------|-----------------------|
| 7850                 | 209.4               | 0.28           | 341               | 550                   |

The warhead model was actually a cylindrical aluminum shell filled with TNT charge, as shown in figure 2. In the test, a detonator with equivalent energy of 1g TNT was used to initiate the explosive. The aluminum shell was assembled by an upper plate and a hollow cylinder. The two parts were connected by 4 M4 countersunk screws. A hole was drilled in the upper plate to install the detonator, ensuring the detonator tightly contact with the TNT charge. Two different charges were involved in the tests, and the specific sizes listed shown in the table 2.

Figure 2. Aluminum shell warhead.

Table 2. Load cases of experimental tests.

| Case | Charge Mass/g | Charge Height /mm | Charge Diameter /mm | Aluminum case Mass/g | Aluminum case Inner height/mm | Aluminum case Inner diameter/mm |
|------|--------------|-------------------|---------------------|----------------------|-------------------------------|--------------------------------|
| #1   | 149.0        | 48.2              | 50.4                | 110.4                | 48.5                          | 50.5                           |
| #2   | 200.0        | 64.7              | 50.3                | 130.5                | 64.5                          | 50.5                           |
Figure 3 shows a schematic of the overall experimental configuration. The aluminum cased TNT charge was firstly hung at the center of the chamber, and then the test plates were clamped to the ends of the chamber to form the fully confined space. Finally, the detonator was triggered by the wire leading out from the small hole at the top of chamber.

![Figure 3. Schematic of experimental configuration (mm).](image)

2.2. **Experimental results and discussion**

After the aluminum warhead detonated, the clamped plate on one side of the experimental setup was removed. It is found that the inner walls of the whole chamber were covered by white powder, as shown in figure 4. Generally, pure aluminum is silvery white. In the chemical reaction, when burned in oxygen, dense white oxide layer of aluminum oxide will be produced. Moreover, aluminum oxide itself has good thermal stability and will not decompose at high temperature. The only possibility is that aluminum oxide can be electrolyzed to produce aluminum and oxygen in the molten state. Obviously, such conditions cannot be achieved in this confined chamber. It was reasonable to speculate that the white substance inside the chamber was aluminum oxide.

![Figure 4. Internal circumstance of chamber after test.](image)

When further observed the interior of the chamber, it can be found that there was no fragment, instead of craters on the wall, as shown in figure 5. The white aluminum oxide accumulated around these craters, which was the particles impacted on the structure. The melting points of aluminum and aluminum oxide are 660°C and 2054°C, respectively, which indicated that when the aluminum case was ruptured by abruptly expanded TNT charge, aluminum, even aluminum oxide on the surface were melted under high temperature. In addition, a part of the melted aluminum would further burn in the
confined space, and the high temperature fragments strike the wall, cratering the chamber wall without any perforations. After the experiments, there was no solid aluminum fragment found inside the chamber, only some small particles of aluminum oxide were observed.

![Figure 5](image1.png)

**Figure 5.** Craters on the inner walls of chamber.

However, when the fragments hit the thinner target plate clamped at the end of the chamber, the phenomena was slightly different. The kinetic energy and internal energy of the fragments were not high enough to totally penetrate the steel plate, but caused a group of bulges instead, as shown in figure 6. In addition, it is found that the bulges were asymmetrically distributed along the height direction of the plate as expected, but grouped at 50–130 mm below the horizontal center line, due to the fact that the initiation point located at the top of the cased charge and the expansion velocities of the different locations along the shell altered accordingly.

![Figure 6](image2.png)

**Figure 6.** Bulges on the outside of the target plate (mm).

The final deflection of the plate after the test was measured by a laser scanner with accuracy of 0.1mm, as shown in figure 7. Although the fragment would produce bulges in the local area, they had limited influence on the overall deflection mode of the plates, which characterized by a global uniform
dome with the maximum deflection at the center of plates. The maximum deflections of the specimens are listed in table 3.

![Laser scanning contour of case # 1 (mm).](image)

Table 3. Permanent mid-point deflections of the plates.

| Case | Thickness/mm | Mid-point deflection/mm |
|------|--------------|-------------------------|
| # 1  | 4.7          | 42.3                    |
| # 2  | 4.7          | 46.8                    |

3. Numerical simulations

3.1. Rapture process of the aluminum case.

3.1.1. Numerical modeling. Explosively driven fragmentation of ductile metals is a very complex phenomenon in which the fragmenting material is plastically deformed by the intense shock followed by high-rate plastic deformation that ultimately leads to fracturing. In this section, in order to evaluate the energy consumed by the shell and fragments, numerical simulations of deformation and fracture process of the cased charge were performed. The numerical models were developed by employing the finite difference engineering package AUTODYN, which is especially good at nonlinear dynamic problems and is widely used in the field of high-speed impact and explosion. In addition, the Smoothed Particle Hydrodynamic (SPH) method was employed, which is based on a gridless Lagrangian hydrodynamics using particles. The most attractive point of the SPH method is that it gets rid of the computation termination due to the possible large element distortion inherent in other
Lagrangian formulation based on finite element methods. The special feature of the SPH method is very advantageous to solve the problem concerning the large deformation and rapture of the shell.

Due to the symmetry of the structure, a quarter symmetric model is allowed, as shown in figure 8. The Y axis is the height direction of the warhead, and the red mark point is the initiation point. The model is established according to the actual schematic and size. Both the aluminum case and the TNT charge were meshed by the SPH particles. Several different particle sizes were studied and finally a diameter of 1.0 mm was chosen, resulting in 220152 particles for case and 234880 particles for TNT charge, respectively.

**Figure 8.** Quarter model of cylindrical warhead.

### 3.1.2. Constitutive equation and failure criterion

The elastic-plastic behavior of aluminum under high pressure and high strain rates was considered with Steinberg-Guinan constitutive model, which takes pressure, temperature and strain rate as variables of yield strength and shear modulus. The dynamic yield strength and shear modulus determined by Steinberg-Guinan constitutive model are expressed as follows,

\[
G = G_0 \left[ 1 + \left( \frac{G_p}{G_0} \right) \frac{p}{\eta} + \left( \frac{G_t}{G_0} \right) (T - 300) \right]
\]

\[
Y = Y_0 \left[ 1 + \left( \frac{Y_p}{Y_0} \right) \frac{p}{\eta} + \left( \frac{G_t}{G_0} \right) (T - 300) \right] (1 + \beta \varepsilon)^n
\]

where \( G_0 \) and \( Y_0 \) are the initial shear modulus and yield strength, respectively, \( \beta \) and \( n \) are the material strain hardening coefficient and the hardening index, \( \varepsilon \) is effective plastic strain, \( T \) is temperature (degrees K), \( p \) is pressure, \( \eta \) is compression, \( G_p, G_t \), and \( Y_p \) are derivative \( dG / dp, dG / dt \) and \( dY / dp \), respectively. The detailed parameters are listed in table 4.
Table 4. Steinberg-Guinan constitutive model parameters of aluminum.

| Parameters                | Units  | Value     |
|---------------------------|--------|-----------|
| Shear modulus             | kPa    | $2.76 \times 10^7$ |
| Initial yield stress      | kPa    | $2.9 \times 10^5$ |
| Maximum yield stress      | kPa    | $6.8 \times 10^5$ |
| Hardening constant        | -      | 125       |
| Hardening exponent        | -      | 0.1       |
| Derivative $dG/dp$        | -      | 1.8       |
| Derivative $dG/dt$        | kPa/K  | $-1.7 \times 10^4$ |
| Derivative $dY/dp$        | -      | 0.0189    |
| Melting temperature       | K      | $9.3 \times 10^2$ |

The Grady Spall model was employed to define the dynamic spallation of metals under shock loading. The critical spall stress for a ductile material can be calculated according to the following formula,

$$ S = \sqrt{2 \rho c^2 Y \varepsilon_c} $$

where $\rho$ is the density, $c$ is the bulk sound speed, $Y$ is the initial yield stress, $\varepsilon_c$ is a critical strain value. The detailed parameters are listed in table 5.

Table 5. Grady Spall failure model parameters of aluminum.

| Parameters                | Units | Value/ State |
|---------------------------|-------|--------------|
| Critical strain value     | -     | 0.35         |
| Stochastic failure        | -     | YES          |
| Stochastic variance       | -     | 16           |
| Minimum fail fraction     | -     | 0.1          |
| Distribution type         | -     | Random seed  |

The JWL state equation is adopted for the charge in the case, and its pressure form is expressed as follows,

$$ p = A \left( 1 - \frac{\omega}{r_1 v} \right) e^{-r_1 v} + B \left( 1 - \frac{\omega}{r_2 v} \right) e^{-r_2 v} + \frac{\omega e}{v} $$

where $A$, $B$, $r_1$, $r_2$ and $\omega$ are the characteristic parameters of the equation, $v$ is the relative volume, $e$ is the initial internal energy per unit volume of the explosive. The detailed parameters are...
listed in table 6.

Table 6. Grady Spall failure model parameters of aluminum.

| Parameters                        | Units   | Value |
|-----------------------------------|---------|-------|
| Density                           | g/cm³   | 1.55  |
| Characteristic parameter $A$      | GPa     | 373.77|
| Characteristic parameter $B$      | GPa     | 3.7471|
| Characteristic parameter $r_1$    | -       | 4.15  |
| Characteristic parameter $r_2$    | -       | 0.9   |
| Characteristic parameter $\omega$ | -       | 0.35  |
| Initial internal energy per unit volume | GJ/m³ | 5.235 |

3.1.3. Rapture process of the aluminum case. In the numerical simulation, the volume expansion of the TNT charge and its transformation into highly pressurized products drives the aluminum case to expand and eventually rupture, as shown in figure 9. At first, deformation occurs at the end of the case under instantaneous high temperature and pressure. With the increase of expansion, the plastic deformation of the material increases gradually, and failure occurs when the maximum fracture strain is reached. Then, the shock wave reaches the other end. Under the superposition of the initial shock wave and the reflected shock wave, the more serious damage effect occurs at the other end. At last, there are cracks on the case, which has obvious circumferential expansion while the expansion near the other end of the initiation point is larger, and the case ends mainly appear normal deformation.

![Figure 9](image_url)  
*Figure 9. Expansion and rapture process of the case.*

Because of the inherent Lagrangian property of SPH algorithm, the state of each point can be easily captured in the numerical simulation. The gauge points distributed on the case are shown in figure 10, among which #6-#21 gauge points are evenly arranged on the side wall of the case. The stable velocity of these gauge points after 1 ms of explosion can be obtained, as listed in table 7.
In the numerical simulation, the x-axis representative the length direction of the chamber, and the y-axis is the height direction. The length of the chamber is 1800mm, that is, the actual flying distance of fragments is 900mm. Then the flying time of fragments can be obtained. It is noted that the whole process of dispersion of fragments took few milliseconds, so the falling of fragments under the gravity will be less than 1mm in this period. According to the time and the initial velocity in y direction, the distance of fragments away from the center line in the height direction can be obtained. It can be found that most of the fragments are located below the horizontal center line. In other word, most of the fragments strike the plate location is at 36-126mm below the center. This result is consistent with the data from tests.

Table 7. Velocity and displacement of Gauge #6-#21.

| Gauge | Velocity in X direction/(m/s) | Velocity in Y direction/(m/s) | Time/ms | Displacement in Y direction/m |
|-------|------------------------------|------------------------------|---------|-----------------------------|
| #6    | 1358.890                     | -190.590                     | 0.662   | -0.126                      |
| #7    | 1355.220                     | -189.935                     | 0.664   | -0.126                      |
| #8    | 1493.790                     | -80.714                      | 0.602   | -0.049                      |
| #9    | 1493.730                     | -82.780                      | 0.603   | -0.050                      |
| #10   | 1499.750                     | -86.297                      | 0.600   | -0.052                      |
| #11   | 1507.250                     | -86.303                      | 0.597   | -0.052                      |
| #12   | 1515.650                     | -86.783                      | 0.594   | -0.052                      |
| #13   | 1523.090                     | -84.640                      | 0.591   | -0.050                      |
| #14   | 1526.200                     | -84.084                      | 0.590   | -0.050                      |
| #15   | 1528.480                     | -83.297                      | 0.589   | -0.049                      |
| #16   | 1530.390                     | -82.931                      | 0.588   | -0.049                      |
| #17   | 1469.260                     | -77.285                      | 0.613   | -0.047                      |
| #18   | 1376.390                     | -56.102                      | 0.654   | -0.037                      |
| #19   | 1378.350                     | -54.386                      | 0.653   | -0.036                      |
| #20   | 1280.990                     | 124.036                      | 0.703   | 0.087                       |
| #21   | 1171.680                     | 170.980                      | 0.768   | 0.131                       |

From the numerical simulations, the detailed information of fragment velocities and the energy change of aluminum case and TNT charge can be clearly reflected. The aluminum case gained the
internal energy and kinetic energy from the explosion of the TNT charge when it converted into detonation products with high temperature and pressure. Based on the consideration of energy transformation, the equivalent bare charge can be obtained by subtracting the internal and kinetic energy of aluminum from total energy of the TNT charge, as listed in table 8. The results show that the equivalent bare charges of the two cased charge are 71.5 g and 108.9 g, respectively.

| Case                                      | #1        | #2        |
|-------------------------------------------|-----------|-----------|
| Initial energy of Explosive/J             | 5.66×10⁵  | 7.55×10⁵  |
| Total energy of aluminum after explosion/J| 2.96×10⁵  | 3.44×10⁵  |
| Residual energy of explosive/J            | 2.70×10⁵  | 4.11×10⁵  |
| Equivalent bare charge of explosive/g     | 71.5      | 108.9     |

3.2. Response of steel plates subjected to confined blast loadings
After obtaining the equivalent bare charge of the cased charges, the confined blast load and subsequent dynamic response of plate were analyzed numerically by employing AUTODYN code combining with Eulerian-Lagrangian fully-coupling method. In the numerical simulations, the energy release from afterburning effect of detonation products was considered. This method was detailedly described and validated in our previous research [19].

3.2.1. Numerical modeling. Lagrangian mesh was used for plates and bolts, and Eulerian grid was used for air domain. figure11 shows the discrete pattern of the fixture frame, the clamping area and the target plate, in which the bolts were discreted by solid element, while the frame and the target plate were discreted by shell elements.

The bolts were constrained in all six degrees of freedom to fix the structure. The inner clamp frame was set as a rigid body, and the pressure was applied on the outer clamp frame to simulate the clamping force provided by the bolts. For the target plate, the possible movement was constrained by the interaction force from the frame and bolts. Considering the possible slip between structures, a friction coefficient 0.2 was introduced into the contact faces. Then, the shell element around the bolts were refined to ensure the reasonable detection of interaction algorithm. The entire numerical model was shown in figure12. As the chamber walls are made of thick high strength steel and enhanced by stiffeners, they were hardly deformed in the experiments. In the numerical simulations, the non-flow boundary condition was applied to the surfaces of air volume corresponding to chamber walls, and flow-out boundary was adopted for the other surfaces.
The mesh convergence studies of the model were performed, as shown in figure 13. Five different grid sizes were selected for the 800 × 800 mm area in the center of the target plate. Considering the balance between accuracy and time cost, the scheme of mesh density of 80×80 was selected for the numerical simulations, in which the mesh dimension is 10 × 10 × 10 mm in air volume.

3.2.2. Constitutive equation and failure criterion. The Johnson–Cook constitutive relation was selected to model the dynamic behavior of the target plates, which considered the yield stress as a function of
strain rate and temperature.

\[ \sigma = \left[ A + B e_p^n \right] \left[ 1 + C \ln \left( \frac{\dot{e}}{\dot{e}_0} \right) \right] \left[ 1 - \left( \frac{T}{T_m} \right)^{m} \right] \]  

(5)

where \( A, B, C, n \) and \( m \) are Johnson–Cook material constants, \( \varepsilon_p \) is the effective plastic strain, \( \dot{\varepsilon}/\dot{\varepsilon}_0 \) is the effective plastic strain rate at a reference strain rate, \( T \) is the material temperature, \( T_m \) is the melting temperature of material. The detailed parameters are shown in Table 9.

| Parameter | Value |
|-----------|-------|
| \( A \) (MPa) | 341   |
| \( B \) (MPa) | 550   |
| \( C \) | 0.058 |
| \( n \) | 0.47  |
| \( m \) | 0.94  |

Table 9. Johnson–Cook parameters of steel plate.

The air domain is described as an ideal gas, and the equation of state is as follows,

\[ P = \rho (\gamma - 1) e \]  

(6)

where \( P \) is the gas pressure, \( \rho \) is the gas density, \( \gamma \) is the adiabatic coefficient, \( e \) is the specific internal energy of gas. The detailed parameters are shown in Table 10.

| Parameter | Value |
|-----------|-------|
| \( P \) (kg/cm\(^3\)) | 1.255 |
| \( \gamma \) | 1.4   |
| \( e \) (J/kg) | 2.068 \times 10^5 |

Table 10. Ideal gas parameters of air.

3.2.3. Response of steel plates subjected to confined blast loadings. The total simulation time of 20 ms was set in the numerical simulations. The deflection of the central point of the plate was obtained. The curve oscillated around a specific value, which is considered as the final deflections of the plates. The results are listed in Table 11. It is found that the deflections of the blast loaded plates calculated by the numerical simulations are smaller than those of measured from experiments, and the relative errors reached -26.2\% and -18.3\%, respectively, although the energy from the after burning of the detonation product was taken into account. In addition, the experimental results of the deflections of steel plates with the same thickness subjected to the confined blast load from the explosion of TNT charge without a shell (bare charge) are compared with the results from the present numerical simulations, as shown in figure 14. It is found that the equivalent bare charge calculated from the numerical simulations in Section 3.1 underestimated the energy released in the experiments. Combining the phenomenon observed in the tests, it is indicated that the energy from the burning of the aluminum shell contributed to the deflection of the plates subjected to the confined blast loading from cased charge. The research
in the reference [20] also showed that the burning of the aluminum shell would enhance the confined blast load. The equivalent bare charge of the cased TNT should be reconsidered.

**Table 11. Results under confined blast loadings.**

| Case   | #1  | #2  |
|--------|-----|-----|
| Charge/g | 71.5 | 108.9 |
| FEM result/mm | 31.2 | 38.2 |
| Test result/mm | 42.3 | 46.8 |
| Relative error | -26.2% | -18.3% |

**Figure 14.** Comparison of response results of bare charge and aluminum cased charge.

4. **Method of calculating equivalent bare charge**

In our previous research work [17], the relationship between the blast energy and the dimensionless deflection of steel plate was proposed, as follows,

\[
\frac{\delta}{H_p} = a\varphi + b = a \cdot \left(\frac{W_d + W_b}{LTN} \right) + b
\]

(7)

where \(a=0.038, b=1.436\) are fitting parameters, \(\delta\) is the final deformation of target plate, \(H_p\) is the thickness of plate, \(W_d\) and \(W_b\) are energy from an explosion of TNT charge. The detonation energy \((W_d)\) released in very short time after the charge is initiated, and the additional energy \((W_b)\) is from the after burning of detonation products. \(L\) and \(B\) are dimensions of the confined space of experimental set up; \(\sigma_y\) is yield stress of material.

Then, considering the charge with aluminum case, the energy release caused by aluminum burning could be taken into account, the equation (7) was rewritten as follows,
\[
\left( \frac{\delta}{H_p} \right) = a\phi + b = a \cdot \left( \frac{W_d + W_b}{(LB)^{1/2}} + \frac{(W_b)_d}{H_p^2\sigma_y} \right) + b \tag{8}
\]

where \((W_b)_d\) is the additional energy from aluminum burning.

From the above formula, the total energy from the explosion of the cased charge that contributed to the deflection of the plate can be expressed as follows,

\[
E = 26.316\delta H_p\sigma_y\sqrt{LB} + 37.789H_p^2\sigma_y\sqrt{LB} \tag{9}
\]

According to the above formula, the total energy of different charges can be obtained by the final deflection of the plates. This energy can be used to calculate the equivalence bare charge from the cased TNT, as listed in table 12.

| Case                  | #1     | #2     |
|-----------------------|--------|--------|
| Actual charge/g       | 149.0  | 200.0  |
| Aluminum case/g       | 110.4  | 130.5  |
| Total energy/MJ       | 1.799  | 2.027  |
| Equivalent bare charge/g | 146.6  | 174.4  |

Then, the numerical simulation of the dynamic response of plates subjected to fully confined blast load were performed by using the equivalent bare charge in table 12. The obtained results were compared with those of from tests, as summarized in table 13. The relative errors to the test results reduced to 5.7 % and 4.9 % for the two cased charge, respectively. The above results indicated that in the conditions of the aluminum cased charge exploded in the confined space, the energy released by the burning of aluminum shell should not be ignored. In the two cases involved in the test, the contribution of aluminum to the plate deflections are approximate 26% and 18%, respectively. In the condition of larger TNT charge and shell mass, the demand for oxygen in the burning process will also increase. When the charge to volume of confined space exceeds a certain proportion, the afterburning effect will be restrained due to the lack of oxygen, resulting in the reduction energy release and subsequent deflection of the loaded plate.

| Case                          | #1     | #2     |
|-------------------------------|--------|--------|
| Charge/g                      | 146.6  | 174.4  |
| FEM result/mm                 | 44.7   | 49.1   |
| Test result/mm                | 42.3   | 46.8   |
| Relative error                | 5.7%   | 4.9%   |

5. Concluding remarks

In this paper, based on the experiments and numerical simulations, a method for analyzing the
equivalent bare charge of an aluminum cased warhead model exploding in confined space was presented. The influences of fragmentation of the shell, the afterburning effect of detonation products and the energy released from the burning of the aluminum shell on the determination of the equivalent bare charge were considered and analyzed. From the results, the following conclusions can be drawn.

(1) The afterburning effect of the detonation products and the aluminum shell should be considered as an important factor in the confined space that enhancing the dynamic response of the structure. In the experiments of this paper, the additional energy from aluminum shell burning results in the increases of plate deflections by 26% and 18%, respectively. The content of the oxygen would affect the energy release from burning event of the aluminum.

(2) The equivalent bare charge converted from the residual deflection related formula can better evaluate the damage effect of an explosive with aluminum case. The method presented in this paper provides an alternative option for predicting the damage ability of an aluminum cased charge in a confined space.

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