Numerical Simulation of High-Speed Fragment Penetrates the Target Plate with Water Wall

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Abstract. Aiming at the problem of large risk factor and low test efficiency of the large-volume ammunition fragmentation test, a new method for comprehensively collecting the damage parameters of the fragments by using the water wall in front of the target plate was proposed. The dynamic simulation software AUTODYN was used to simulate the process of the fragment penetration the target plate with the water wall and without the water wall. The influence of the thickness of the water wall on the penetration capability was analyzed. The calculation results show that compared with the target plate without the water wall, the target plate with the water wall can greatly reduce the penetration ability of fragment, and the greater the thickness of the water wall, the weaker the penetration ability.

1. Introduction

With the change of the war mode, the frequency and role of large-volume ammunition in combat are increasing, and the high-speed fragments produced by it can have a huge killing effect on personnel and equipment. At present, in order to truly improve the actual combat lever of the troops and win the modern war under the conditions of high and new technology, it is necessary to require the combat training of the troops to be closer to actual combat [1]. Therefore, in the equipment combat damage test, more and more large-volume ammunition will be used for equipment strike tests. In order to make the design of the test plan more reasonable, it is necessary to analyze the damage power of the large-volume ammunition.

At present, the analysis of the damage of ammunition fragmentation mainly adopts the fracture test and the scattering test[2]. These two types of tests mainly refer to the procedures and methods in the corresponding national military standards. The common method of the fracture test is sandboxing method. Zhang Zhibiao [3]uses the sandbox static explosion method to recover the natural fragments generated by the expansion. Song Guifei[4] designed a new type of explosive container device for recovering the fragments of the warhead. However, neither of them can obtain fragmentation data while acquiring fragmentation quality data and it is only suitable for small-volume ammunition. The commonly used methods of the scattering test are the fan-shaped target method and the spherical target method [5]. The spatial scattering data of the fragments are collected by setting the pine target. This method is also only applicable to the collection of small-volume ammunition fragmentation data.

In response to this defect, Wang Lin [6] studied the scattering characteristics of the large-volume ammunition fragments by changing the target material and the way of setting the target plate, but it is unable to obtain the mass distribution law of the fragments at the same time. Therefore, in order to obtain the complete fragmentation damage power parameters, it can only increase the number of ammunition explosions and increase the requirements for the test site. However, for large-volume ammunition, it is not only expensive, but also has a huge damage. The increase in the number of tests...
will greatly increase the test cost and the test risk factor, and the method of improving the test site requirements will greatly reduce the test efficiency. Therefore, it is of great significance to explore a new method for testing the damage of large-volume ammunition fragments.

2. Test Principle
The static explosion test is usually used to obtain the damage power parameters of the ammunition fragment. A schematic diagram of a certain type of ammunition static explosion test is shown in Fig. 1. By arranging a certain number of metal target plates on one side of the ammunition, and collecting the number of perforations and pits on the target plate after the ammunition explosion, the number of fragments in the corresponding scattering interval can be obtained, thereby the overall distribution of the ammunition fragmentation field can be deduced. For large-volume ammunition, such as missiles, the initial velocity of the fragments is usually 2000~2500m/s, so the fragments can almost penetrate the target, which makes it impossible to obtain the quality of the fragments in one test. Therefore, this paper aims to quickly reduce the penetration ability of the fragments by setting the water wall in front of the target plate, and to make up for the defects that the conventional test method cannot collect the fragment quality data at the same time. The schematic diagram is shown in Fig. 2.

![Figure 1. Layout of static explosion test](image1)

![Figure 2. Schematic diagram of target plate with the water wall](image2)

3. Numerical Simulation Model
3.1. Establishment of Finite Element Model
The finite element simulation software AUTODYN is used to simulate the process of the high-speed fragment penetrates the target plate with water wall. Taking a square fragment as an example, its size is 7mm×7mm×7mm, the mass is about 3g, the initial velocity is 1500m/s, the thickness of the target is 3mm, the length and width are 50mm×50mm. The periphery of the target plate is rigidly fixed to achieve the effect of fixing the target plate in the simulated test. In order to simulate the process of fragment fly in the air and through the water wall, an air field of 100 mm × 50 mm × 50 mm is built around the fragment and the target. And part of air is replaced by water using filling method, thereby establishing the water wall in front of the target. Both the fragment and the target use the Lagrange algorithm. The air and water adopt the Euler algorithm, and the Flow-out boundary conditions are set at the boundary between the air and the water to realize the outflow of the boundary energy in the air and water. All model unit mesh sizes are 1mm. The fluid-solid coupling algorithm is used to define the interaction between the fragment and the water wall, as well as the water wall and the target, and the
erosion contact algorithm is used to simulate the process of the fragment penetrates the target. The established model is shown in Fig. 3.

![Finite element model (1/2 model)](image)

**Figure 3.** Finite element model (1/2 model)

### 3.2. Establishment of Material Model

#### 3.2.1 Material Model of Fragment and Target Plate

The fragment material is tungsten alloy, and the target material is steel. These two materials are described by using the Shock state equation and the Johnson-Cook strength model. The Shock state equation expression is: 

\[ U_s = c + s_1 u_p + s_2 u_p^2 \]

Under strong impact conditions, for most materials, the expression can satisfy: 

\[ U_s = c + s u_p. \]

The parameters of the two materials are shown in Table 1.

|                        | Tungsten alloy | Steel  |
|------------------------|----------------|--------|
| Density \((\text{kg/m}^3)\) | 17.8E+3        | 7.8E+3 |
| Gruneisen              | 1.54           | 1.6    |
| \(C_1(\text{m/s})\)    | 4.03E+3        | 3.98E+3|
| \(S_1\)                | 1.237          | 1.58   |
| Reference temperature  | 300.0          | 300.0  |
| Specific heat \((\text{J/kgK})\) | 134            | 408    |

The Johnson-Cook strength model is commonly used for metal materials with high strain rates and high temperatures. The yield stress in this model is determined by the strain, strain rate and temperature of the material. The expression is:

\[
Y = (A + B \varepsilon_p^*)(1 + C \log \varepsilon_p^*)(1 - T_H^n)\]

\[
T_H = (T - T_{\text{room}}) / (T_{\text{melt}} - T_{\text{room}})\]

Where \(\varepsilon_p\) is the effective plastic strain, \(\varepsilon_p^*\) is the reference effective strain rate, \(T_H\) is the relative temperature, \(T\) is the material temperature at the time of the test, \(T_{\text{melt}}\) is the melting point of the material, and \(T_{\text{room}}\) is room temperature. \(A, B, C, n\) and \(m\) are constants, and their values are determined by the material itself and can be measured by tests. The strength model parameters of the two materials are shown in Table 2.
Table 2. Strength model parameters[7,8]

|                | Tungsten alloy | Steel |
|----------------|---------------|-------|
| Shear modulus (GPa) | 150           | 77    |
| Yield stress A(GPa)  | 1.200         | 0.95  |
| Hardness B(GPa)      | 0.177         | 0.611 |
| Hardening index n    | 0.12          | 0.26  |
| Strain rate constant C | 0.016       | 0.014 |
| Temperature softening index m | 1.0     | 1.0   |
| Melting point $T_{melt}$ (K) | 1748     | 1818  |

3.2.2 Material Model of Air and Water. Describe the air using the ideal gas equation of state:

$$p_1 = (\gamma - 1)\rho_a e + p_{shift}$$

(3)

Where $p_1$ is the pressure; $e$ is the specific thermodynamic energy; $\gamma$ is the multi-index, and $p_{shift}$ is the pressure offset. In the air model, $\gamma$ is taken as 1.4, density $\rho_a$ is 1.225 mg/cm3, and $e$ is 2.068×105. The water adopts the NULL material model, and its state equation adopts the Grüneisen equation of state[9].

$$p = \frac{\rho_0 c_0^2 \mu [1+(1-\gamma_0)\mu - \frac{\alpha}{2}\mu^2]}{[1-(S_1-1)\mu-S_2\mu^2-S_3\mu^3(1+\mu)^2]} + (\gamma_0 + \alpha\mu)E$$

(4)

Where $p$ is pressure, $E$ is volume internal energy, $c_0$ is the initial sound velocity in the medium, taken as 1480m/s, $S_1$, $S_2$, $S_3$ are shock wave input parameters, usually determined according to the impact test data of the water medium, this paper takes $S_1=1.75$, $S_2=0$, $S_3=0$. $\rho_0$ is the initial density of water at normal temperature, $\rho$ is the current density of water, $\mu$ is the medium compression ratio, and $\mu = p/p_0$. $\gamma_0$ is the initial coefficient of Grüneisen, which is taken as 0.4934, and $\alpha$ is a correction term of Grüneisen coefficient.

4. Results and Analysis of Numerical Simulation

4.1. Analysis of High Speed Fragment Penetration Process

The numerical calculation of the process of the fragment penetrates the target with water wall is carried out, and the information of different penetration state of the fragment is shown in Fig. 4. Fig. 4 (a) ~ Fig. 4 (d) is the shock wave pressure cloud diagram in the water wall, Figure 4 (e) ~ Figure 4 (f) is the internal stress cloud diagram of the metal material.

![Figure 4](image-url)
It can be seen from the figure that at the initial moment when the fragment enters the water wall, due to the inertial pressure of the water, a huge pressure is generated in the contact area between the fragment and the water, and the fragment is deformed accordingly. At the same time, the shock wave will also be generated in the water wall due to the impact of the fragment, and the shock wave will continue to propagate forward with the advancement of the fragment and always lead the fragment. Therefore, the shock wave is first contacted with the target plate, and the shock wave causes reflection on the surface of the target plate due to the blocking action of the target plate, and overlaps with the shock wave that has not yet reached the target plate, generating a larger shock wave overpressure at the interface. Under the action of overpressure, the target plate produces a certain plastic deformation, and the speed of the fragment is further reduced. When the fragment penetrates the water wall, it continues to penetrate the target at the remaining speed and eventually penetrates the target.

The velocity change data of the fragment from the initial time to the time of penetrating the target plate is shown in Fig. 5 and the velocity change data when the fragment penetrates the target plate without water wall is shown in Fig. 6.

**Figure 5.** Speed curve of fragment penetrates the target plate with the water wall

**Figure 6.** Speed curve of fragment penetrates the target plate without the water wall

It can be seen from Fig. 5 that when the target plate is protected by the water wall, the fragment penetrates the target into two stages. The first stage is the crossing of the water wall stage, that is, the high-speed fragment traverses the water wall in the 0~88us time period. In this process, the speed of the fragment decreases from 1500m/s to 1010m/s, with a decrease of 32.7%. In the process of 67us~88us, due to the rebound superposition effect of the shock wave under the action of the target plate, the falling rate of the speed is increased, but the contact area between the fragment and the shock wave is small, so the decline is not large. The second stage is the stage of penetrating the target, that is, at 88us~120us, the fragment begins to penetrate the target. In the early stage, due to the buffering effect of the water wall, the speed of the fragment drops gently during the penetration process, and the penetration time continued for a long time. The final residual speed is 599 m/s, which
is 60.1% lower than the initial speed. It can be seen from Fig. 6 that when there is no water wall in front of the target plate, the fragment flies in the air during the period of 0~ 68us and the speed of the fragment does not decrease during the process. At 68us, the fragment touches the target plate and began to penetrate the target. The entire penetration process end at 83us, and then the fragment continues to fly forward. At this time, the residual speed of the fragment is 1128m/s, which is 24.8% lower than the initial speed. Therefore, as can be seen from Fig. 5 and Fig. 6, the water wall has a significant effect on the penetration ability of the high-speed fragment, and the speed can be reduced 35.3% compared with the state without the water wall protection.

4.2. Influence of Thickness of Water Wall on Penetration Ability of High Speed Fragment

The initial thickness of the water wall is set to 40mm, and the thickness is increased by 10mm for each simulation, and the initial velocity of the fragment is kept unchanged at 1500m/s. The remaining speed of the fragment is as shown in Fig. 7. The scatter point in the figure is the numerical calculation result, and the solid line is the fitting curve.

![Figure 7. Residual velocity of fragment](image)

It can be seen from the figure that the residual velocity of the fragment penetrating the target plate with water wall is linear with the thickness of the target. Under the condition that the fragment quality, shape and target thickness remain unchanged, the residual speed of the fragment decreases with the increase of the thickness of the water wall. For every 10 mm thick water wall, the speed of the fragment drops by about 40 m/ s. By using the fitting curve, it can be obtained that when the thickness of the water wall is increased to 287 mm, the residual speed of the fragment can be reduced to zero.

5. Conclusions

Through the numerical simulation method, the process of high-speed fragment penetrates the target plate with water wall is analyzed. The results show that by providing a water wall in front of the target plate, the penetration capability of the high-speed fragment can be greatly reduced. Under the same simulation conditions, the residual speed of the fragment after penetrating the target plate with water wall can be reduced by 35.3% compared with the case of penetrating the target plate without water wall. With the increase of the thickness of the water wall, the penetration ability of the high-speed fragment gradually decreases, and the extent of the decline is linear with the thickness of the water wall.

6. References

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