Numerical simulation and experimental research on EFP penetrating the ceramic composite armored target

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Abstract. To research the protective performance of the newly designed ceramic composite armored target against 50mmRHA EFP, this paper used AUTODYN numerical simulation software to simulate the process of EFP penetration into the ceramic composite armored target, and verified the simulation results through the target test. The results showed the mass of EFP has a great impact on its penetration capability; the designed ceramic composite armored target with 274kg/m² areal density could effectively prevent the penetration of 50mmRHA EFP; the vertical penetration depth was about 30 mm; and the back plate had a slight back convex phenomenon. The research results can provide reference for the protective structure design of light tanks and armored vehicles.

1. Introduction

Explosion-formed projectile (EFP) is a new technology developed in the past two decades. Explosion-formed projectile (EFP) is a high-speed projectile formed by crushing and overturning a large-cone-shaped or spherical-shaped liner through the detonation of explosives, thereby penetrating the armored target with kinetic energy [1]. It is a projectile between armor-piercing and armor-piercing projectiles. It is a combination of the two to a certain extent. It has the advantages of insensitivity to explosive height, small interference from explosive reaction armor, and large penetration aftereffect [2]. Existing active protection technologies are difficult to respond to destruction and cannot provide effective protection. They can only rely on passive protective armor for defense, while the current traditional armor protection technology cannot effectively protect. Therefore, there is an urgent need to develop a new armor module that can protect the terminal sensitive EFP.

EFP's penetration of armored target plates involves the complex thermo-mechanical coupling process of high temperature, high pressure, high strain rate, and large deformation of the material. It is difficult to understand the entire process only by theoretical analysis and experimental research, so simulation research is indispensable. In this paper, AUTODYN software was used to simulate the process of EFP penetration into the ceramic composite armored target, and the simulation results were
verified through the target test.

2. Numerical simulation of EFP penetration into ceramic composite armored target

2.1. Simulation model and calculation method

The 50mmRHA EFP charge structure design was shown in figure 1. The charge diameter was 80mm, the charge height was 74.5mm, and the charge density was 1.8g/cm³. The liner was a high-conductivity oxygen-free copper with equal thickness. The shell was aluminum.

![Figure 1. Schematic diagram of EFP charge structure.](image)

The numerical simulation of the EFP molding process was performed on the AUTODYN software. The EFP molding process involved large deformation behaviors such as explosive explosion, reversing and stretching of the liner. The Lagrange method was difficult to accurately simulate the EFP molding process, so only the multi-material Euler algorithm could be used [3]. For the multi-material Euler algorithm, in addition to the energy accumulation device, an air grid sufficient to cover the entire projectile range needed to be established, and pressure was applied to the boundary nodes of the model to flow out of the boundary conditions to avoid the reflection of pressure on the boundary.

After the EFP was formed, the material, shape, and speed parameters of the EFP were mapped from the two-dimensional multi-material Euler model to the three-dimensional Lagrange model through mapping technology. A ceramic composite armored target model was established for simulation analysis of the penetration process. Due to the symmetry of vertical penetration, in order to reduce the amount of calculation, a 1/4 model was used for simulation calculation.

2.2. Material model and parameter selection

Material model of high explosive and JWL state equation were selected in simulation calculation. JWL state equation accurately described the pressure, volume and energy characteristics of detonation products in the process of explosive driving. Table 1 showed the detonation performance parameters and the main parameters of JWL state equation of 8701 high explosive.
Table 1. Detonation performance parameters and JWL state equation parameters of 8701 high explosive.

| $\rho$ (g/cm$^3$) | $P_{CJ}$/GPa | $D_{CJ}$/(m/s) | $A$/MPa | $B$/MPa | $R_1$ | $R_2$ | $\omega$ |
|------------------|-------------|----------------|---------|---------|-------|-------|---------|
| 1.8              | 34          | 8400           | 5814    | 68.01   | 4.1   | 1.0   | 0.35    |

The liner material was copper. The constitutive model of Johnson-Cook and Gruneisen state equation were used to describe the dynamic response behavior of the liner material under the action of detonation wave, which could accurately simulate the deformation of the liner material under high strain rate($>10^3$S$^{-1}$) conditions. The parameters of Johnson-Cook constitutive model and Gruneisen equation of copper were shown in table 2.

Table 2. Model and state equation parameters of copper.

| $\rho$ (g/cm$^3$) | $C_1$ (m/s) | $\gamma$ | $S_1$ | $G$   | $A$(Gpa) | $B$(Gpa) | $c$ | $n$ | $m$ |
|------------------|-------------|-----------|-------|-------|---------|---------|-----|-----|-----|
| 8.96             | 30940       | 1.489     | 46    | 292   | 0.025   | 0.31    | 1.09|

The ceramic composite armored target consisted of SiC ceramic panel and the back plate of 685 armored steel. The SiC ceramic was described by the Johnson-Holmquist model, and the 685 armored steel was described by the Johnson-Cook constitutive model. The SiC ceramic parameters of JH-1 model was shown in table 3. The parameters of Johnson-Cook constitutive model of 685 armored steel was shown in table 4.

Table 3. SiC ceramic parameters of JH-1 model.

| $\rho$ (g/cm$^3$) | $G$(Gpa) | $\sigma_{HEL}$(Gpa) | $S_1$(Gpa) | $S_2$(Gpa) | $P_1$(Gpa) | $P_2$(Gpa) |
|------------------|---------|---------------------|------------|------------|------------|------------|
| 3.2              | 193.5   | 11.7                | 7.1        | 12.2       | 2.5        | 10         |
| $c$              | SFMAX (Gpa) | HEL(Gpa) | $\sigma_T$(Gpa) | $P_3$(Gpa) | $\beta$ |
| 0.009            | 1.3     | 6.0                 | 0.4        | 0.75       | 99.75      | 1.0        |

Table 4. Model parameters of 685 armored steel.

| $\rho$ (g/cm$^3$) | $G$(Gpa) | $T_{mel}$(K) | $A$(Gpa) | $B$(Gpa) | $c$ | $n$ | $m$ |
|------------------|---------|-------------|---------|---------|-----|-----|-----|
| 7.86             | 77.5    | 1793        | 1.65    | 1.8     | 0.02| 0.63| 0.94|

3. Simulation result and analysis

Figure 2 showed the simulation result of the anti-EFP penetration of the ceramic composite armored target. The simulation results showed that the ceramic composite armored target could effectively prevent the penetration of EFP, and the back material had no obvious damage on the back, and the penetration depth was 33mm.
Figure 2. Numerical simulation result of the anti-EFP penetration of ceramic composite armored target.

The kinetic energy of EFP was extracted and derived from the simulation results. The result was shown in figure 3 and figure 4.

![Figure 3](image1.png)  ![Figure 4](image2.png)

**Figure 3.** Curve of kinetic energy of EFP over time  **Figure 4.** Differential curve of kinetic energy of EFP over time

It could be seen from figure 3 and figure 4 that the downward trend of the kinetic energy of EFP could be divided into the following parts: 0-5μs, the stage of the open pit of EFP, during which the damage in the ceramic was concentrated on the ceramic surface, which had the strongest hindrance effect on EFP, as shown figure 5a; 5-10μs, the stage of deformation of EFP, during which the back damage of the ceramic layer had been formed, but penetrating damage zone was not formed, as shown figure 5b; 10-20μs, similar to the resident phase of EFP, which showed that the ceramic layer directly under EFP had no failure. During this stage, EFP was greatly deformed, and the mass of EFP began to lose a lot, as shown figure 5c; 20-45μs, the stable penetration stage in the ceramic layer, which showed the core damage area was gradually approaching the back of the ceramic layer. During this stage, the quality of EFP was greatly reduced, as shown in figure 5d; 45-55μs, the tail of EFP contacted the ceramic layer, the velocity of EFP decreased, and the aperture formed in the ceramic layer was enlarged; 55-80μs, EFP penetrated into the back plate, EFP entered the secondary pit and secondary deformation stage, the mass of EFP was almost left, the speed of EFP gradually decreased, and finally stopped, as shown in figure 5e.
The curve of EFP velocity over time during the penetration was shown in figure 6. It could be seen from figure 6 that during the ceramic penetration stage (0-55μs), the speed of EFP decreased less, only from 1750m/s to about 1600m/s. This shows that the kinetic energy loss of this type of projectile is mainly dominated by the mass loss. After the mass loss has basically ended, the speed begins to decrease significantly. Therefore, the mass of this type of projectile has a great impact on its penetration capability.
4. Experimental research

4.1. Test plan and arrangement

Figure 7 showed the test site layout. The explosion height was 500mm, which was the same as the simulation calculation. The gap between the ceramic composite armored target plate and the after-effect plate was 50mm, and the after-effect plate used GY4 armored steel.

The EFP used in the test has an armor penetration power of 50mm RHA when the bomb height is 500mm. The EFP charge structure was the same as that of the simulation, as shown in figure 1.

The structure of the ceramic composite armored target was the same as that of the simulation. The areal density of the ceramic composite armored target was 274kg/m².

4.2. Test results

Figure 8 showed the deformation and penetration depth of the back plate after the ceramic composite armored target plate resisted EFP penetration.
It could be seen from figure 8 that the back plate had no damage, the deformation of the back plate was about 45mm×25mm, the vertical penetration depth was 30mm, the back convex was about 32mm, and there was no back crack, which was basically consistent with the simulation results. It belonged to the qualified damage range and achieved effective protection for EFP.

5. Summary
(1) The 50mmRHA EFP penetration process into the ceramic composite armored target with 274kg/m² areal density was researched by the numerical simulation and the target test.
(2) The simulation results showed that the kinetic energy loss of EFP was mainly dominated by the mass loss. After the mass loss had basically ended, the speed began to decrease significantly. Therefore, the mass of EFP has a great impact on its penetration capability.
(3) The designed ceramic composite armored target could effectively prevent the penetration of 50mmRHA EFP; the vertical penetration depth was about 30 mm; and the back plate had a slight back convex phenomenon.
(4) The test results were basically consistent with the simulation results, indicating that the simulation calculation method and material parameters were credible.

References
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