Research on structural design and anti-penetration performance of ceramic composite armor

Youchun Zou1, Chao Xiong*,1, Junhui Yin1, Huiyong Deng1, Kaibo Cui1

1 Department of Artillery Engineering, Army Engineering University of PLA, Shijiazhuang 050003, China

email: ljgcdxxiongchao@plaust.edu.cn

Abstract. Two types of composite armor were designed (Composite armor I alumina ceramic/Kevlar/616 armored steel; Composite armor II alumina ceramic/616 armored steel/Kevlar). Through penetration tests and numerical simulations, the anti-penetration performance and anti-penetration mechanism of the composite armors were studied, and the influences of material arrangement on its anti-penetration performance were discussed. The results show that the established finite element models can reliably simulate the penetration process of composite armors. The failure modes of Kevlar and 616 armored steel in composite armor I are tensile failure and spalling damage, respectively. The failure mode of Kevlar and 616 armored steel in composite armor II is shear failure. The shear failure of 616 armored steel and Kevlar is a low energy consumption damage mode. Therefore, the structure form of composite armor II can give full play to the anti-penetration performance of the material, and the anti-penetration performance is better than that of composite armor I.

1. Introduction
Modern war puts forward higher requirements for the mobility and protection of equipment. Ceramic composite armor has become one of the research hotspots in the field of protection due to its relatively low quality and good protection performance.

The materials used in composite armor mainly include ceramics, fiber composite materials and metals. The more widely used structural forms include ceramic/metal, ceramic/fiber composite materials and metal/fiber composite materials. An et al. studied the anti-penetration mechanism of ceramic/metal composite armor. The results show that the ceramic/metal structure has good anti-penetration performance and effectively reduces the quality and thickness of the composite structure. Through the penetration tests of SiC/UHMWPE composite armor, Hu et al. found that the structural form of the hard face plate and the flexible support plate has guiding significance for the lightweight design. Cai et al. studied the failure mechanism of foamed aluminum/ultra-high molecular weight polyethylene composite armor under explosion and fragment loading. It is found that foamed aluminum/ultra-high molecular weight polyethylene has good comprehensive protection capabilities.

At present, there are few researches on the anti-penetration performance and anti-penetration mechanism of ceramic composite armor composed of ceramic, metal and fiber composite materials. Two composite armors were designed using ceramic, Kevlar and armored steel. Through penetration tests and numerical simulations, the anti-penetration performance and anti-penetration mechanism of composite armors were studied, which provides a theoretical basis for the design of multilayer composite armor.
2. Materials and methods

The materials that make up the composite armors include alumina ceramic, Kevlar and 616 armored steel, with thicknesses of 10 mm, 10 mm and 6 mm, respectively. As shown in Table 1, based on three materials, two composite structures were designed. The cross-sectional dimension of the composite armor is 150 mm × 150 mm. Projectiles made of T12 steel were used in the tests. The size of the projectile and the test device are shown in Figure 1. In order to reduce the error, three samples of each structure were prepared for three tests and the average of the results was taken. As shown in Figure 2, the DOP method was used to evaluate the protection performance, and the protection coefficient N was calculated from the reference penetration depth and the remaining penetration depth of 603 steel [1, 4]. The formula is as follows.

\[ N = \frac{\rho_s (T_0 - T_r)}{\rho_c \delta_c} \]  

(1)

\( T_0 \) is the reference penetration depth; \( T_r \) is the remaining penetration depth of the 603 steel after the projectile penetrates the composite armor to be tested at the same speed; \( \rho_s \) is the density of 603 steel; \( \rho_c \) and \( \delta_c \) are the average density and thickness of the composite armor to be tested.

| Composite armor number | Structure form |
|------------------------|---------------|
| Composite armor I      | 10 mm alumina ceramic/10 mm Kevlar/6 mm 616 armored steel |
| Composite armor II     | 10 mm alumina ceramic/6 mm 616 armored steel/10 mm Kevlar |

LSDYNA finite element software was used to simulate the penetration process. In order to improve the calculation efficiency, a quarter model of the structure was established. The model and mesh
division are shown in Figure 3. The fixed boundary condition was set at the boundary of the composite structure, and the displacement constraint was imposed on the symmetry plane. CONTACT_ERODING_SURFACE_TO_SURFACE was used to define the interfaces between the projectile and each layer of composite armor, and CONTACT_SURFACE_TO_SURFACE was used to define the interfaces between composite armor. The material parameters are shown in Table 2-4.

![The model and mesh division](image)

**Table 2. Material parameters of ceramic[5]**

| ρ(g/cm³) | G(GPa) | ε̇(s⁻¹) | T(GPa) | ℋEL(GPa) | HEL(GPa) | A  | B  | C  |
|----------|--------|----------|--------|----------|----------|----|----|----|
| 3.7      | 90.16  | 1        | 0.2    | 5        | 10       | 0.93| 0.31| 0  |
| M        | N      | β        | D₁     | D₂       | K₁(GPa)  | K₂(GPa) | K₃(GPa) |
| 0.6      | 0.6    | 1        | 0.005  | 1        | 220      | 191 | 112 |

**Table 3. Material parameters of Kevlar**

| ρ(g/cm³) | E₁(GPa) | E₂(GPa) | E₃(GPa) | ν₁₂ | V₁₂ | V₁₃ | V₁₄ | G₁₂(GPa) |
|----------|---------|---------|---------|-----|-----|-----|-----|----------|
| 1.35     | 40.6    | 40.6    | 2.6     | 0.008| 0.044| 0.044| 1.75|
| G₁₀(GPa) | G₁₁(GPa) | MACF | K₁(F(GPa)) | S₁(GPa) | X₁(GPa) | Y₁(GPa) | Y₄(GPa) |
| 1.6      | 1.6     | 3       | 2.2     | 0.35 | 0.725| 0.725| 0.69 |

**Table 4. Material parameters of bullet, 616 steel and 603 steel [6]**

| ρ(g/cm³) | G(GPa) | A(GPa) | B(GPa) | n   | C   | m   | T(ad)(K) | ε̇(s⁻¹) |
|----------|--------|--------|--------|-----|-----|-----|----------|--------|
| bullet   | 7.8    | 81.8   | 1.7    | 0.2 | 0.12| 0.16| 1.27     | 1793   |
| 616 steel| 7.83   | 77     | 1.47   | 0.51| 0.26| 0.014| 0.9      | 1723   |
| 603 steel| 7.86   | 77     | 0.95   | 0.6 | 0.26| 0.016| 1.03     | 1760   |
| C₀(J/kg/K)| 477    | 2.17   | 5054   | 1.49| 0   | 0.33| -1.5     | 0      |
| bullet   | 455    | 2.17   | 5328   | 1.49| 0   | 0   | 0        | 0      |
| 616 steel| 383    | 1.67   | 4570   | 1.33| 0.07| 1.7 | 0.07     | -0.012 |
| 603 steel| 383    | 1.67   | 4570   | 1.33| 0.07| 1.7 | 0.07     | -0.012 |

3. Results and discussion

3.1. Test results and simulation results

The test results and simulation results are shown in Table 5. The penetration resistance of composite armor I is better than that of composite armor II. The test results and the simulation results have relatively small errors, and the established finite element model can accurately simulate the penetration process of the composite armor.
Table 5. Test results and simulation results

| Armor number | Projectile velocity m/s | $\rho_c$ (g/cm$^3$) | $T_r$ /mm | $N$ | Simulation error /% |
|--------------|--------------------------|---------------------|------------|----|---------------------|
| I-1          | 1016.5                   | 3.74                | 0.34       | 3.45 |                     |
| I-1          | 1017.8                   | 3.77                | 0.46       | 3.41 | 0.60                |
| I-1          | 1019.4                   | 3.76                | 0.21       | 3.44 |                     |
| II-1         | 1016.3                   | 3.69                | 2.02       | 3.36 |                     |
| II-1         | 1012.1                   | 3.74                | 2.19       | 3.30 | 3.05                |
| II-1         | 1009.6                   | 3.77                | 2.21       | 3.27 |                     |

3.2. Failure Mechanism Analysis

As shown in Figure 4-5, the typical state and material damage morphology of the composite armor I in the penetration process are combined to analyze the damage mechanism. In the process of projectile penetrating ceramic, pressure is generated at the interface between projectile and ceramic. The pressure reaches the yield limit of the projectile, the head of the projectile is plastically deformed, and the ceramic is broken. With further penetration, the ceramic begin to act on the Kevlar. The strength and rigidity of 616 armored steel are greater than that of Kevlar, which leads to tensile failure of Kevlar on the front surface. The 603 armored steel provides support for the 616 armored steel, which leads to spalling damage of 616 armored steel.

Figure 6-7 shows the typical state and material damage morphology of composite armor II. The strength and rigidity of Kevlar are much smaller than that of 616 armored steel, so it is not enough to provide support for the deformation of 616 armored steel, which leads to shear failure of 616 armored steel. The Kevlar suffered shear failure due to the restraining effect of 603 armored steel and 616 armored steel. The shear failure of armored steel and Kevlar is a low energy dissipation damage mode, so the penetration resistance of composite armor II is less than that of composite armor I.
Fig. 6 Penetration process of composite armor II

(a) $t=0.012\text{ms}$  (b) $t=0.026\text{ms}$  (c) $t=0.038\text{ms}$

Fig. 7 Damage morphology of composite armor II

(a) ceramics  (b) 616 armored steel  (c) Kevlar

4. Conclusion

(1) The failure modes of Kevlar and 616 armored steel in composite armor I are tensile failure and spalling damage respectively.

(2) The failure mode of Kevlar and 616 armored steel in composite armor II is shear failure.

(3) The shear failure of 616 armored steel and Kevlar is a low energy consumption damage mode, so the penetration resistance of composite armor II is less than that of composite armor I. Under the same material conditions, the structure form of composite armor II can give full play to the anti-penetration performance of composite armor.

References

[1] An X, Tian C, Sun Q and Dong Y 2020 Effects of material of metallic frame on the penetration resistances of ceramic-metal hybrid structures Defence Technology 16 77-87

[2] Hu D, Zhang Y, Shen Z and Cai Q 2017 Investigation on the ballistic behavior of mosaic SiC/UHMWPE composite armor systems Ceramics International 43 10368-76

[3] Cai S, Liu J, Zhang P, Li C, Cheng Y and Chen C 2021 Experimental study on failure mechanisms of sandwich panels with multi-layered aluminum foam/UHMWPE laminate core under combined blast and fragments loading Thin-Walled Structures 159 107227

[4] Anderson C E and Royal-Timmons S A 1997 Ballistic performance of confined 99.5%-Al203 ceramic tiles International Journal of Impact Engineering 19 703-13

[5] Li R, Sun Y, Zhou L, Sun Q, Zhao Y and Feng J 2017 Influence of heat transfer on long-rod projectiles penetrating into ceramic targets Baozha Yu Chongji/Explosion and Shock Waves 37 332-8

[6] Yan K B, Huang Z x and Liu R Z 2014 Numerical and experimental research on ceramic/rubber/steel composite armor penetrated by jet Gaoya Wuli Xuebao/Chinese Journal of High Pressure Physics 28 467-72