Numerical Simulation of Wedge-shaped Multi-sandwich Reactive Armor Interfering with Shaped Jet

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Abstract. In order to obtain the explosive reaction armor with better interference capability to jet, a king of wedge-shaped multi-sandwich explosive reaction armor was designed on the basis of the existing wedge-shaped and flat structure explosion reaction armor. ANSYS/LSDYNA was used to simulate the interference process of the wedge-shaped multi-sandwich reaction armor on jet. Focusing on the research on the interference effects of four kinds of explosive reactive armors on jet penetration at 0° and 68°, it is found that one of the new explosive reactive armors has better jet interference effect than the other three explosive reactive armors at the impact angle of 0°. And the new explosive reactive armor is obviously best than other explosive reaction armors when jet penetrate at an angle of 68°. Finally, the relationship between the interference effect of explosive reactive armors on jet and the penetration angle of the jet was studied.

1. Introduction

Explosive reactive armors (ERA) have been widely produced and equipped in armored vehicles and tanks as add-on-armors against shaped change jets and long rod armor piercing projectiles since Herd proposed the theory. Explosive reactive armor consists of two steel plates and a layer of explosives. When a shaped-charge jet penetrates the interlayer explosive, the explosive will explode, and it will accelerate the two plates to move outwards in their normal directions. Then the jet will be disturbed by the two moving plates and detonation products of the interlayer explosive. As a result, the jet may bend, break and scatter around its original axis and the penetration into the primary target behind the reactive armor will reduce\textsuperscript{[1,2]}. 

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Now in order to increase the capability of interfering with jet, a number of experimental and analytical studies have been made to find new explosive reactive armors on the basis of the traditional ERA. And with the development of computer technologies, numerical simulation approaches have been applied in the formation and penetration of shaped charge jets.

Gao et al. have studied the effect of wedge-shaped charges on the jet-interference ability of ERA based on the existing double-layer flat-charged explosive structure, and found that the reasonable use of wedge-shaped charges can make jet cutting more uniform and enhance the tank’s protective performance[3]. Mao et al. studied the interference of V-type sandwich explosives on jets by the numerical simulation, and found that the degree of structural interference of V-type sandwich explosives increased with the angle increasing. The change of the V-angle does not significantly interfere with the penetration depth of the jet[4,5]. Wan and others designed a multi-sandwich structure reactive armor, and studied its interference effect on the jet through numerical simulation and experiment[6]. Zhang Ming and others studied the interference of ERA on jet penetrating at different target positions on the centerline of the double-wedge-shaped reactive armor [7]. And Ji et al studied the motion features of flying plates of double-layer wedged explosive reactive armor[8].

This paper aims to present a wedge-shaped multi-sandwich explosive reactive armor on the exiting flat-charged and wedge-shaped ERA. The finite element code LS-DYNA was used to study the jet formation and the disturbance interactions between the jet and the ERA target. Based on the numerical simulation results, the influence the impact angle on jet performance is discussed.

2. Numerical and material model

2.1. Numerical model

The wedge-shaped multi-sandwich explosive reactive armor consists of three steel plates and two layers of explosives. The two layers of explosives are respectively wedge and flat. According to the relative position of the two layers of explosives, the wedge-shaped multi-sandwich explosive reactive armor can be divided into two structures as the figure1 shows. One is the wedge-shaped explosive is upper the flat explosive, marked as new ERA1#, and another is the flat explosive is upper the wedge-shaped explosive, marked as new ERA 2#.

![Figure 1](image-url)

**Figure 1.** Wedge-shaped multi-sandwich explosive reactive armor structures.
The size of three steel plates is 420 mm (length)×50 mm(Width)×2 mm (thickness). And the size of three flat explosive is 420 mm (length)×50 mm(Width)×4 mm (thickness). The length and width of
wedge-shaped explosive are the same as the flat explosive, while the thicknesses at both ends are 3 mm and 5 mm. The shaped-charge is 100 mm in diameter and 95.12 mm in height. The liner is 100 mm in caliber diameter and 5.12 mm in thickness. And the angle of the liner is 85°. The stand-off distance from the bottom of shaped-charge to the main target is 300 mm and the distance between the ERA and the main target is 100 mm.

The axis-symmetric modeling techniques are used in the numerical simulation due to the structural symmetry of model. And the schematic diagram of numerical model is shown in Figure 2.

![Figure 2. Schematic diagram of numerical model (unit: mm).](image)

2.2. Material models and properties

The interaction process between the jet and the reactive armor and the target plate is a high-speed collision process with large deformation and high strain rate. The formation and stretching of the shaped jet, the explosion of the reactive armor and the penetration of the jet into the target plate will all cause large distortion of the grid. The use of Euler grid modeling and ALE algorithm can not only overcome the numerical calculation difficulties caused by severe distortion of the element, but also realize the dynamic analysis of fluid-solid coupling.

Therefore, the ALE algorithm was used in the simulation. The Eulerian element formation is employed for the liner, shaped charge and the air, while for ERA plates, interlayer explosive and the main target, Lagrangian element formulation is used to ensure the stability of the numerical process. And the Fluid-solid coupling algorithm is used between the target plate, air and the shape charge.

2.2.1. shaped-charge explosive

The shaped-charge explosive is RDX-8701, which is described by the “Mat_High_Explosive_Burn” material option and the JWL equation of state. The JWL equation of state defines the pressure as:

\[
p = A(1 - \omega/R_1V)e^{-R_1V} + B(1 - \omega/R_2V)e^{-R_2V} + \omega E/V
\]  

(1)

which is usually used for detonation products of high explosives. Where \(A, B, R_1, R_2\) and \(\omega\) are material constants. \(E\) is the initial internal energy and \(V\) is the relative volume. And the material constants in Equation (1) are listed in Table 1.
2.2.2. Liner, ERA plates and the main target

The materials of the liner, ERA plates and the main target respectively are copper, steel4043. They are all described by the Johnson-Cook model and the Gruneisen equation of state. The Johnson-Cook model express the flow stress as:

$$\sigma_y = (A + B\varepsilon^p)(1 + c \ln \varepsilon^p)(1 - T^m)$$  \hfill (2)

where $A$, $B$, $c$, $n$, and $m$ are input constants; $\varepsilon^p$ is the effective plastic strain; $T^*$ is the homologous temperature, expressed as:

$$T^* = (T - T_{room})/(T_{melt} - T_{room})$$  \hfill (3)

The strain at fracture is given by:

$$\varepsilon^f = \max([D_1 + D_2\exp D_3\varepsilon^p][1 + D_4\ln\varepsilon^*][1 + D_5T^*], \text{EFMIN})$$  \hfill (4)

where $D_1$, $D_2$, $D_3$, $D_4$ and $D_5$ are material constants, EFMIN is the lower bound for calculated strain at fracture. Fracture occurs when the damage parameter $D = \Sigma \Delta \varepsilon^p/\varepsilon^f$ reaches the value of 1.

And the material constants are list in Table 2. And the values of $D_1$, $D_2$, $D_3$, $D_4$ and $D_5$ are taken from Ref [11], respectively as 0.05, 3.44, -2.12, 2×10⁻⁴ and 0.61.

2.2.3. The interlayer explosive of ERA

The interlayer explosive of ERA is PBX9404, which is described by the “Ignition-and-Growth-of-Reaction-in HE” equation of state and Elastic_Plastic_Hydro model. The “Ignition-and-Growth-of-Reaction-in HE” equation of state is used to calculate the shock initiation (or failure to initiate) and detonation wave propagation of solid high explosives. A JWL equation of state defines the pressure in the unreacted explosive as:

$$P_e = r_1 e^{-\gamma_1} + r_2 e^{-\gamma_2} + r_3 \frac{T_e}{V_e}, \quad (r_3 = \omega_s c_V)$$  \hfill (5)

where $V_e$ and $T_e$ are the relative volume and temperature of the unreacted explosive respectively. Another JWL equation of state defines the pressure in the reaction products as:

$$P_p = a e^{-\gamma_p} \frac{V_p}{V} + b e^{-\gamma_p} \frac{T_p}{V} + g \frac{T_p}{V_p}, \quad (g = \omega_p c_V)$$  \hfill (6)

where $V_p$ and $T_p$ are the relative volume and temperature of the reaction products respectively.

And the material constants and parameters involved are listed in Table 3.

| Table 1. Parameters of material model and equation of state for PBX8701. |
|---------------------|-----|-----|-----|-----|-----|-----|-----|
| $\rho$/g·cm⁻³ | A/GPa | B/GPa | $R_1$ | $R_2$ | $\omega$ | $E/J$ | D/(m·s⁻¹) |
|---------------------|-------|-------|-------|-------|-------|-------|-------------|
| 1.695 | 854.5 | 20.49 | 4.56 | 1.35 | 0.25 | 9500 | 8425 |
Table 3. Parameters of material model and equation of state for PBX9404.

| Material     | $\rho$ (g·cm$^{-3}$) | $A$/GPa | $B$/GPa | $C$  | $n$  | $m$  | $G$/GPa | $T_{melt}$/K |
|--------------|----------------------|---------|---------|------|------|------|----------|--------------|
| Copper       | 8.96                 | 90.00   | 292.00  | 0.025| 0.31 | 1.09 | 47.7     | 1360.00      |
| Steel 4340   | 7.85                 | 792.00  | 510.00  | 0.014| 0.26 | 1.03 | 81.8     | 1793.00      |

3. Result and discuss

3.1. Normal penetration

A large number of experiments and simulations show that the traditional explosive reaction armor has no obvious interference effect on the jet when the jet penetrates vertically. In this paper, in order to test the interference effect of the new explosive reactive armor against vertical jet, the following 4 sets of simulation schemes were designed: jet penetrate the main target with traditional flat ERA, wedge-shaped charge ERA, new ERA 1#, new ERA 2# respectively, without ERA as a control. The sizes of the flat ERA and wedge-shaped charge ERA are the same as the flat and wedge part of the new ERA. And the penetration depth into the main target and residual tip velocity of jet at time 135μs are listed in Table 4.

Compared with penetration into the main target without ERA, it can be seen that the penetration depth of jet with four kinds of ERA only reduced respectively by 23.85%, 17.67%, 21.71%, 31.98%, which indicated the disturbance of four kinds of ERA to jet penetration is not very distinct in the normal direction. However, it can also be seen that the penetration depth and residual velocity of jet with new ERA 2# is the smallest, which indicate the disturbance of new ERA 2# to jet is best than the other three types of ERA when jet penetrates vertically.

Table 4. penetration depth and residual velocity of jet at time 135 μs.

|                  | Flat ERA | Wedge-shaped charge ERA | New ERA 1# | New ERA 2# | WithoutERA |
|------------------|----------|-------------------------|------------|------------|------------|
| Penetration depth/mm | 51.27    | 55.43                   | 52.71      | 45.8       | 67.33      |
| Residual velocity/(m·s$^{-1}$) | 3210     | 3162                    | 3026       | 2764       | 3148       |

Figure 3 shows the velocity of the jet with time from the time jet contacts the ERA to penetrate the main target. From Figure 3, it can be found that before penetrating the main target, the tip velocity of
the jet with new ERA2# is always bigger than new ERA1#. However, the final penetration depth of the jet with new ERA2# is less than new ERA1#. It can be found from Figure 4 that although the tip velocity of the jet with new ERA2# is bigger, it has broken before it penetrates the target plate, which severely weakens its penetration ability. It may be due to the angle of the second steel plate of new ERA2#, increasing the cutting effect of the steel plate on the jet, which causes the jet to break earlier and weakens its penetration ability.

![Figure 3. Tip velocity of jet vs time.](image)

**Figure 3.** Tip velocity of jet vs time.

![Figure 4. result of jet penetration into ERA at time 75 μs.](image)

**Figure 4.** result of jet penetration into ERA at time 75 μs.

### 3.2. Oblique penetration

When the jet penetrates the ERA non-vertically, the typical angle is 68° between the jet and the normal direction of the ERA. In this section, when studying the interference effect of the new explosive reactive armor on the obliquely penetrating jet, the jet penetrating the above four explosive reactive armors at an impact angle of 68° was numerically simulated. The interaction processes of the jet penetrating into ERA at an impact angle of 68° are shown in Figure 5. And the penetration depth to the main target and residual tip velocity of the jet are shown in the Table 5.

**Table 5.** Penetration depth and residual velocity of jet at time 135 μs
From the Table 5, we can see that the ERA disturbs the jet more significantly during oblique impact. When the interlayer explosive is detonated by the jet, the detonation products drive the steel plates move outward. And the moving plates cut the jet directly, thus disturbing the penetration process of jet severely. When the jet penetrates the four kinds of ERA, the penetration depths into main target are reduced by 43.75%, 50.69%, 80.42%, 82.22% compared with the penetration depth without ERA, which indicates that the disturbance of new ERA to jet is better than the flat ERA and wedge-shaped charge ERA. When the jet penetrate the ERA at an impact angle of 68°, we can also find that the penetration depth of with wedge-shaped charge ERA is smaller than the penetration depth of with flat ERA, which indicates that the disturbance of wedge-shaped charge ERA to jet is better than the flat ERA.

| Penetration depth/mm | Flat ERA | Wedge-shaped charge ERA | New ERA 1# | New ERA 2# | Without ERA |
|----------------------|----------|-------------------------|------------|------------|-------------|
|                      | 37.87    | 33.2                    | 13.18      | 11.97      | 67.33       |
| Residual velocity/(m·s⁻¹) | 2550    | 2669                    | 2010       | 2147       | 3148        |

a.Flat ERA

b.Wedge-shaped charge ERA
c.New ERA1#
From Figure 5, we can find that after the traditional explosive reactive armor or wedge-shaped charge ERA is detonated, the jet only penetrates the second layer of steel plate at the moment of contact. The movement of the second steel plate has little cutting effect on the jet. It can be explained that the interference of these two ERAs on the jet is mainly caused by the movement of the first steel plate of the ERA and the effect of the detonation products. As for the new multi-sandwich structure, the second layer of steel plate of the new explosive reactive armor is almost still due to the combined effect of the explosive detonation on both sides. The jet continues to contact with the second layer of plate and the detonation product of the second layer of explosive detonation. Therefore, the jet is broken and deflected more severely, which greatly weakens the jet's penetration ability.

Besides, comparing the new explosive reactive armors 1#, 2# and wedge-shaped charge ERA with flat ERA, due to the wedge angle, the penetration angle between the first layer of steel plate and the jet becomes slightly larger. At the same time, due to the asymmetry of the wedge-shaped charge, when the first layer of interlayer explosive is detonated, the first steel plate will deflect when it moves outward in its normal direction. Therefore, the cutting effect of ERA on the jet will become stronger.

3.3. The effect of impact angle

In this section, the jet penetration into the new ERA and the main target at impact angles of 0°, 20°, 40°, 60° and 68° were simulated to study how the angle of jet penetration influence the ability of ERA to interfere with jet.
Figure 6 shows that the relationship between penetration depth of jet and penetration angle at time 135 μs.

It can be seen that as the penetration angle increases, the penetration depth of the jet into the target plate decreases under the interference of the two explosive reactive armors. Moreover, the penetration depth of the jet into the target plate after penetrating the new explosive reaction armor 1# and the penetration angle are approximately linear. We can also find that the interference effect of new ERA 2# on the jet at a small angle (less than 20°) is better than new ERA 1#. From the analysis in Section 3.1, it may be explained as followings:

At small angles, the angle of the middle steel plate has a great influence on the interference effect of the ERA on jet. When the angle of jet penetration increases to a certain extent, the influence of the angle of the middle steel plate is negligible and the interference effects of the two reactive armors on jet are almost the same.

4. Conclusion
A new type of multi-sandwich wedge-shaped reactive armor was designed, and the interference processes of the two structures of the new ERA, the traditional flat ERA and wedge-shaped ERA with the jet were simulated. The following conclusions are drawn from the present numerical study on the jet penetration into the main target with four kinds of ERA.

(1) The study found that when the jet penetrated the four explosive reactive armors vertically, the interference effect of the ERAs on the jet was not obvious. However, the ability of the new ERA 2# to interfere with the jet is significantly better than the other three reactive armors.

(2) When the jet penetrated the explosive reactive armor at an impact angle of 68°, all four explosive reactive armors could cause obvious interference effects on the jet. At the same time, it was found that the interference ability of the new explosive reactive armor to the jet is significantly better than the traditional ERA armor and wedge-shaped charge ERA. The existence of the wedge angle can increase the interference ability of ERA to the jet.
(3) When penetrating explosive reactive armor at a large angle (68°), the double-layer explosive reactive armor mainly relies on the movement of the first steel plate and the detonation products to cause cutting effect and interference to the jet. The second steel plate of the new ERA and the detonation products of the second layer of explosives continue to interfere and cut the jet, increasing the interference effect of the reactive armor on the jet.

(4) The penetration depth of the jet into the main target after the interference of the two new ERAs decreases with the increase of the impact angle. The new ERA 2# has a better interference effect on the jet when the jet penetrates at a small angle (less than 20°) than new ERA 1#.

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