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Simulation Study of the Effect of Projectile Length-Diameter Ratio on Anti-Penetration Performance of Composite Armor

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Abstract. We studied the failure modes of 55 g cylindrical projectile penetrating ceramic/titanium alloy/gap/polyethylene/gap/921A steel composite armor structure by numerical simulation, obtained the influence of projectile length-diameter ratio on the anti-penetration performance of structure by analysis. The results showed that, ceramic breaks in-plane and forms ceramic cone, titanium alloy target shows shear failure and bending deformation, 921A steel target shows adiabatic shear failure mode when it is penetrated, bulging when it is not penetrated, the front polyethylene target shows compressive shear deformation, the rear polyethylene target shows bending deformation, and fiber tensile failure is the main failure mode, the impact fiber layer has obvious delamination and degumming phenomenon. Under the same mass condition, the larger the length-diameter ratio of the projectile, the smaller the size of the breach and the greater the penetration depth. With the further increase of the length-diameter ratio, the impact of the projectile on the penetration effect is weakened.

1. Introduction

Anti-ship missiles are developing all over the world. Semi-armour-piercing anti-ship missiles invade and explode inside the ship. The high-speed fragments produced will seriously affect the important cabins and personnel of the ship. Therefore, the anti-armour-piercing problem of the ship bulkhead has attracted wide attention. In order to improve the vitality of warships, the armor of warships has gradually evolved from single homogeneous metal armor to composite armor. Ceramic armor has the characteristics of low density, high hardness and high compressive strength, so it is suitable for the bullet-proof panel of composite armor [1], however, because of its poor plasticity and low fracture strength, ceramics cannot be used as protective armor alone, so it needs rigid backplane support [2]. With the development of bullet-proof armor, fiber reinforced composites (FRC) will be widely used in naval armor structures because of their high specific strength, specific stiffness and good impact resistance. Yuxin Xu [3-4] carried out experimental and numerical simulation studies on sandwich panels with different ratios of aramid FRC laminates as sandwich materials under high-speed impact of 10 g FSP. It was concluded that aramid laminates as sandwich materials have better elastic resistance. Masta et al. [5] designed four structural models of polyethylene (PE) with a total thickness of 11.7 mm before and after wrapping 31.6 mm thick aluminium alloy plate. High-speed ballistic experiments were carried out with 12.7 mm spherical projectile. It was concluded that the anti-penetration performance of the rear wrapping structure is the best.

In this paper, finite element analysis software ANSYS/LS-DYNA was used to study the failure mode of 55g cylindrical projectile penetrating ceramic/titanium alloy/gap/polyethylene/gap/921A steel

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composite armor structure. The influence of the length-diameter ratio of projectile on the elastic performance of the structure was obtained through analysis.

2. Finite Element Simulation

The finite element software ANSYS/LS-DYNA was used to simulate the penetration of high-speed cylindrical projectile into ceramic/titanium alloy/gap/polyethylene/gap/921A steel composite armor structure. The projectile bodies adopted 55g cylindrical projectile with sizes of *d* (diameter) 12.2mm and *l* (length) 60mm, *d*13.4mm and *l*50mm, *d*15mm and *l*40mm, *d*17.4mm and *l*30mm, *d*21.2mm and *l*20mm. In the structure, the size of ceramics is 100 mm x 100 mm x 10 mm, the size of titanium alloy plate is 200 mm x 200 mm x 6 mm, the bullet-proof layer of polyethylene is made of four polyethylene laminates, the size of single polyethylene laminate is 200 mm x 200 mm x 20 mm, the size of 921A steel plate is 200 mm x 200 mm x 8 mm, and the structural gap is 20 mm. Solid 164 three-dimensional solid elements with 8 nodes and Lagrange mesh were used to model the projectile, ceramic, titanium alloy, polyethylene and 921A steel plates. The projectile body was divided into 1 mm 1 mesh along the diameter and length direction, and the ballistic layer was divided into 1/2 mm uniform mesh along the thickness direction. The in-plane mesh was densified in the penetration area and transited to the surrounding sparse. The numerical model was based on cm-g-us unit system. The finite element model (projectile *d*15mm, *l*40mm) is shown in figure 1 and 2.

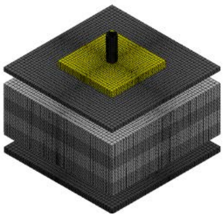

Figure 1. The Finite Element Integral Model

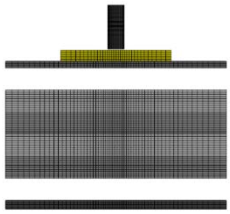

Figure 2. Cutaway of Finite Element Model

The projectile material is 35CrMnSiA low alloy ultra-high strength steel. The projectile and 921A steel adopt MAT_PLASTIC_KINEMATIC bilinear elastic-plastic constitutive model. The strain rate effect of the model is described by Cowper-Symonds model. The material parameters are shown in table 1.

Table 1. Mechanical Properties of Steel

Material	ρ/g·cm^{-3}	E/Gpa	μ	σ_y/Mpa	E^T/Mpa	C	P
35CrMnSiA	7.85	210	0.3	1280	525	40	5
921A	7.80	210	0.3	590	450	40	5

SiC ceramics are described by Johnson-Holmquist_ceramics material model and Gruneisen equation of state. The material parameters are shown in table 2.

Table 2. Material Parameters of SiC Ceramics

Parameter	Figure	Parameter	Figure	Parameter	Figure
ρ/g cm^{-3}	3.10	σ_{HEL}/GPa	6.7	D_2	0.45
G/GPa	192	P_{HEL}/GPa	5.9	K_1	2.05
A/GPa	0.96	T/GPa	1.37	K_2	0
B/GPa	0.35	m	1	K_3	0
C	0.0	n	0.65	FS	1.6
$EPSI$	1×10-6	D_1	0.005		

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Titanium alloys are described by Johnson-cook material model and Gruneisen equation of state. The material parameters are shown in table 3.

Table 3. Material Parameters of Titanium Alloys

Parameter	Figure	Parameter	Figure	Parameter	Figure
ρ/g cm^{-3}	4.51	m	1.1	D_3	0
A/GPa	0.922	T_m/K	1941	D_4	0
B/GPa	0.7	T_0/K	300	D_5	0
n	0.93	D_1	0.8		
c	0.014	D_2	0		

Mat_Composite_Damage material model is used to define the brittle failure criterion of polyethylene laminates by Chang-Chang. The material parameters are shown in table 4.

Table 4. Material Parameters of Polyethylene

Parameter	ρ/g cm^{-3}	E_1/GPa	E_2/GPa	E_3/GPa	υ_{12}	υ_{13}	υ_{23}	G_{12}/GPa	G_{13}/GPa	G_{23}/GPa	K_{fail}/GPa
Figure	0.97	30.7	30.7	30.7	0.008	0.044	0.044	0.85	0.67	0.67	2.2
Parameter	AOPT	MACF	S_c/GPa	X_t/GPa	Y_t/GPa	Y_c/GPa	α	S_n/GPa	S_{yz}/GPa	S_{xz}/GPa	
Figure	0	1	0.48	3.5	3.5	2.5	0.5	0.95	0.95	0.95	

3. Numerical Calculation and Analysis

3.1. Effect of Length-Diameter Ratio of Projectile on Structural Failure Modes

In order to study the influence of projectile length-diameter ratio on the failure modes of composite armor structures, five kinds of projectile sizes were adopted: *d* (diameter) 12.2mm and *l* (length) 60mm, *d*13.4mm and *l*50mm, *d*15mm and *l*40mm, *d*17.4mm and *l*30mm, *d*21.2mm and *l*20mm, the initial velocity of the projectile was defined as 1600 m/s. Through numerical simulation, the deformation of the composite structure under penetration by different length-diameter ratios of projectiles is obtained. The concrete results are shown in figure 3.

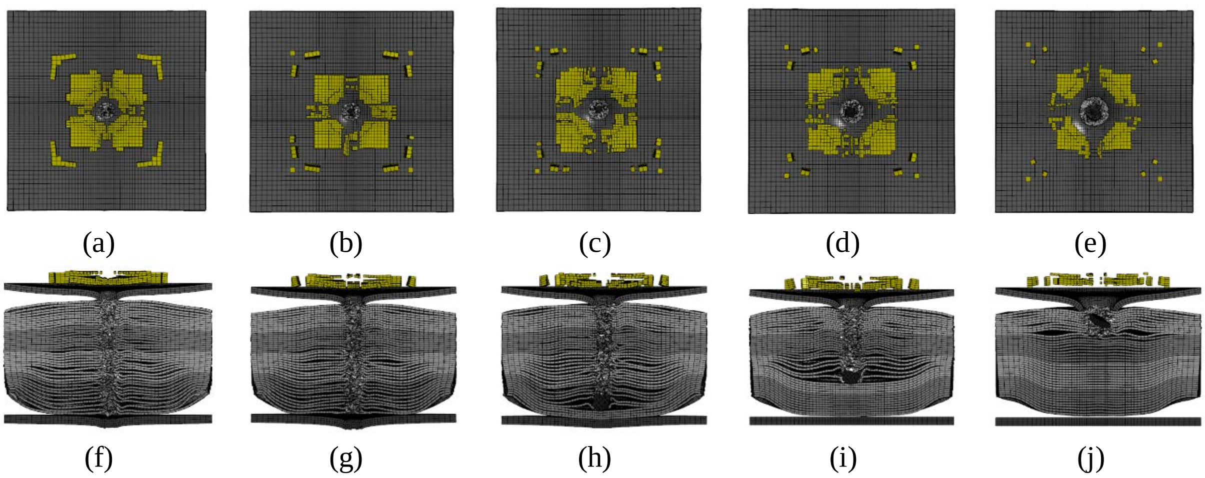

Figure 3. Failure Modes of the Rear Plane of Targets: (a) Front View of test1, (b) Front View of test2, (c) Front View of test3, (d) Front View of test4, (e) Front View of test5, (f) Side View of test1, (g) Side View of test2, (h) Side View of test3, (i) Side View of test4, (j) Side View of test5

Figure 3 shows the failure morphology of the front and side view of the structure in test 1-5. From the observation of figure 3 (a) ~ (e), it can be seen that due to the non-uniformity of ceramics, irregular

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cracks are formed in the panel after impact by the projectile. The compression wave formed when the projectile contacts the ceramic panel reflects to the tensile wave through the boundary, and the microcracks in the plane propagate under the action of the tensile wave, which ultimately leads to the failure of the ceramic panel. Comparing with figure 3 (a) ~ (e), it is found that the size of ceramic crack is much larger than the diameter of projectile, and the smaller the length-diameter ratio of projectile, the larger the size of crack, the more serious the cracking degree of ceramic panel. As the length-diameter ratio decreases, the diameter of projectile body increases, and the cross-sectional area of projectile cavity increases correspondingly when the projectile penetrates the structure. From the observation of figure 3 (f) ~ (j), it can be seen that the titanium alloy target plate shows shear failure accompanied by bending deformation; the front polyethylene target plate shows compressive shear deformation, the rear polyethylene target plate shows bending deformation, and tensile failure of fibers is the main failure mode, and the impacted fiber layer is accompanied by obvious delamination and degumming phenomenon. The 921A steel target plate shows adiabatic shear failure mode when it is penetrated, it will form bulge when it is extruded by the rear polyethylene plate. Compared with figure 3 (f) ~ (j), it is found that with the increase of the length-diameter ratio of projectile, the contact section between the projectile and the target decreases, the resistance suffered during the penetration process decreases correspondingly, and the penetration depth increases.

3.2. Effect of Length-Diameter Ratio of Projectile on Anti-penetration Performance of Structure

In order to study the impact of the projectile length-diameter ratio on the anti-penetration performance of composite armor structure, the initial velocity of the projectile body was defined as 1000 m/s, increasing 100 m/s one by one until 1300 m/s. The above 20 conditions were calculated by numerical simulation, and the effects of different projectile length-diameter ratios on the penetration depth of polyethylene bullet-proof plate and the break size of titanium alloy target plate in composite structures were obtained. The results are shown in table 5.

Table 5. Numerical Results of Structural Anti-penetrating

Number	Initial velocity （m/s）	Length-diameter ratio	Penetration depth （h_s/mm）	Break size （d_s/mm）	Number	Initial velocity （m/s）	Length-diameter ratio	Penetration depth （h_s/mm）	Break size （d_s/mm）
1		0.94	4	28.5	11		0.94	8	28.7
2		1.72	14	22.6	12		1.72	26	22.9
3	1000	2.67	26	19.2	13	1200	2.67	44	19.5
4		3.73	40	17.7	14		3.73	66	17.3
5		4.92	50	14.7	15		4.92	80	15.3
6		0.94	8	28.5	16		0.94	10	29.3
7		1.72	20	22.9	17		1.72	32	23.2
8	1100	2.67	34	19.2	18	1300	2.67	50	19.7
9		3.73	52	15.9	19		3.73	76	17.9
10		4.92	66	15	20		4.92	80	15.4

According to the data in table 5, the curves of penetration depth h_s of PE bullet-proof plate and break size d_s of titanium alloy target plate with the different projectile length-diameter ratios are drawn, as shown in figure 4 and 5.

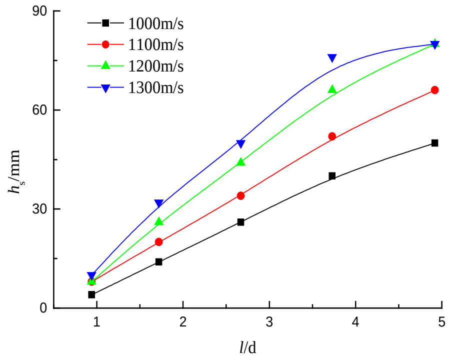

Figure 4. Curve of Penetration Depth with Length-diameter Ratio

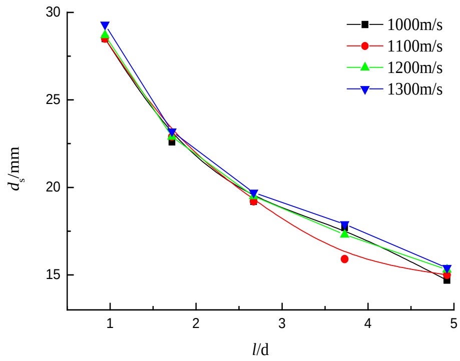

Figure 5. Curve of Break Size with Length-diameter Ratio

Observing figure 4 and 5, it is found that under the same mass condition, the larger the length-diameter ratio of the projectile, the smaller the size of the breach of the titanium alloy target, and the greater the penetration depth of the polyethylene target. This is because the larger the length-diameter ratio of the projectile, the smaller the contact force surface, and the smaller the pit opening range of the structure on the projectile face, which results in the decrease of the resistance of the projectile and the deeper penetration depth per unit weight. With the further increase of length-diameter ratio, the impact of projectile on penetration effect decreases.

4. Conclusion

In this paper, the finite element analysis software ANSYS/LS-DYNA was used for numerical simulation. The failure modes of 55 g cylindrical projectile penetrating ceramic/titanium alloy/gap/polyethylene/gap/921A steel composite armor structures were studied. The influence of the length-diameter ratio of the projectile on the anti-penetration performance of the structure was discussed. The main conclusions are as follows:

(1) Ceramics break in-plane and form ceramic cones. Titanium alloy target shows shear failure and bending deformation. 921A steel target plate shows adiabatic shear failure mode when it is penetrated, it will form bulge when it is extruded by the rear polyethylene plate.

(2) The front polyethylene target shows compression shear deformation, the rear polyethylene target shows bending deformation, and fiber tensile failure is the main failure mode, the impact fiber layer accompanied by obvious delamination degumming phenomenon.

(3) Under the same mass condition, the larger the length-diameter ratio of the projectile, the smaller the size of the breach and the greater the penetration depth. With the further increase of the length-diameter ratio, the impact of the projectile on the penetration effect is weakened.

5. References

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