Study on Penetration Resistance of Ceramic Composite Armor under Different Contact Stiffness

Li Feng¹, Shi Quan² and Chen Cai³

¹Department of equipment command and management, Shijiazhuang campus, Army Engineering University, Shijiazhuang, 050003
²Department of equipment command and management, Shijiazhuang campus, Army Engineering University, Shijiazhuang, 050003
³Department of equipment command and management, Shijiazhuang campus, Army Engineering University, Shijiazhuang, 050003

E-mail address: 1121373995@qq.com

Abstract. The finite element software ANSYS/LS-DYNA is used to simulate the penetration of tungsten alloy long rod projectile into ceramic composite armor. The penetration effect of tungsten alloy long rod projectile penetrating ceramic composite armor was obtained under different contact stiffness. At the same time, the theoretical model is used to calculate the residual velocity of tungsten alloy long rod projectile. It is found that the simulation results and theoretical calculation results are better. According to the fitting of simulation data, the relationship between penetration depth and loss velocity and incident velocity is obtained according to the different contact stiffness. It will provide some reference and reference value for studying the penetration effect of tungsten alloy long rod projectile on ceramic composite armor at a certain speed.

1. Introduction

In the future war, with the rapid development of science and technology, the speed of military attack is faster and faster, the probability of hitting weapon system is higher and higher, and the ability of damage is stronger and stronger. The protective performance of single material armor can no longer meet the requirements of future war. Therefore, the research of composite material armor is getting more and more popular. Ceramic composite armor has the characteristics of high strength, high hardness, corrosion resistance, high wear resistance and light weight. It is widely used in the protection of tanks, aircraft, ships, vehicles and other fields[1]. Experiments have proved that the protective performance of many advanced tank armors in the world has been greatly improved by using high-performance ceramics. Ceramics have become one of the indispensable materials for composite armor[2]. Wu Hai Ling[3] obtained the best match between ceramic and panel by changing the thickness of the panel. Sun Sujie[4], Cao Bing[5], Wang Jinhu[6] and others reasonably analyzed the anti-elastic performance of ceramic composite target by changing the different materials of target plate by numerical simulation and experiment. Xiong Fei[7] established homogeneous steel equivalent target of ceramic composite armor by changing penetration speed. However, these studies do not analyze the influence of contact stiffness on the penetration resistance of the projectile.
2. Establishment of finite element model

2.1. Finite element model
The finite element model is composed of tungsten alloy long rod projectile and three layers of target plate. Each part is composed of eight-node hexahedron element. The length of tungsten alloy long rod projectile is 93mm, the head of the missile body is hemispherical, the diameter is 6mm, and the aspect ratio is 15. The ceramic composite target plate is sandwich structure. The first layer and the third layer are 4043 armored steel of 100mm x 100mm x 5mm and 100mm x 100mm x 15mm respectively. The second layer is 100mm x 100mm x 30mm ceramic target plate. In order to ensure the calculation accuracy of the model, the mesh of the contact area between the projectile and the target plate is 1 mm, and the other meshes are 2 mm. Lagrange algorithm is used for all elements, which attaches the mesh to the material. The deformation of the mesh can well reflect the deformation of the material, thus accurately describing the structural changes of the material. Based on the symmetry of the model, the calculation time is saved, and the whole 1/4 of the model is used to model and calculate, and the symmetrical boundary is applied on the symmetrical surface. In order to ensure that the contact can still be carried out in the remaining units after the failure of the projectile unit, ERODING_SURFACE_TO_SURFACE is used to contact the projectile and the target plate. The finite element model is shown in Figure 1.

![Figure 1](image)

2.2. Selection of material parameters
The constitutive model of tungsten alloy long rod elastic material is Plastic_Kinematic. The mechanical properties of 4043 armor steel are described by Johnson_Cook material model and Gruneisen equation of state. The ceramic material is described by Johnson_Holmquist_Ceramics. The determination of material parameters is shown in table 1~ table 3.

| Parameter | Numerical value | Parameter | Numerical value | Parameter | Numerical value |
|-----------|----------------|-----------|----------------|-----------|----------------|
| \( \rho/(g\cdot cm^{-3}) \) | 7.83 | B/MPa | 510 | TM/K | 1793 |
| G/GPa | 77 | n | 0.26 | TR/K | 294 |
| A/MPa | 792 | c | 0.014 | C | 477 |

**Table 1. Material parameters of 4340 steel[7]**

**Table 2. Material parameters of tungsten alloy projectile[8]**
| Parameter       | Numerical value | Parameter       | Numerical value | Parameter       | Numerical value |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| \(\rho/(g\cdot cm^{-3})\) | 17.5            | \(\sigma/GPa\)  | 0.23            | C               | 40              |
| E/GPa           | 310             | Et/GPa          | 0               | P               | 5               |
| \(v\)           | 0.3             | \(\beta\)       | 1               | Fs              | 0.3             |

| Parameter       | Numerical value | Parameter       | Numerical value | Parameter       | Numerical value |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| \(\rho/(g\cdot cm^{-3})\) | 3.25            | n               | 0.6             | K1/GPa          | 220             |
| G/GPa           | 90.16           | HEL/GPa         | 10              | K2/GPa          | 0               |
| A/GPa           | 0.93            | PHEL/GPa        | 5               | K3/GPa          | 0               |
| B/GPa           | 0.31            | T/GPa           | 0.3             | Fs              | 1.6             |
| c               | 0               | D1              | 0.005           | \(\varepsilon\) | 0               |
| m               | 0.6             | D2              | 1               |                 |                 |

Table 3. Material parameters of alumina ceramic[9]

3. Theoretical model

3.1. General form of de Mar formula

In experimental study on the equivalent relationship between anti-fragment penetration of target plates of different materials, the experiment of tungsten ball penetrating armored steel is carried out, and the conclusion that the main penetrating factor of tungsten ball penetrating armored steel is shear punching plug is obtained, and the composite coefficient of armored steel is 52935. Therefore, the De Marr formula which can well reflect this phenomenon is used to calculate. The general formula of the de Mar formula for the vertical penetration of tungsten alloy long rod projectile is formula (1):

\[
V_j = K \frac{d^{0.75} \times b^{0.7}}{m^{0.5}}
\]  

In the formula, \(V_j\) is the limit penetration velocity (m/s), \(d\) is the projectile diameter (m), \(b\) is the thickness of the first target plate (m), and \(K\) is the composite coefficient of penetration.

De Marr formula can calculate the ultimate penetration velocity more accurately when tungsten alloy long rod projectile penetrates armor steel of the same material. In experimental study on penetration failure modes of targets with different materials, the residual velocity of projectile is calculated by using the formula. Through comparative analysis, it is concluded that the residual velocity calculated by this algorithm is basically the same as that obtained by test. But when tungsten alloy long rod projectile penetrates ceramic composite armor, the ultimate penetration velocity of long rod projectile cannot be calculated accurately only by using the general De Mar formula because of the different material of target.

3.2. Revised De Mar formula

The general form of de Mar formula reflects a comprehensive coefficient of the physical properties of armored materials. For ceramic composite armor, the armor is composed of many kinds of materials. Because of the different materials, the shear strength of each layer of target plate is different, and the value varies with the material. At the same time, when the tungsten alloy long rod projectile penetrates the ceramic composite armor at different speeds, the ceramic composite armor resists the tungsten alloy long rod projectile. The elastic energy is also different, so it is necessary to correct the general form of De Mar formula.
The revised DeMar formula is shown in equation (2):

\[
V_j = \left( \sum_{i} K_i \frac{d^{0.75} \times b_i^{0.7}}{m^{0.5}} \right) \times (A + B) \quad i = 1, 2, 3, n
\]

(2)

\[
A = \frac{G_i}{G_{\text{armored steel}}}
\]

(3)

\[
B = f_s \frac{V_j - \mu}{\sigma}
\]

(4)

In the formula, \( V_j \) is the ultimate penetration velocity (m/s), \( d \) is the diameter of the projectile (m), \( b_i \) is the thickness of the first target plate (m), \( K_i \) is the composite coefficient of armor piercing, which comprehensively reflects the factors affecting armor piercing, such as the properties of the target plate and projectile material. \( A \) is the ratio of shear strength of the first target plate to that of armor steel, \( B \) is the penetration of projectile by velocity. When the target is obstructing velocity, \( f_s \) is the coefficient of dynamic friction.

4. Analysis of simulation results

4.1. Comparison between Theory and Simulation Results

Table 4. Comparison between theoretical calculation and simulation test results

| Incident velocity (m/s) | Theoretical results (m/s) | Simulation results (m/s) | Error(%) |
|------------------------|--------------------------|--------------------------|----------|
| 1000                   | 402.86                   | 369.42                   | 8.30%    |
| 1100                   | 420.35                   | 391.18                   | 6.94%    |
| 1200                   | 443.59                   | 440.18                   | 0.77%    |
| 1300                   | 451.65                   | 453.15                   | -0.33%   |
| 1400                   | 465.71                   | 454.87                   | 2.33%    |

Table 4 is a comparison between the theoretical calculation residual velocity and the simulation test value of the penetration of ceramic composite target plate by tungsten alloy long rod projectile with different velocity under the condition of contact stiffness 8. From the results in Table 4, it can be seen that the theoretical calculation model is in good agreement with the simulation test results, and the errors under the above conditions are less than 10%. The rationality of the simulation model, parameters, algorithm and the reliability of the results are explained.

4.2. Contact Stiffness Analysis

According to the finite element model (Figure. 1) established above, the numerical simulation is carried out by changing the incident velocity so that the projectile penetrates vertically into the target plate with different contact stiffness at different incident velocities. A total of 50 cases are calculated, and the ceramic composite assembly of the projectile body with different contact stiffness at different incident velocities is obtained. A penetration depth and loss velocity. The results are shown in Table 5 and Table 6.

Table 5. Penetration depth of projectiles penetrating different contact stiffness targets at different incident velocities

| Contact stiffness | Incident velocity (m/s) |
|-------------------|-------------------------|
| 1                 | 1000 1100 1200 1300 1400|
|                   | 36.25 37.00 37.95 38.75 40.32 |
As shown in Table 5, with the increase of contact stiffness, the anti-penetration ability of the target decreases, and the target penetrates the target eventually. Laterally, the penetration depth increases with the increase of incident velocity. When the contact stiffness is 1, the penetration depth is less than 50 mm and does not penetrate the target plate. This shows that the target plate can achieve a good protection effect under this contact stiffness.

Table 6. LOSS VELOCITY OF PROJECTILE PENETRATING DIFFERENT CONTACT STIFFNESS TARGETS AT DIFFERENT INCIDENT VELOCITIES

| Contact stiffness | Incident velocity (m/s) | 1000  | 1100  | 1200  | 1300  | 1400  |
|------------------|-------------------------|-------|-------|-------|-------|-------|
| 1                | 1000.00                 | 1100.00 | 1200.00 | 1300.00 | 1400.00 |
| 2                | 1000.00                 | 1100.00 | 1200.00 | 845.94  | 906.45 |
| 3                | 1000.00                 | 1100.00 | 766.78  | 853.02  | 934.73 |
| 4                | 1000.00                 | 713.63  | 777.86  | 847.89  | 923.27 |
| 5                | 1000.00                 | 718.49  | 784.97  | 849.27  | 940.92 |
| 6                | 1000.00                 | 689.27  | 786.09  | 870.93  | 936.39 |
| 7                | 1000.00                 | 706.02  | 772.79  | 862.90  | 935.95 |
| 8                | 630.58                  | 708.82  | 759.82  | 846.85  | 945.13 |
| 9                | 666.06                  | 690.12  | 775.77  | 835.02  | 924.66 |
| 10               | 645.90                  | 711.90  | 781.35  | 854.37  | 937.95 |

From Table 6, it can be seen that, in the case of penetrating the target plate, the velocity of projectile loss varies slightly, but slightly, due to the different contact stiffness. From the transverse point of view, in the case of penetrating the target plate, the greater the incident velocity of the projectile, the greater the loss of the projectile velocity caused by the target plate. This shows that the elastic performance of the composite target plate is not the only determinate one. The elastic performance of the composite target plate varies greatly under different working conditions. The greater the incident velocity of the projectile in this range of velocity, the velocity of the target plate against the projectile will be increased. The ability to weaken is stronger.

Generally speaking, the penetration effect of tungsten alloy long rod projectile with different contact stiffness is different. When the contact stiffness is set to 1, even if the incident velocity of the projectile is changed, the projectile does not penetrate the target plate, which achieves good protection effect. When the contact stiffness is set to 8, 9 and 10, the protective effect of the target plate is the worst. Even at the speed of 1000m/s, the projectile can penetrate the target plate.

In the case of non-penetrating target (contact stiffness is 1), the penetration depth of projectiles at different velocities is fitted by polynomials, and the normalized incident velocities are obtained as shown in Figure 2:
\[ h = 0.1178x^3 + 0.2661x^2 + 1.308x + 37.84 \]

**Figure. 2** Fitting curve of penetration depth and incident velocity.

In the case of penetrating the target plate (i.e. contact stiffness is 8, 9 and 10 respectively), the projectile loss velocities at different velocities are polynomially fitted, and the normalized incident velocities are obtained as shown in Tables 7, Figure 3, Figure 4, and Figure 5.

**Table 7.** Relationship between projectile loss velocity and incident velocity under different contact stiffness

| Contact stiffness | Projectile loss velocity (m/s) | Goodness of fit |
|------------------|-------------------------------|-----------------|
| 8                | \[ V_{s8} = 12.68x^3 + 13.59x^2 + 104.1x + 767.4 \] | 0.998           |
| 9                | \[ V_{s9} = -10.28x^3 + 18.71x^2 + 118.7x + 763.4 \] | 0.993           |
| 10               | \[ V_{s10} = 2.342x^3 + 6.916x^2 + 111.7x + 780.8 \] | 0.999           |

**Figure. 3** Fitting curve of relation between projectile loss velocity and incident velocity when contact stiffness is 8.

**Figure. 4** Fitting curve of relation between projectile loss velocity and incident velocity when contact stiffness is 9.

**Figure. 5** Fitting curve of relation between projectile loss velocity and incident velocity when contact stiffness is 10.
When the contact stiffness is set to 1, the penetration depth of tungsten alloy long rod projectile can be estimated according to the fitting formula. When the contact stiffness is set to 8, 9 and 10, the loss velocity of tungsten alloy long rod projectile can be estimated according to the fitting formula. The calculated formula can save a lot of time and get more accurate results.

5. Conclusion
The penetration of tungsten alloy long rod projectile into ceramic composite armor was simulated by finite element software, and the residual velocity of tungsten alloy long rod projectile was obtained. Based on the theoretical model, the limit penetration velocity of tungsten alloy long rod projectile is calculated, and then the residual velocity of target plate is calculated. The rationality of the model is verified by comparing the two results. The penetration depth and loss velocity of tungsten alloy long rod projectile penetrating ceramic composite armor at different incident velocities under different contact stiffness were calculated by simulation, and the results were analyzed. The results show that when the contact stiffness is set to 1, the anti-penetration ability of ceramic composite armor is the best. With the increase of contact stiffness, the anti-penetration ability of ceramic composite armor decreases. When the contact stiffness is greater than 8, the anti-penetration ability of ceramic composite armor is the worst, and it can not protect tungsten alloy long rod projectile whose velocity is more than 1000m/s.

References
[1] Kang Y and Chai X 2011 Research and development of ceramic composite armor materials. Foshan ceramics, 21 (1), 44-45.
[2] Shen F 1992 Research progress of vehicle and human protective materials. Ordnance material science and engineering, 22(6): 53-57.
[3] Wu H L, Wu X, Wang J H, Wang Q, Zhong T, Miao C, Li S T and Bai L H 2012 Experimental study on the effect of panel thickness on the elasticity of ceramic composite targets. Ordnance material science and engineering, 35 (1), 62-65.
[4] Sun S J, Zhao B R, Wang J and Wang Z Q 2006 Study on the influence of different backplanes on the elastic resistance of ceramic composite armor. Ordnance material science and engineering, 29 (2), 70-72.
[5] Cao B 2006 Experimental study on the equivalent relationship between anti-fragment penetration of target plates of different materials. Journal of Missile and Guidance, 26 (4), 113-114.
[6] Wang J H, Jiao J H and Li Q 2013 Experimental study on penetration failure modes of targets with different materials. Journal of Zhongbei University (Natural Science Edition), 34 (6), 623-627.
[7] Xiong F, Shi Q, Wang G Y and Chen Cai 2015 Establishment of equivalent homogeneous steel target plates for ceramic composite armor at different penetration velocities. Fire control and command control(4), 72-75.
[8] Wu Y H 2006 ceramic composite target. Beijing. Beijing Institute of Technology.
[9] Ma Z Y, Zeng S Y and Jiang Z G 2007 Numerical simulation and analysis of the resistance of ceramic composite target to long-rod projectiles. Journal of China University of Science and Technology, 37 (7), 727-731.