Investigation on the Damage Mode and Anti-penetration Performance of B₄C/UHMWPE Composite Targets for Different Incident Velocities and Angles

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Abstract. To found out the effects of incident velocity and incident angle on the damage mode and anti-penetration performance of ceramic composite targets, and provide a certain basis for optimizing the structural design of ceramic composite armor. The penetration of 7.62 mm bullet into oblique boron carbide (B₄C)/UHMWPE composite target was investigated by ballistic testing and numerical simulation. The effects of incident velocity and incident angle on the fragmentation degree of bullet and ceramic panel were analyzed, also the damage mode of bullet penetrating ceramic composite target was developed preliminarily to estimate the anti-penetration performance of ceramic composite targets. Based on the testing and simulation results, it was found that the fragmentation degree of bullet and ceramic panel increases gradually with the increase of incident velocity and incident angle, but the fragmentation degree of bullet and ceramic panel decreases obviously when the incident velocity exceeds the ballistic limit; the damage mode of UHMWPE laminate is mainly tensile failure when the bullet's incident velocity is lower than the ballistic limit, and the increase of incident velocity or incident angle makes UHMWPE laminate more prone to shear failure and delamination failure. With the increase of incident angle, the ballistic limit of B₄C/UHMWPE composite target increases significantly, the deflection angle of bullet increases similarly, and the optimal thickness ratio of ceramic panel and backplate tends to decrease with the increase of incident angle.

1. Introduction
In modern warfare, the high performance and lightweight requirements of composite bulletproof materials are increasingly important. How to improve the ballistic performance of composite armors under the same areal density requirements is a hot-spot issue in the field of composite armors. Wilkins et al. [1-2] (1960) first proposed the concept of ceramic composite armor through experimental research. Ceramic materials have been widely used as armor protection materials due to the advantages of high hardness, high strength, low density, etc. The anti-penetration mechanism and ballistic performance of ceramic composite armors have been extensively investigated by scholars at home and abroad [3-6]. The anti-penetration performance of ceramic composite armors is affected by many factors, such as ceramic thickness [7], ceramic panel size [8-9], bullet's incident angle [10-12], etc. Guo Yingnan [9] found that the attitude of 12.7 mm armor-piercing projectile would deflect when the impact point of projectile is close to the edge of ceramic panel through the ballistic testing of ceramic composite armors; Chen Bin et al. [10] found that the penetration efficiency of projectile decreased with the increase of oblique angle through the ballistic testing of 30 mm semi-armor-piercing projectile into ceramic/steel composite target. Li Xiaojun [11] carried out the simulation and testing of 7.62 mm armor-piercing bullet impacting on inclined Al2O3 ceramic composite armor, and found that the ballistic limit increased significantly with the increase of the incident angle; Wang Weizhan [12] proved that the ballistic limit improved significantly and the integrity of steel core reduced gradually with the increase of the oblique angle of targets through the numerical simulation and ballistic testing of 12.7 mm kinetic energy bullet penetrating into ceramic composite armor obliquely. The above studies are mostly aimed at the research direction of alumina ceramic (Al2O3) composite armor and vertical penetration. Compared with Al2O3 ceramic, boron carbide ceramic (B4C) have higher hardness and lower density; and fiber backplate materials, such as UHMWPE laminate and aramid board, have higher specific strength, higher specific modulus, lower density than metal materials, ceramic composite armor composed of B4C ceramic and UHMWPE laminate shows higher ballistic protection efficiency [13]. The optimized design and practical application of B4C/UHMWPE composite armor are greatly significant to the development of light armor materials. However, the research of B4C/UHMWPE composite armor against bullet's oblique penetration is rarely reported.

In this study, the author carried out the ballistic testing and numerical simulation of 7.62 mm bullet into B4C/UHMWPE ceramic composite targets with different oblique angles, to investigate the impact of incident velocity and incident angle on the fragmentation degree of bullet, deflection angle of bullet and anti-penetration performance of composite target, and then the damage mode of bullet obliquely penetrating ceramic composite target was preliminarily analyzed to provide a certain basis for the optimal structural design of ceramic composite armor.

2. Numerical simulation

2.1. Calculation model

In order to found out the effects of incident velocity and incident angle on the damage mode and the anti-penetration performance of ceramic composite targets, and effectively supplement the test data, the nonlinear finite element calculation program LS-DYNA was adopted to numerically simulate the process of bullet penetrating ceramic composite target,
The calculation model is shown in Figure 1, including 7.62 mm bullet, B₄C / UHMWPE composite target, and the structural parameters of bullet and target were consistent with the penetration testing. The numerical calculation model used lagrange algorithm and was meshed with the constant stress hexahedron solid elements, and the side boundary of targets plate was defined as non-reflective constraint. Automatic surface-to-surface contact was applied to bullet components and target layers respectively; bullet and target were set to eroding surface-to-surface contact; tiebreak surface-to-surface contact was set on the interface of ceramic panel and UHMWPE laminate, and the normal and tangential failure strength are 43 MPa and 25 MPa respectively\cite{14}.

2.2. Material model

The Johnson-Cook constitutive model was adopted to describe the behavior of steel core, lead filler and steel bullet jacket that make up the bullet in the finite element analysis\cite{15}, the strength model of the metal is defined as:

$$\sigma_y = [A + B\varepsilon_p^n] \left[ 1 + C \ln \left( \frac{\varepsilon}{\varepsilon_0} \right) \right] \left[ 1 - \left( \frac{T - T_r}{T_{melt} - T_r} \right)^M \right]$$

(1)

Where $\sigma_y$ is the flow stress of material, $A$, $B$, $C$, $n$ and $M$ are material constants, the parameters of the bullet materials are listed in Table 1. $\varepsilon_p^n$ is the effective plastic strain, $\varepsilon$ is the effective strain rate, $\varepsilon_0$ is the quasi-static threshold strain rate, $T$, $T_r$ and $T_{melt}$ represents current temperature, room temperature, and melting temperature.

**Table 1.** Johnson-Cook parameters of the bullet materials \cite{16}.

| Material | $\rho$ (g·cm$^{-3}$) | $A$ (MPa) | $B$ (MPa) | $C$ | $n$ | $M$ |
|----------|----------------------|----------|----------|-----|-----|-----|
| Steel    | 7.85                 | 235      | 414      | 0.11| 0.25| 1.03|
| Lead     | 11.0                 | 10.3     | 41.3     | 0.0033| 0.21| 1.03|

The Johnson-Holmquist plasticity damage model was proposed to describe the brittle response of ceramic materials undergoing large deformations\cite{17}. The constitutive relationship is modeled by an intact normalized strength, $\sigma_i^*$, a fractured normalized strength, $\sigma_f^*$, and the hydrostatic pressure to volumetric strain relationship. The normalized equivalent stress, $\sigma^*$, is calculated from the intact normalized strength, the fractured normalized strength and the damage parameter, $D(0 < D < 1)$.

$$\sigma^* = \sigma_i^* - D(\sigma_i^* - \sigma_f^*)$$

(2)

$$\sigma_i^* = A[P^* + T^*]N[1 + C\ln \varepsilon^*] \quad \text{(3)}$$

Figure 1. Calculation model of bullet and target.
\[ \sigma_f^* = B[P^*]^M[1 + C \ln \varepsilon^*] \quad (4) \]

\[ D = \frac{\Delta \varepsilon_p}{D_1[P^* + T^*]^{\alpha_2}} \quad (5) \]

\[ P = K_1 \mu + K_2 \mu^2 + K_3 \mu^3 \quad (6) \]

Where \( A, N, B, M, C \) are the normalized intact and fracture strength constants, \( \varepsilon \) is the strain rate constant, while \( P^* \) and \( T^* \) are the pressure and maximum hydrostatic tensile strength which are normalized by the pressure at the Hugoniot elastic limit (HEL), \( D_1, D_2 \) are the damage constants of the ceramic material, \( K_1, K_2 \) and \( K_3 \) are the equation of state material constants \[15\]. The main material parameters of boron carbide ceramic (B\(_4\)C) faceplate are listed in Table 2.

### Table 2. Material parameters of boron carbide ceramic \[18\].

| Material Parameter | Value |
|-------------------|-------|
| \( P \) (g\( \cdot \)cm\(^{-3} \)) | 2.51  |
| \( A \) | 0.97  |
| \( B \) | 0.73  |
| \( C \) | 0.005 |
| \( N \) | 0.67  |
| \( M \) | 0.85  |
| \( D_1 \) | 0.001 |
| \( D_2 \) | 0.5   |
| \( K_1 \) (GPa) | 233   |
| \( K_2 \) (GPa) | -593  |
| \( K_3 \) (GPa) | 2800  |
| \( \sigma_f^* \) (GPa) | 0.50  |
| \( T \) (GPa) | 0.26  |
| HEL (GPa) | 19    |
| \( P_{HEL} \) (GPa) | 8.71  |
| \( \beta \) | 1     |

The UHMWPE laminate material was modeled with composite failure solid model, which corresponds to an orthotropic material with damage \[15\], the parameters of material are listed in Table 3.

### Table 3. Main material parameters of UHMWPE laminate \[19\].

| Material | \( E_{11} \) (GPa) | \( E_{22} \) (GPa) | \( E_{33} \) (GPa) | \( v_{12} \) | \( v_{23} \) | \( v_{31} \) | \( G_{12} \) (MPa) | \( G_{23} \) (MPa) | \( G_{31} \) (MPa) |
|----------|------------------|------------------|------------------|-------------|-------------|-------------|-----------------|-----------------|-----------------|
| UHMWPE   | 26.9             | 26.9             | 3.62             | 0.013       | 0           | 0.50        | 30.7            | 30.7            | 42.3            |

### 3. Ballistic testing

#### 3.1. Ballistic testing procedure

Ballistic testing was performed in the testing center of Nanjing University of Science and Technology, using 7.62 mm bullet to penetrate the B\(_4\)C/UHMWPE ceramic composite targets with different oblique angles. The testing setup and site layout are shown in Figure 2, and the testing setup mainly includes ballistic gun, high-speed camera, scaleplate, target frame. The bullet was fired from a 7.62 mm ballistic gun, the penetration process and incident velocity of bullet were recorded and measured by the high-speed camera and scaleplate, and the incident angles of bullet were adjusted by the obliquity of targets. The bullet used in the testing was type 53 7.62 mm ordinary bullet, as shown in Figure 3 (Left and middle); the ceramic panel and the UHMWPE laminate were bonded with polyurea adhesive, and the front of ceramic panel was protected by monolayer aramid fabric. Four ceramic composite targets (A-1, A-2, A-3, A-4) were prepared for the ballistic testing, as shown in Figure 3 (Right), and their structure and size parameters are shown in Table 4.
Ballistic testing of 7.62 mm bullet penetrating the B$_4$C/UHMWPE ceramic composite target was performed, and some effective experimental data was obtained, as shown in Table 5.

### Table 5. Partial effective data of 7.62 mm bullet into ceramic composite target.

| Targets number | Crater number | Incident angle (°) | Incident velocity (m·s$^{-1}$) | Testing results |
|----------------|---------------|--------------------|-------------------------------|-----------------|
| A-1            | 1#            | 0                  | 400                           | PP              |
|                | 2#            |                    | 344                           | PP              |
| B-1            | 1#            | 0                  | 384                           | PP              |
|                | 2#            | 0                  | 408                           | PP              |
|                | 3#            | 384                |                               |                 |
| A-3            | 1#            | 0                  | 400                           | PP              |
|                | 2#            | 30                 | 800                           | CP              |
|                | 3#            |                    | 600                           | PP              |

Note: partial penetration (PP); complete penetration (CP)

According to the testing data in Table 5, when 7.62 mm bullet penetrate the B$_4$C/UHMWPE ceramic composite target vertically, the ballistic limit of the target A-2 is within the velocity range of 408~432 m/s, that of target B-1 is within the velocity range of 384~408 m/s, and the ballistic limit of target A-3 is higher than 600 m/s. The conclusion can be drawn that the anti-penetration performance of target A-2 (incident angle, 0°) is better than that of target B-1.
(incident angle, 0°), and the anti-penetration performance of target A-3 (incident angle, 30°) is much higher than that of target A-2 (incident angle, 0°).

3.3. Comparison of testing results and simulation results
In order to found out the penetration process of 7.62 mm bullet into B₄C/UHMWPE ceramic composite target, the following numerical simulation was carried out in advance: Composite target A consisting of 8 mm B₄C and 5 mm UHMWPE laminate was penetrated vertically by the bullet with the velocity of 408 m/s and 432 m/s, as shown in the Figure 4, the numerical simulation results consist with the ballistic testing results, the former didn’t penetrate target A and the latter did, and the bulge height behind the target of testing results and numerical simulation was also similar. At the same time, composite target B consisting of 6 mm B₄C and 10 mm UHMWPE laminate was penetrated vertically by the bullet with the velocity of 408 m/s and 432 m/s, the former didn’t penetrate target A and the latter did, which indicated that the experimental results consist with the numerical simulation results.

![Figure 4.](image_url) 

**Figure 4.** Equivalent plastic strain diagrams of bullet into composite target at beginning and ending moments.

4. Analysis and discussion

4.1. Damage mode of bullet and target

![Image](image_url)

**Figure 5.** Front and rear images of composite targets tested against 7.62 mm bullet.

From the images of B₄C ceramic panels and UHMWPE laminates tested against 7.62 mm bullet in Figure 5, bullet 1# and bullet 2# on target A-1 didn’t penetrate the composite target, The degree of fragmentation of bullet 1# and bullet 2# was similar, the fragmentation of
ceramic panel at crater 1# was stronger than that at crater 2#, and the bulge height behind the target at crater 1# was higher than that at crater 2#; bullet 1# on target A-2 penetrated the target plate (bullet 1# was lost), bullet 2# didn’t penetrate the composite target, the fragmentation of ceramic panel at crater 2# was stronger than that at crater 1#; bullet 1# and 2# on target B-1 didn’t penetrate the composite target, bullet 3# penetrated the target (bullet 3# was lost), bullet 1# was more broken than bullet 2#, the fragmentation of ceramic panels from small to large are crater 3#, 2#, 1# respectively, and the bulge height behind the target at crater 1# is higher than that of crater 2#; bullet 1# and 3# on target A-3 didn’t penetrate the composite target, bullet 2# penetrated the target, the broken degree of bullet 3# is higher than that of bullet 1#, the broken degree of ceramic panels at crater 1#, 3#, 2# increased gradually, and the bulge height behind the target at crater 3# is higher than that of crater 1#.

The images of ceramic panels on target A-1 and target A-2 in Figure 5 indicate that the fragmentation degree of bullet and ceramic panel increases gradually with the increase of bullet's incident velocity, but the fragmentation degree of ceramic panels decreases significantly when the incident velocity of bullet exceeds the ballistic limit of targets. The bullet and composite target have sufficient contact time when the incident velocity of bullet is lower than the ballistic limit, and bullet's kinetic energy was completely absorbed through the abrasion and fragmentation of bullet and composite target, the ceramic panel would absorb more bullet's kinetic energy with the increase of bullet's incident velocity, therefore, the fragmentation degree of bullet and target would also increase gradually; the contact time between bullet and target decreases when the incident velocity of bullet exceeds the ballistic limit of targets, and the fragmentation of bullet and ceramic panel also decreases obviously. The damage of UHMWPE laminates at different incident velocities on target A-1 and target A-2 shows that the damage mode of UHMWPE laminates is mainly tensile failure when the incident velocity of bullet is lower than the ballistic limit of composite target, and the shear failure becomes more obvious in the damage mode of UHMWPE laminates when the bullet velocity exceeds the ballistic limit of composite target.

In Figure 5, bullet 1# of target A-1, bullet 2# of target A-2, bullet 1# of target A-3 have the same incident velocity, and the incident angles are 0°, 0°, 30° respectively. None of the above three bullet penetrated composite targets, the kinetic energy of bullet was completely converted into the energy of the fragmentation and deformation of bullet and composite targets. Compared with the first two, the fragmentation degree of bullet and ceramic panels in target A-3 was significantly stronger. Bullet and ceramic panels absorbed more bullet kinetic energy through fragmentation and deformation, while UHMWPE laminates reduced the energy absorbed, accordingly, the plastic deformation of UHMWPE laminates decreased. At the same time, for the damage mode of UHMWPE laminate, with the increase of bullet's incident angle, the partial velocity of bullet parallel to the direction of target and the contact area between bullet and targets increases gradually, as a result, UHMWPE laminate began to fail with degumming and spalling, while the shear failure forms significantly reduced.

4.2. Analysis of anti-penetration performance of targets
Taking target A composed of 8 mm B4C and 5 mm UHMWPE as an example, the ballistic testing with incident angles of 0°and 30°was performed, and the simulation conditions with incident angles of 0°, 10°, 20°, 30°were supplemented. Combined with the testing results and simulation results, the ballistic limit and deflection angle of composite target A under
different incident angles are shown in Table 6. Figure 6 is bullet's attitude diagrams at the ending moment of penetration under different incident angles (To display the deflection angle of bullet, UHMWPE laminate is hidden).

### Table 6. Ballistic limits at different incident angles (Target A).

| Incident angle(°) | 0   | 10  | 20  | 30   |
|-------------------|-----|-----|-----|------|
| Ballistic limit (m/s$^{-1}$) | 408–432 | 440–470 | 520–580 | 620–680 |
| Deflection angle(°) | 6.2 | 9.6 | 11.2 | 23.2 |

![Figure 6. The diagrams of bullet attitude with the same incident velocity and different incident angles (UHMWPE laminate is hidden).](image)

The ballistic limits of different incident angles in Table 3 indicate that the ballistic limit of B$_4$C/UHMWPE composite target is significantly improved with the increase of bullet's incident angle; the deflection angle of bullet increases with the increase of incident angle, and the deflection of bullet further improves the anti-penetration performance of composite target.

The incident angle of bullet not only affects the anti-penetration performance of ceramic composite target, but also affects the damage mode of the B$_4$C/UHMWPE composite target. Therefore, the effect of bullet's incident angle on the optimal thickness ratio of ceramic panel and backplate must be considered. From the analysis of the thickness ratio of composite armor by Hetherington$^{[20]}$, it can be seen that the optimal thickness ratio of ceramic panel and backplate under the condition of a given areal density satisfies:

$$\frac{t_c}{t_b} = \rho_b (r - r_p) - \rho_c (r - r_p)$$

(7)

Where $r_p = 0.8 \left( r + \frac{2A}{\rho_c} \right)$, $r$ is the radius of bullet, $A$ is the given areal density, $\rho_c$ and $\rho_b$ are the density of ceramic and backplate, and $t_c$ and $t_b$ are the thickness of ceramic and backplate.

For the B$_4$C/UHMWPE composite target with an areal density of 2.5g/cm$^2$, other parameters are known, the optimal thickness ratio of ceramic panel and backplate $t_c/t_b=1.25$. The effect of bullet's incident angle on the optimal thickness ratio of ceramic panel and backplate was investigated by the method of numerical simulation: the bullet with incident angles of $0^\circ$ and $30^\circ$ were fired to penetrate target C (7.5 mm B$_4$C + 6.0 mm UHMWPE, $t_c/t_{\text{targetC}}=1.25$) and target D (7.0 mm B$_4$C + 7.5 mm UHMWPE, $t_c/t_{\text{targetD}}=0.93$).

The results of simulation shows that the ballistic limit of target C is higher than that of target D when the bullet's incident angle is $0^\circ$; on the contrary, the ballistic limit of target D is higher than that of target C when the bullet's incident angle is $30^\circ$. The following conclusion
can be drawn: as the incident angle of bullet increases, the optimal thickness ratio of ceramic panel and backplate tends to decrease.

5. Conclusion
In this paper, the ballistic testing of 7.62 mm bullet into B4C/UHMWPE ceramic composite targets with different oblique angles was performed, and the testing results were validated and supplemented by the numerical simulation results of LS-DYNA platform. By analyzing the effects of incident velocity and incident angle on the bullet and target, the results are concluded as follows:

(1) With the increase of bullet's incident velocity, the fragmentation degree of bullet and ceramic panel increases gradually, the degree of fragmentation of bullet and ceramic panel decreases significantly when the incident velocity of bullet exceeds the ballistic limit. The damage mode of UHMWPE laminate is mainly tensile failure when the incident velocity of bullet is lower than the ballistic limit, and the shear failure form becomes obvious gradually when the speed approaches or exceeds the ballistic limit.

(2) With the increase of bullet's incident angle, the ballistic limit of the B4C/UHMWPE composite target improves significantly, the fragmentation degree of bullet and ceramic panel increases significantly, and the deflection angle of bullet increases gradually, also the optimal thickness ratio of ceramic panel and backplate tends to decrease gradually as the incident angle increases.

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