Research on dynamic response of pbo fiber-reinforced composite under high-speed penetration

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Abstract. The damage mode and failure mechanism of the PBO composite are studied of the penetrating speed from 900 m/s to 1900 m/s, based on the dynamic response of the PBO fiber-reinforced composite target under high-speed penetration. Firstly, the mechanical properties of the projectile and the target material under high strain rate were characterized, and then the penetration of high-speed projectile into target is simulated. Finally, the penetration test is verified. The results show that the dynamic response mechanism of PBO composite target under high-speed penetration varies significantly with the penetrating speed.

1. Introduction
In addition to high specific strength, high specific modulus and strong designability compared with traditional metal materials, fiber-reinforced composite materials also have outstanding advantages, such as preservative, anti-penetration and anti-fragmentation [1]. Therefore, fiber-reinforced composite materials are widely used in the field of armor protection, such as armor lining, bulletproof vest, bulletproof helmet and so on [2]. In the battlefield environment, fiber-reinforced composites are faced with various kinds of high-speed kinetic energy projectile and high-speed fragment penetration, so it is of great significance to study the dynamic response of fiber-reinforced composites under high-speed penetration [3-5]. In this paper, the failure mode and mechanism of PBO composite target under the high-speed penetration are studied by the method of simulation calculation and test verification, which is of great guiding significance for the design of new armor composite material and the further improvement of armor protection ability.

2. Mechanical properties of the materials
The projectile and target have the characteristics of high strain rate, high overload and large deformation in the process of high-speed penetration. In order to accurately study the dynamic response of PBO fiber reinforced composite under high-speed penetration, it is necessary to characterize the key mechanical properties of projectile and target materials.

Figure 1 shows the stress-strain curve of the projectile material under quasi-static compression (strain rate of $10^{-3}$/s) and dynamic compression (strain rate of $10^{3}$/s). As can be seen from the figure, the projectile material shows a significant strain rate reinforcement effect.
Figure 1. the projectile material under quasi-static and dynamic compression.

Figure 2 shows the stress-strain curve of PBO composites under quasi-static tensile (strain rate of $10^{-3}$/s) and dynamic tensile (strain rate of $10^3$/s). It can be seen from the figure 2 that the PBO composite has obvious high-speed toughness at high strain rate, and its fracture absorption ability is obviously improved.

3. Simulation of PBO fiber-reinforced composite target under high-speed penetration

3.1. Constitutive model of fiber-reinforced composite

Orthotropic constitutive model is currently the most widely used composite material model. When the composite structure was simulated under high overload conditions, it will present diversity and complexity due to different failure criteria [6]. The failure of fiber-reinforced composite materials is generally considered to be a progressive failure process [7]. Chang-Chang proposed a progressive failure model for predicting the ultimate strength of laminates with open holes under the tensile load in 1987. The Chang-Chang criterion is mainly described by five material strength parameters: S1, S2, S12 and C2 are obtained from material strength measurement, $\alpha$ is defined by material shear stress-strain measurements [8-9].

In plane stress, the strain expressed by stress as:

$$\varepsilon_1 = \frac{1}{E_1}(\sigma_1 - \nu_1\sigma_2)$$

$$\varepsilon_2 = \frac{1}{E_2}(\sigma_2 - \nu_2\sigma_1)$$

$$2\varepsilon_{12} = \frac{1}{G_{12}} \tau_{12} + \alpha \tau_{12}^3$$

(1)
where $e_{11}$, $e_{22}$, $e_{12}$ is the strain, $\sigma_1$, $\sigma_2$, $\tau_{12}$ is the stress, $E_1$, $E_2$, $G_\alpha$ is the modulus, $v_1$, $v_2$ is the Poisson's ratio, $\alpha$ is the nonlinear shear stress parameter.

The third equation defines the nonlinear shear stress parameter $\alpha$. A fiber matrix shearing term augments each damage mode (which is the ratio of the shear stress to the shear strength):

$$
\overline{\tau} = \frac{\frac{G_\alpha}{2} + \frac{1}{2} \alpha \tau_{12}^2}{\frac{G_\alpha}{2} + \frac{1}{2} \alpha S_{12}^2}
$$

Three criteria are embedded in the failure criterion of Chang-Chang composite materials, The matrix cracking failure criteria, The compression failure criteria and the fiber breakage criterion.

(1) The matrix cracking failure criteria is determined from

$$
F_{matrix} = \left( \frac{\sigma_2}{S_2} \right)^2 + \overline{\tau}
$$

where failure is assumed whenever $F_{matrix} > 1$. If $F_{matrix} > 1$, then the material constants $E_2$, $G_\alpha$, $v_1$, $v_2$ are set to zero.

(2) The compression failure criteria is given as

$$
F_{comp} = \left( \frac{\sigma_1}{S_1} \right)^2 + \left( \frac{C_{12}}{S_{12}} \right)^2 - 1 \left( \frac{\sigma_2}{S_2} \right)^2 + \overline{\tau}
$$

where failure is assumed whenever $F_{comp} > 1$. If $F_{comp} > 1$, then the material constants $E_1$, $v_1$, $v_2$ are set to zero.

(3) The final failure mode is due to fiber breakage.

$$
F_{fiber} = \left( \frac{\sigma_1}{S_1} \right)^2 + \overline{\tau}
$$

Failure is assumed whenever $F_{fiber} > 1$. If $F_{fiber} > 1$, then the constants $E_1$, $E_2$, $G_{12}$, $v_1$, $v_2$ are set to zero.

### 3.2. Construction of finite element model

A finite element model was established for the process of the cylindrical projectile penetrating the PBO composite target, as shown in figure 3. According to the actual situation, a series of specific solution methods and boundary conditions were established. For example, multi-node parallel computing is set up, and the calculation starts from the projectile approaching the target; non-reflective boundary conditions are applied to avoid the impact of stress wave reflection; surface-to-surface erosion contact is defined to describe penetration; the destructive behavior of the material is described by the two failure criteria of equivalent stress and principal strain.

![Figure 3. The finite element model.](image-url)
3.3. The simulation results of PBO fiber-reinforced composite under penetration

Table 1 shows the summary of simulation results of PBO fiber-reinforced composite target under penetration. According to the results shown in the table 1, it can be seen that all the PBO composite targets were pierced through. Figure 4 shows the velocity-time curve of projectile with different initial velocities.

Table 1. The summary of simulation results of the penetration.

| Conditions | Size of target (mm) | Initial velocity (m/s) | Residual velocity (m/s) |
|------------|---------------------|------------------------|-------------------------|
| 1          | 100×100×15          | 900                    | 804                     |
| 2          | 100×100×15          | 1200                   | 1055                    |
| 3          | 100×100×15          | 1400                   | 1239                    |
| 4          | 100×100×15          | 1500                   | 1324                    |
| 5          | 100×100×15          | 1700                   | 1493                    |
| 6          | 100×100×15          | 1900                   | 1668                    |

(a)$V_0=900\text{m/s}$      (b)$V_0=1200\text{m/s}$
(c)$V_0=1400\text{m/s}$      (d)$V_0=1500\text{m/s}$
Figure 4. The velocity-time curve of projectiles with different initial velocities.

3.4. The dynamic response of PBO fiber-reinforced composites under penetration

The simulation results show that the dynamic response of PBO composite target is variant under different penetrating speeds. Secondly, the simulation results at speed of 900m/s and 1500m/s are selected for detailed analysis.

3.4.1. Simulation results of the penetration with initial velocity of 900m/s

Figure 5 shows the plastic damage process of PBO composite target against cylindrical projectile with a speed of 900m/s. According to figure 5, it can be concluded that after the high-speed projectile hits the target, the PBO target quickly show a pitting damage due to the impacting and punching effect. The erosion damage of the PBO composite target deepens with continuous high-speed penetration, at the same time an obvious punching shear failure appear inside the target, forming a punching plug block with the same diameter as the projectile. The dorsal bulge of the target is very obvious, and at this time, the composite material on the back of the target is mainly subjected to tensile failure, and the whole PBO target occurs the typical interlayer damage. Under the further penetration, the composite target is run through, the damage and failure between the layers are more obvious. At the back of target, the delamination range far exceeds the diameter of the projectile.

Figure 5. The plastic damage process of PBO target (projectile speed is 900m/s).

3.4.2. Simulation results of the penetration with an initial velocity of 1500m/s

Figure 6 shows the plastic damage process of PBO composite target against the cylindrical projectile with a speed of 1500m/s. It can be seen that the dynamic response of the PBO composite target at a penetrating speed of 1500m/s is similar to that at 900m/s. The biggest difference is that the destruction range and peeling
degree of the several layers that on the back of the target are relatively small. The preliminary analysis is that at the penetrating speed of 1500 m/s, the action time is shorter, the damage and failure do not have enough time to spread to a larger area when the penetration is over.

**Figure 6.** The plastic damage process of PBO target (projectile speed is 1500m/s).

4. Experimental verification
In order to verify the validity of the simulation method and the accuracy of the simulation results, the simulation results are compared with the test results. The statistics of simulation and test results are shown in table 2, and the comparison of target damage and failure modes is shown in figure 7. Through comparison, it is found that the speeds are very close, and the damage modes of the target are basically the same, which verifies the reliability of the calculation method and the accuracy of the simulation results.

**Table 2.** The statistics of the results of simulation and test.

| Conditions | Results of simulation | Results of test | error of equivalent V50 (%) |
|------------|-----------------------|-----------------|-----------------------------|
|            | Initial velocity (m/s) | Residual velocity (m/s) | equivalent V50 (m/s) | Initial velocity (m/s) | Residual velocity (m/s) | equivalent V50 (m/s) |                  |
| 1          | 900                   | 804             | 404                        | 911                     | 795.9             | 443                        | 8.8               |
| 2          | 1200                  | 1055            | 571                        | 1195.3                  | 1072.4            | 528                        | 8.1               |
| 3          | 1400                  | 1239            | 652                        | 1435.2                  | 1238.7            | 724                        | 9.9               |
| 4          | 1500                  | 1324            | 704                        | 1498.5                  | 1339.9            | 671                        | 4.9               |
| 5          | 1700                  | 1493            | 812                        | 1684.1                  | 1508.7            | 748                        | 8.6               |
| 6          | 1900                  | 1668            | 910                        | 1882.2                  | 1641.7            | 921                        | 1.2               |
5. Conclusion

Aiming at the dynamic response of PBO composite target under high-speed penetration, firstly, the key mechanical properties of projectile and target material are characterized in this paper. Then the PBO fiber-reinforced composite material against penetration at different speeds are simulated, the response mechanism and damage mechanism of composite target under high-speed penetration are analyzed. Finally, the simulation results are compared with the test results, the error is within the controllable range. After comprehensive analysis of the above simulation results and test results, the conclusions are as follows:

(1) Within the speed range of this paper, the PBO composite target is completely penetrated. As the initial speed increases, the speed difference between the front and back of the target gradually increases, and the error range of equivalent V50 is 1.2% -9.9%.

(2) The simulation results agree well with the experimental results. During the penetration, the PBO target show a pitting damage due to the impacting and punching effect. Then an obvious punching shear failure appear with the continuous high-speed penetrating, and form a punching plug block with the same diameter as the projectile. The dorsal bulge of the target is very obvious, and the composite material on the back of the target is mainly subjected to tensile failure. Under the further penetration, the composite target is run through, the damage and failure between the layers are more obvious. At the back of target, the delamination range far exceeds the diameter of the projectile.

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