Simulation Study on the Performance of Kevlar Fibre Reinforced Composites Under the Penetration of Fragment

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Abstract. Aiming at the problem of Kevlar fibre reinforced composite target anti penetration of wedge-shaped fragment, the finite element models of Kevlar fibre reinforced composite targets with different thickness and the fragments are established. The simulation calculation of Kevlar fibre reinforced composite target against penetration of different velocity fragments is carried out. The anti-ballistic V\textsubscript{50} of Kevlar fibre reinforced composite target with different thickness is obtained, and the damage failure mode of the Kevlar fibre reinforced composite target in the process of anti fragment penetration is analyzed, and the simulation results are verified by experiments. This simulation provides scientific basis and data support for the optimization design of composite structure armor and armor lining.

1. Introduction

In addition to high specific strength, high specific modulus and strong designability compared with traditional metal materials, fibre-reinforced composite materials also have outstanding advantages, such as anti-penetration and anti-fragmentation\textsuperscript{[1]}. Therefore, fibre-reinforced composite materials are widely used in the field of armor protection, such as armor lining, bulletproof vest, bulletproof helmet and so on\textsuperscript{[2]}. In the battlefield environment, fibre-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 fibre-reinforced composites under penetration\textsuperscript{[3-5]}. In this paper, the failure mode and mechanism of Kevlar composite target under the fragment penetration are studied by the method of simulation calculation and test verification, which is of great guiding significance for the design of composite structure armor and composite armor lining.

2. Units and algorithms
In this paper, a three-dimensional finite element model of Kevlar fibre reinforced composite target against wedge-shaped fragment penetration is established, and the solid164 (a three-dimensional 8-node solid element) is selected for solid mesh generation. There are three kinds of algorithms commonly used in dynamic simulation software: Lagrangian algorithm, Euler algorithm and ALE (arbitrary Lagrangian Euler) algorithm. Generally speaking, Lagrangian algorithm has high accuracy and efficiency, but it is not suitable for extreme deformation. ALE algorithm and Euler algorithm are suitable for solving large deformation problems, but the complexity of the algorithm increases, the computational efficiency decreases accordingly, the material interface is not clear, it is unable to accurately simulate the material thermodynamic behaviour related to history and strain rate, and the computational accuracy is usually lower than Lagrangian algorithm. In this paper, The simulation mainly focuses on the anti penetration performance of composite materials, considering the calculation accuracy and efficiency, and the penetration problem does not involve great deformation, so Lagrangian explicit integration algorithm is adopted.

3. Constitutive model of fibre-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 fibre-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: $S_1$, $S_2$, $S_12$ and $C_2$ 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:

$$
\begin{align*}
\epsilon_1 &= \frac{1}{E_1}(\sigma_1 - \nu_1\sigma_2) \\
\epsilon_2 &= \frac{1}{E_2}(\sigma_2 - \nu_2\sigma_1) \\
2\epsilon_{12} &= \frac{1}{G_{12}}\tau_{12} + \alpha\tau_{12}^3
\end{align*}
$$

(1)

where $\epsilon_1$, $\epsilon_2$, $\epsilon_{12}$ is the strain, $\sigma_1$, $\sigma_2$, $\tau_{12}$ is the stress, $E_1$, $E_2$, $G_{12}$ is the modulus, $\nu_1$, $\nu_2$ is the Poisson's ratio, $\alpha$ is the nonlinear shear stress parameter.

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

$$
\bar{\tau} = \frac{\tau_{12}^2 + \frac{1}{4}\alpha\tau_{12}^4}{\frac{S_{12}^2}{G_{12}} + \frac{1}{4}\alpha S_{12}^4}
$$

(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 fibre breakage criterion.

(1) The matrix cracking failure criteria is determined from


\[ F_{\text{matrix}} = \left( \frac{\sigma}{\sigma_y} \right)^2 + \bar{\tau} \]  

(3)

where failure is assumed whenever \( F_{\text{matrix}} > 1 \). If \( F_{\text{matrix}} > 1 \), then the material constants \( \epsilon, \ \gamma, \ \nu_1, \ \nu_2 \) are set to 0.

(2) The compression failure criteria is given as

\[ F_{\text{comp}} = \left( \frac{\sigma}{\sigma_y} \right)^2 + \left[ \left( \frac{C_{11}}{2\sigma_y} \right)^2 - 1 \right] \frac{e_1}{e_1} + \bar{\tau} \]  

(4)

where failure is assumed whenever \( F_{\text{comp}} > 1 \). If \( F_{\text{comp}} > 1 \), then the material constants \( \epsilon, \ \nu_1, \ \nu_2 \) are set to 0.

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

\[ F_{\text{fiber}} = \left( \frac{\sigma}{\sigma_y} \right)^2 + \bar{\tau} \]  

(5)

Failure is assumed whenever \( F_{\text{fiber}} > 1 \). If \( F_{\text{fiber}} > 1 \), then the constants \( \epsilon, \ \gamma, \ \nu_1, \ \nu_2 \) are set to 0.

4. Construction of finite element model

A finite element model was established for the process of the fragment penetrating the Kevlar fibre reinforced composite, as shown in Figure 1. 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 fragment 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 behaviour of the material is described by the two failure criteria of equivalent stress and principal strain.

![Figure 1. The finite element model.](image)

5. The simulation results of Kevlar fibre reinforced composites anti penetration

According to the simulation results of different thickness Kevlar fibre reinforced composite target against wedge-shaped fragment penetration, the anti-ballistic \( V_{50} \), the damage failure mode of the
target plate and the velocity variation law of the projectile body were obtained. The anti-penetration condition of fragment penetrate the Kevlar fibre reinforced composite target plate with a thickness of 3.7 mm is selected as an example for detailed analysis.

5.1. The simulation results of the fragment with initial velocity of 540 m/s

Figure 2 shows the process of the wedge fragment penetrating the Kevlar composite target with an initial velocity of 540 m/s, and Figure 3 shows the plastic damage process of the Kevlar composite target. According to the figure, after the fragment hits the target at a higher velocity, the Kevlar composite target plate is directly crushed by impact and showed open pit damage, forming a cross-shaped damage on the front of the target plate Strain zone, with the continuous intrusion of the fragment, the erosion damage of the Kevlar composite target plate deepens, and there is obvious stamping shear damage inside the target plate, forming a punch hole equivalent to the diameter of the fragment, while the back of the target is convex, the composite material on the back of the target plate is stretched, at this time, the interior of the whole laminated target plate appears typical and significant inter-layer damage. With the reduction of the fragment’s speed, the intrusive effect weakened, the damage between the layers of the composite target plate is more obvious, and finally in the back of the Kevlar composite target, form a back convex drum bag that is far beyond the diameter of the fragment.

Figure 2. The process of the penetrating.

Figure 3. The plastic damage process of Kevlar Composite target.
Figure 4 shows the speed-time curve of the fragment in the process of invading the Kevlar composite target plate, it can be derived from the figure that as the invasion progresses, the speed of fragment is gradually decreased, and at about 70 μs moment, the bullet body speed began to rebound, at this moment the fragment has not yet run through the Kevlar composite target plate, there are still multiple layers of composite material can play a protective role. Subsequently, the fragment rebounded due to the last few layers of the target deformation rebound.

![Figure 4. The speed-time curve of the fragment.](image)

5.2. The simulation results of the fragment with initial velocity of 560 m/s
Figure 5 shows the process of the fragment penetrating the Kevlar composite target with an initial velocity of 560 m/s, and Figure 6 shows the plastic damage process of the Kevlar composite target. According to the figure, after the fragment hits the target at a higher velocity, the Kevlar composite target plate is directly crushed by impact and showed open pit damage, forming a cross-shaped shape on the front of the target plate. With the continuous intrusion of the fragment, the erosion and destruction of the Kevlar composite target plate is deepening, and there is obvious stamping shear damage inside the target plate, forming a punch hole equivalent to the diameter of the chip, while the back of the target is convex, the composite material on the back of the target plate is stretched, at this time, the interior of the whole laminated target plate appears typical and significant inter-layer damage. With the gradual decrease of the breaking speed, the intrusive effect gradually weakened, the damage between the layers of the composite material target plate is more obvious, and finally the composite target plate is run through, the damage between the layers is more significant, especially in the back of the Kevlar fibre composite target plate, the layering and stripping range of the laminate is much larger than the diameter of the fragment.

![Figure 5. The simulation results of the fragment with initial velocity of 560 m/s.](image)

![Figure 6. The plastic damage process of the Kevlar composite target.](image)
Figure 5. The process of the penetrating.

Figure 6. The plastic damage process of Kevlar Composite target.

Figure 7 shows the speed-time curve of the fragment in the process of invading the Kevlar composite target plate, it can be derived from the figure that as the invasion progresses, the speed of fragment is gradually decreased, and at about 50 μs moment, the breaking speed stops attenuating, and at this moment the fragment penetrate through the Kevlar composite target plate, the speed of fragment become constant.

Figure 7. The speed-time curve of the fragment.

5.3. The verification of calculation results
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 1, and the comparison of target damage and failure modes is shown in Figure 8. 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 1.** The statistics of the results of simulation and test.

| Conditions | Results of simulation | Results of test |
|------------|-----------------------|-----------------|
|            | Thickness (mm) | V<sub>50</sub> (ms<sup>-1</sup>) | Thickness (mm) | V<sub>50</sub> (ms<sup>-1</sup>) |
| 1          | 2.0          | 380              | 2.1          | /              |
| 2          | 2.6          | 440              | 2.6          | 438            |
| 3          | 3.1          | 460              | 3.1          | 453            |
| 4          | 3.7          | 550              | 3.7          | 565            |
| 5          | 4.4          | 580              | 4.5          | /              |
| 6          | 5.1          | 600              | 5.0          | /              |
| 7          | 6.0          | 640              | 6.1          | /              |

**Figure 8.** The comparison of failure models of target.

6. Conclusion
In this paper, The simulation calculation of Kevlar fibre reinforced composite target against penetration of different velocity fragments is carried out. The anti-ballistic V<sub>50</sub> of Kevlar fibre reinforced composite target is obtained, and the damage failure mode of the Kevlar fibre reinforced composite is analyzed, and the reliability and accuracy of the simulation calculation method are verified. It is found that with the increase of Kevlar sheet thickness, its anti-ballistic V<sub>50</sub> continuously improved, but it is not linear. Under the effect of Penetration, the Kevlar composite target plate is crushed and showed open pit damage, with the continuous intrusion, the erosion and destruction of the Kevlar composite target is deepening, and there is obvious stamping shear damage inside the target, forming a punch hole with a diameter equivalent to the fragment, the back of the target is stretched, and the interior of the whole laminated target appears typical and significant inter-layer damage, and finally the composite target plate is run through, the damage between the layers is more significant,
especially in the back of the Kevlar fibre composite target, the layering and stripping range of the laminate is much larger than the diameter of the fragment.

7. References
[1] Gao Hua, Xiong Chao, Yin Junhui 2019 Dynamic response and anti penetration performance of multi layered heterogeneous. composite structure Acta Materiae Compositae Sinica 36 1284-1294
[2] Deng Yunfei, Yuan Jiajin, Xu Jianxin 2018 Penetration characte ristics of woven composite laminates impacted by hemispherical. nosed proiectiles at different angles Acta Materiae Compositae Sinica 35 843-849
[3] Xu Bin, Wang Chen, Zang Liwei, Gao Tong, Liu Yajun 2019 Numerical Simulation on the Impact of Explosion Shock Wave on Bullet-Proof Vest Transactions of Beijing Institute of Technology 39 131-134
[4] Huang Xiaoming, Fang Zhiwei, Hou Hailiang, et al 2018 Anti-penetration of fibre reinforced composite material light armor subjected to impact of FSP Engineering Plastics Application 46 92–97
[5] ZHOU Q, HE Y M, LIU T 2019 Bulletproof performance and bulletproof mechanism of inter laminar hybrid composite armor plate Acta Materiae Compositae Sinica 36 837-847
[6] Paris F A 2001 Study of Failure Criteria of Fibrous Composite Materials NASA/CR 2001-210661
[7] Cui Weicheng 1996 Computational simulation of progressive failure in composite structures Acta Metallurgica Sinica (English letters) 13 102-111
[8] Chang F K and Chang K Y 1987 Post-Failure Analysis of Bolted Composite Joints in Tension or Shear-Out Mode Failure J. of Composite Materials 21 809-833
[9] Chang F K and Chang K Y 1987 A Progressive Damage Model for Laminated Composites Containing Stress Concentration J. of Composite Materials 21 834-855