Study on the high-speed impact resistance of porous composite laminates at high temperature

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Abstract. The impact resistance of composite laminates is an important reference for the design of composite structures. In this paper, based on ABAQUS software In this paper, based on ABAQUS software and numerical simulation, the influence of the position of the 0° ply on the impact resistance of Carbon Fibre Reinforced Plastics(CFRP) laminates with symmetrical ply design is analyzed. The results show that the protection performance of the 0° ply is the worst when it is located in the middle and outermost layers. In the layup design, the strength of the symmetrical side can be reduced to 0°. The results show that the protection performance of the 0° ply is the worst when it is located in the middle and outermost layers.

Keywords: CFRP laminates; impact resistance; numerical simulation; ABAQUS.

1. Introduction

Carbon fibre resin matrix composites are widely used in aerospace applications due to their light weight, high specific strength, high specific stiffness, corrosion resistance, designability, vibration resistance and impact resistance.[1][2] The composites are widely used in aerospace field. The composite structural parts of aircraft will inevitably be subjected to different impact loads during service and maintenance, and their impact resistance has become a very important reference in the process of aircraft structural design and strength analysis, so the research on the impact resistance of the composite structural parts has become a hot issue for scholars at home and abroad in recent years.

Morye et al.[3] used high-speed camera technology to monitor the penetration process of composite laminates, and found that there were obvious deformations during high-speed penetration of composite laminates, and the damage modes of laminates were dominated by the tensile fracture of fibres.Wang et al.[4] studied the response process of carbon fibre reinforced polymer laminates under high-speed impact by experimental and data analysis methods, and found that tensile failure is the main failure mode under low-speed impact.Xu et al.[5] investigated the effect of size effect on the response characteristics of carbon fibre laminates to low-speed impacts through experiments and numerical simulations, and found that larger sized laminates have higher energy absorption levels and greater impact damage. Wang et al.[6] The impact resistance of carbon fibre epoxy resin composite laminates with three different ply thicknesses was investigated by changing the impact energy, and it was found that the impact resistance of the composites increased with the increase of composite ply thickness under the same ply condition. Liang et al.[7] investigated the effect of impactor material properties on the impact damage of composite laminates under the same impact energy, and preliminarily explained the law that the elastic properties of the impactor affect the contact stiffness and the degree of impact damage.Ozaslan et al.[8] Carbon fibre composite laminates containing holes were subjected to tensile experiments, and the effects of different double-hole arrangements on the laminates were investigated. khashaba et al.[9] experimentally investigated the relationship between the compressive strength of carbon fibre composites and the size of the open holes, and found that an increase in the size of the holes results in a consequent decrease in the compressive strength and stiffness of the composites. Wanget al.[10] found that open holes in helicopter composites affect the life of the blade, and open holes in rotor blades produce greater stress concentrations.Kim[11] It was found that the strength of T700 reinforced epoxy resin matrix composites increases and then decreases with decreasing temperature. Luo et al.[12] investigated the effect of exposure of carbon fibre/epoxy resin to different low temperatures for different times on its tensile properties and damage mechanisms, using scanning electron microscopy (SEM) to find that its tensile strength shows a trend of increasing and then decreasing with the growth of low temperature exposure time.

In summary, the mechanical properties of carbon fibre composites are greatly affected by either open holes or temperature changes. However, the existing research on the impact resistance of composite laminates focuses on a single temperature, thickness, or material of the impactor, and there are fewer studies on the impact resistance of high-temperature porous composite laminates. Therefore, this paper uses ABAQUS finite element software to establish a finite element model of carbon fibre resin composite laminates to simulate the high-speed impact failure behaviour of porous carbon fibre resin composite laminates at high temperatures, and thus study the high-speed impact resistance of porous composite laminates at high temperatures.

2. finite element modelling

2.1 Material properties

The intrinsic model used for the composite monolayer is orthotropic anisotropy, which requires the definition of nine parameters with the expression calculated using Eq. (1).

$$\boldsymbol{\sigma} = \begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_x \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & & 0 \\ & C_{22} & C_{23} & 0 & 0 & & 0 \\ & & C_{33} & 0 & 0 & & 0 \\ & & & C_{44} & 0 & & 0 \\ & & & & C_{44} & C_{35} & 0 \\ \tau_x & & & & C_{66} & & 0 \\ \tau_{xy} & & & & & & C_{66} \end{bmatrix} \begin{bmatrix} \boldsymbol{\varepsilon}_x \\ \boldsymbol{\varepsilon}_y \\ \boldsymbol{\varepsilon}_z \\ \boldsymbol{\varepsilon}_z \\ \boldsymbol{\gamma}_{yz} \\ \gamma_{zz} \\ \gamma_{zy} \end{bmatrix} = \mathbf{C}\boldsymbol{\varepsilon} \tag{1}$$

Whereσ is the stress component,ε is the strain component,Cij is the stiffness coefficient and satisfies Cij=Cji . The matrix consisting of the stiffness coefficients Cij is called the stiffness matrix, which is not only a symmetric matrix, but also the inverse of the flexibility matrix. The expression for the flexibility matrix is given by Eq. (2).

$$\mathbf{S} = \begin{bmatrix} \frac{1}{E_1} & -\frac{V_{12}}{E_2} & -\frac{V_{13}}{E_3} & 0 & 0 & 0 \\ -\frac{V_{21}}{E_1} & \frac{1}{E_2} & -\frac{V_{23}}{E_3} & 0 & 0 & 0 \\ -\frac{V_{31}}{E_1} & -\frac{v_{32}}{E_2} & \frac{1}{E_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{23}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{31}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}} \end{bmatrix} \tag{2}$$

where the nine independent material constants contained in the flexibility matrix determine the various mechanical behaviours of orthotropically anisotropic materials. For the T800 prepreg used in this paper, the relevant material parameters at elevated temperatures are shown in Table 1.

Table 1 Main mechanical property parameters of T800 unidirectional prepregs

parametric	notation	numerical value	unit (of measure)

Longitudinal modulus of elasticity	E_{11}	172000	MPa
Transverse modulus of elasticity	E_{22}	7000	Mpa
Normal modulus of elasticity	E_{33}	7000	Mpa
1-2 In-plane shear modulus	G_{12}	4	Gpa
2-3 In-plane shear modulus	G_{23}	3	Gpa
1-3 In-plane shear modulus	G_{13}	4	Gpa
1-2 in-plane Poissons ratio	V_{12}	0.3	-
2-3 in-plane Poissons ratio	V_{23}	0.29	-
1-3 in-plane Poissons ratio	V_{13}	0.3	-
Longitudinal tensile strength	X_t	2630	Mpa
Longitudinal compression strength	X_c	1480	Mpa
Transverse tensile strength	Y_t	62	Mpa
Longitudinal shear strength	S_{12}	109	Mpa
Transverse shear strength	S_{23}	109	Mpa

Vmn (m, n=1, 2, 3) is Poissons ratio; Gmn (m, n =1, 2, 3) is shear modulus . E1, E2, E3 are fibre direction, perpendicular to fibredirection and normal direction modulus of the monolayer, respectively. In addition, the two-dimensional Hashins failure criterion is used in this chapter to determine the failure behaviour of CFRP laminates, and its failure criterion parameters are shown in Table 1. Let the positive stresses along the 1 and 2 directions of a single ply plate be σ1 and σ2 respectively, and the tangential stress in the 1-2 plane be τ , then the Hashin failure criterion is expressed as follows：

Fibre stretch failure

$$\left(\frac{\sigma_1}{X_t}\right)^2+\left(\frac{\tau_{12}}{S_{12}}\right)^2=1 \tag{3}$$

where X_t is the longitudinal tensile strength of the fibre; S_{12} is the shear strength in the 1-2 plane.

Fibre compression failure

$$\left(\frac{\sigma_1}{X_c}\right)^2=1 \tag{4}$$

where X_c is the longitudinal compressive strength of the fibre.

Substrate tensile failure

$$\left(\frac{\sigma_2}{Y_t}\right)^2+\left(\frac{\tau_{12}}{S_{12}}\right)^2=1 \tag{5}$$

Where Y_t is the transverse tensile strength of the fibre.

Substrate Compression Failure Substrate Compression Failure

$$\left(\frac{\sigma_2}{Y_c}\right)\left[\left(\frac{Y_c}{2S_{23}}\right)^2 - 1\right] + \left(\frac{\sigma_2}{2S_{23}}\right)^2 + \left(\frac{\tau_{12}}{S_{12}}\right)^2 = 1 \tag{6}$$

Where Y_c is the transverse compressive strength of the fibre.

2.2 Geometric Modelling and Grid Planning

ABAQUS software is used to establish the finite element model, the model mainly includes two parts: the bullet, CFRP plywood. The focus of the bullet impact simulation of the composite plate is the damage of the composite plate after the impact, so the finite element model will be used to simulate the bullet with a hemisphere with a diameter of 32mm, and the punch will be constrained to be a rigid body (Rigid Body) in the contact attribute (Interaction), so it does not take into account the deformation of the punch in the process of the impact, and it only provides the kinetic energy of impact and contact attribute between the unit and the bullet. Therefore, the deformation of the punch in the impact process is not considered. After the punch is constrained as a rigid body, it can be approximated as a mass point with shape but with mass concentrated in one point, a reference point is set outside the punch, and the motion form of the punch is defined by applying the boundary conditions and velocity field to the reference point, which simplifies the computation of the finite element model and does not have a great influence on the simulation results. The punch is divided by Structure method, and the mesh attributes are the default rigid body mesh attributes, which divides the punch into 8760 mesh cells, and the cell type is C3D10M.

Composite ply monolayers are directional, so the material orientation of the monolayers is defined in the ABAQUS module, i.e. the fibre direction is specified. The specific ply is $[45/-45/90/0]_s$, the thickness of each single ply is set to 0.2mm, and the geometry of the square plywood is 300mm×300mm. the ply is divided along the plywood thickness direction by the swept (Sweep) method, and the attribute of the mesh is COH3D8, which divides the plywood into 32400 mesh cells of the cell type S4R.

The mesh division of composite plywood is divided into two parts: punch mesh division and plywood mesh division. Considering that the loss range caused by the impact of the rigid body on the centre of the laminate is mainly concentrated in the centre part, in order to make the calculation results more accurate and reduce the related calculation volume, the mesh is encrypted in the core area of the impact, and the mesh is relatively sparsely distributed far away from the impact area.

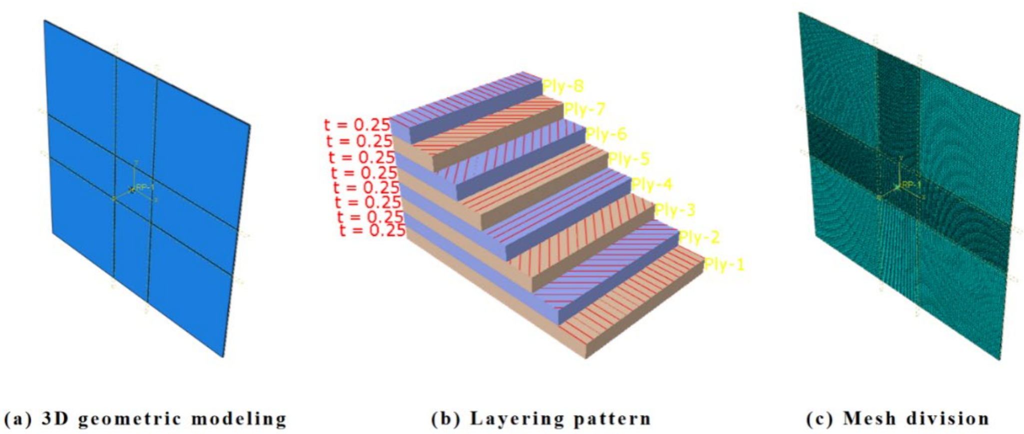


Fig. 1 Finite element model

2.3 Boundary conditions and loads

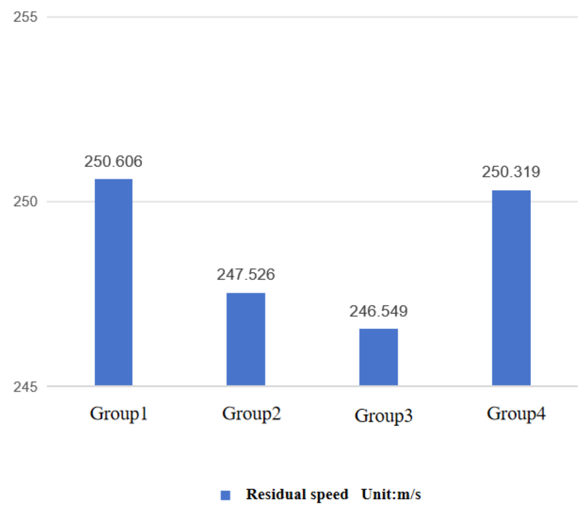
In this paper, the boundary conditions of the finite element model are set to be fixed around the square composite plate, i.e., "fixed" constraints are added to the outer boundary of the laminate. At the same time, the bullet is restricted to have degrees of freedom in other directions, leaving only the translational degrees of freedom along the Z-direction, so as to ensure that the bullet impacts vertically to the composite plate, and that the bullet is not deflected in the process of impacting the CFRP laminate. The initial velocity of the bullet is set to be 300m/s, and the bullet is in the position of just contacting with the laminate, which is the starting point of the impact.

3. Results and discussion

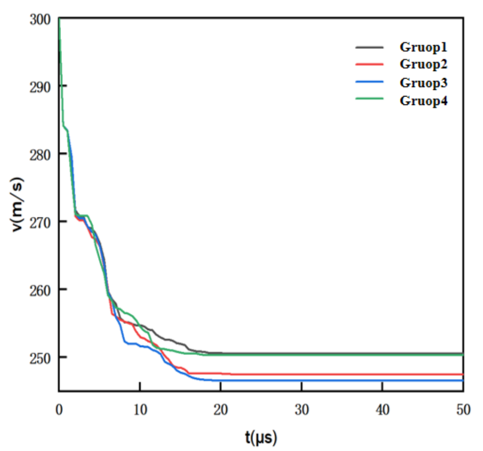
In this section, the impact response of four types of CFRP laminates with different 0-degree layups against the impact of the punch is calculated using the aforementioned finite element model to investigate the effect of the change of the 0-degree layup position on the protective performance of T800 plywood composite structures. Among them, the 1st group of lay-ups is $[45/-45/90/0]_s$, the 2nd group of lay-ups is $[45/0/-45/90]_s$, the 3rd group of lay-ups is $[45/-45/0/90]_s$, and the 4th group of lay-ups is $[0/45/-45/90]_s$, and the difference between them is that the distances between the 0° lay-ups and symmetry surfaces of the laminates are from near to far.

3.1 Residual velocity of bullets

After observing the change rule of residual velocity with time (Fig. 2) during the process of bullet perpendicularly penetrating the composite structure of T800 resin matrix composite laminate including the above four lay-up sequences with an initial velocity of 300m/s respectively, it is found that the residual velocity of the bullets in the first and the fourth groups is greater than that in the second and the third groups, and the curves of the residual velocities of the bullets of the first and the fourth groups with respect to the change of time are basically overlapped, and the curves of the bullet residual velocity with respect to the change of time of the second and The curves of the bullet residual velocities with time of the third group are basically coincident. The bullet residual velocity of the first group is 250.606m/s, the bullet residual velocity of the second group is 247.526m/s, the bullet residual velocity of the third group is 246.549m/s, and the bullet residual velocity of the fourth group is 250.319m/s, which is reduced by 16.46, 17.49, 17.82, and 16.5 per cent, respectively, when compared with the incident velocity. It shows that the protection performance is the worst when the 0-degree symmetric layup is located in the middle and the outermost layer, and the best when it is located in the 3rd and 6th layers.



(a) Residual velocities of each group



(b)Variation of residual velocities with time under different initial velocities of bullets

Fig. 2 Law of change of residual velocity when the bullet is shot at 300m/s.

3.2 Intrusion state analysis

Figure 3 illustrates the process of bullet penetration into T800 plywood. Regardless of the position of the 0-degree ply, the penetration process is probably similar and can be divided into the early stage of penetration, the middle stage of penetration, and the end of penetration. Firstly, in the early stage of the penetration, only the interaction between the front part of the bullet and the plywood occurred, and the contact area between the plywood and the bullet generated a large stress under the impact of the bullet, when the velocity of the bullet was high. Subsequently, when the front part of the bullet completely enters into the interior of the plywood and causes a more obvious bulging deformation of the plywood, it can be considered that the penetration process enters into the middle stage of penetration, and the slope of the residual velocity versus time curve of the bullet is slightly larger than that of the curve of the early stage of penetration in this stage. During this period, the stress-generating area on the plywood is gradually expanding to the area on both sides of the bullet hole. When the bullet completely penetrates from the back of the plywood, it can be considered that the process of penetration has entered the end of penetration, at which time the contact area between the bullet and the plywood basically no longer changes, so that the velocity of the projectile also basically does not change.

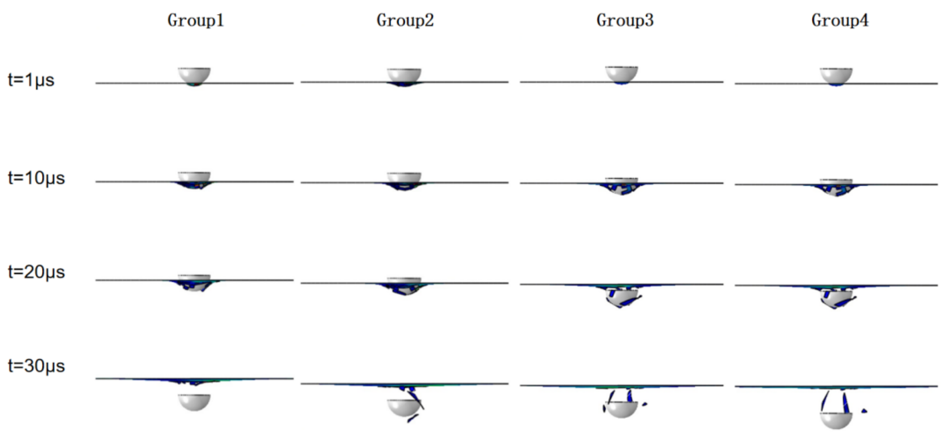


Fig. 3 The penetration state of each group when the bullet is projected at 300m/s.

In addition to this, in some details, there are some effects on the state of penetration of CFRP plywood when the 0 degree layup position is changed.

3.3 Stress states and forms of failure

When the bullet impacts on the plywood, the 0˚ layers are located at different positions and are subjected to different stresses. the closer the 0˚ layers are located to the centre, the less obvious the area of the plywood that is affected by the stresses is, and in the first layer, the area that is affected by the stresses is the largest, which means that the damage and destruction are most likely to start from this layer first. The layer above the comparison is directly subjected to the impact of the punch, the shock wave in the process of propagation along the thickness direction, in the back of the plywood, the nature of the shock wave will change, from compression wave into tensile wave, resulting in an increase in stress amplitude, in the symmetrical position of the layer, easy to occur in the damage.

With the increase of penetration time, the stress area of the plywood is expanding outward with the bullet hole as the centre, and the direction of expansion is along the transverse direction, and the stress state basically shows a symmetrical distribution of "ripple shape". Comparing the stress state diagram when the position of 45˚ ply is changed, it is found that except for the 45˚ ply, the extension direction of the stress is along 45˚ and the stress state is also symmetrically distributed in a "corrugated" manner, and the same with the 0˚ ply, the closer to the middle of the ply, the less obvious the stress state is.

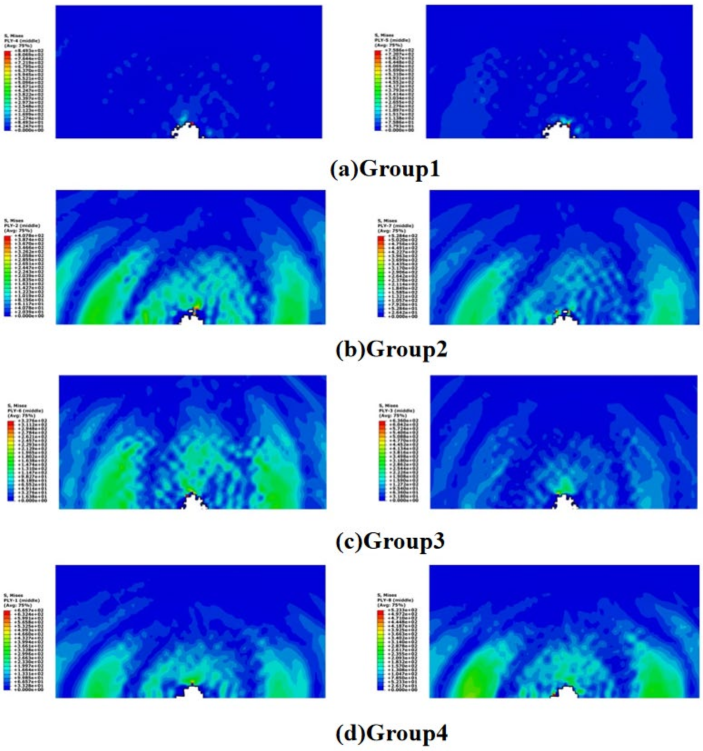


Fig. 4 Mises stress on the projectile-facing surface of CFRP plywood for a bullet incident at 300m/s.

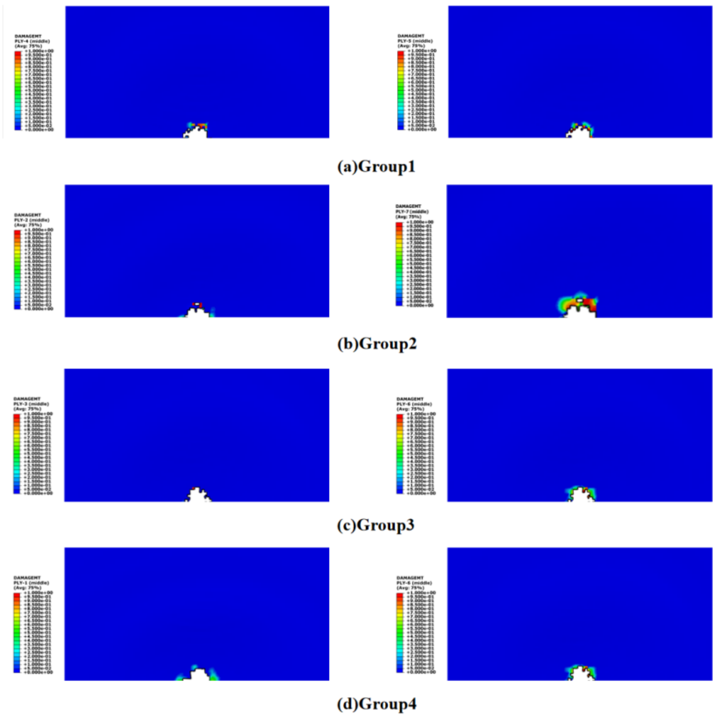


Fig. 5 Matrix tensile failure of CFRP plywood on the face of the bullet when the bullet is incident at 300m/s.

bservation and analysis of the four groups of CFRP laminates each 0 ° ply matrix tensile failure can be found when the 0 ° ply distance from the symmetry plane the greater the range of matrix tensile failure, the greater the impact.

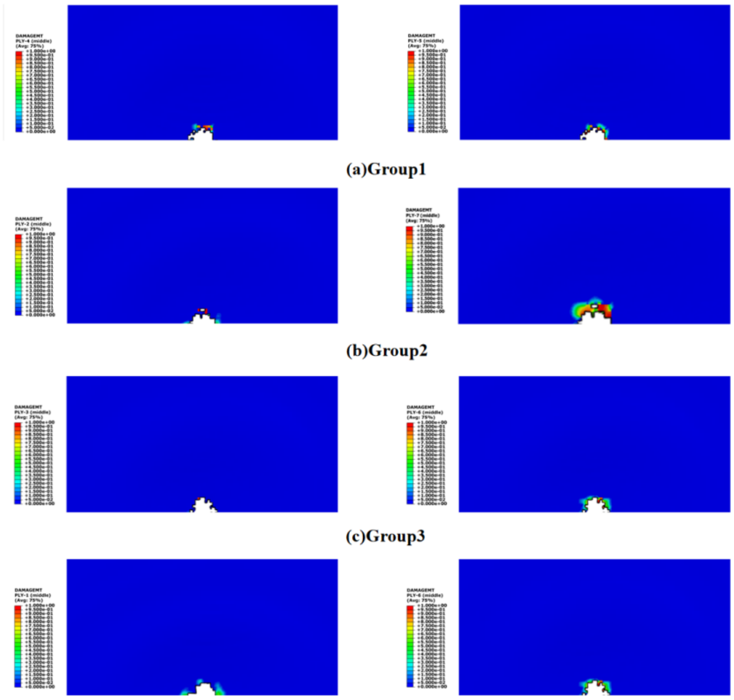

(a)Group1
(b)Group2
(c)Group3
(d)Group4

Fig. 6 Compression failure of CFRP plywood on the face of the bullet when the bullet is fired at 300m/s

The compression damage of CFRP plywood is more obvious under the four sets of simulation results, and the damage of CFRP plywood is mainly caused by compression damage.

4. Summary

The effect of 0° ply in different positions on the impact resistance of CFRP laminates was simulated using the finite element software ABAQUS. It provides a good basis for analysing the tensile mechanical properties and damage of carbon fibre/epoxy composite laminates with symmetric ply design. When the ply sequence is selected, 0° ply on the innermost side should be avoided. In addition, because when the CFRP ply with symmetric ply design is subjected to impact, on the backside of the ply, the nature of the impact wave will be changed from compression wave to tensile wave, which leads to the increase of stress amplitude, and the damage is easy to occur in the symmetric position of the ply. In the design of the pavement, the strength of the symmetrical side can be considered to be strengthened by increasing the layer thickness and other methods.

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