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Numerical Simulation on Impact Response of Plain-woven C/SiC Composite

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Abstract: The Thermal Protection System of the spacecraft will inevitably suffer the external shocks in service. 2D plain-woven C/SiC (2D-C/SiC) composite is a typical ceramic-matrix composite, which has been widely applied in the thermal protection structure. In this paper, firstly, the experiments that the steel balls impact to 2D-C/SiC composite under the velocity of 79 m/s ~ 219m/s are investigated by using the air gun. Secondly, the material parameters of 2D-C/SiC are obtained based on an orthotropic constitutive material model in Autodyn, and numerical simulations corresponding to experimental conditions are carried out based on Smooth Particle Hydrodynamics method. The comparisons of the debris cloud structure, the B scan results and the axis velocity of debris cloud between the calculation results and the experimental data validate the ability of this model for describing the brittle characteristics and the softening behaviour of 2D-C/SiC under the impact load. Finally, the limit penetration depth of 2D-C/SiC under the impact by steel ball is predicted based on the simulation results.

Key Words: *ceramic-matrix composites, debris cloud, high-speed photography, Smooth Particle Hydrodynamics, orthotropic constitutive model*

1 Introduction

The structural material in the thermal protection system (TPS) of the hypersonic vehicle should be lightweight, high temperature, environmental stability and so on, in order to meet long-range secure service requirements. In recent years, The ceramic-matrix composite material is widely used in the large-area TPS, which is 50% weight as conventional metal TPS and reduces the manufacturing cost.

2D plain-woven C/SiC (2D-C/SiC) is a typical ceramic-matrix composite, which is of low density, high specific strength and more excellent oxidation resistance than traditional C/C composite and is becoming an ideal material for thermal protection of aircraft structures[1-3].

However, 2D-C/SiC plate in TPS will inevitably suffer the low-speed external shocks, such as hailstones, tools fall off and so on during takeoff, landing and ground maintenance process of the spacecraft[4]. This paper will focus on the experimental and numerical study on the low-speed impact to 2D-C/SiC composite plate, which is of great significance for the design of TPS in engineering.

2 2D-C/SiC low-speed impact experiment

2D-C/SiC used in this experiment is developed by the Ultra-high Temperature Composites Laboratory in Northwestern Polytechnical University. After the chemical vapor deposition, 2D-C/SiC material was cut into the size of 115mm × 115mm, thickness of 3mm, density of about 2.11 g/cm^3 as the target plate in the experiment.

2.1 Low-speed impact experiment

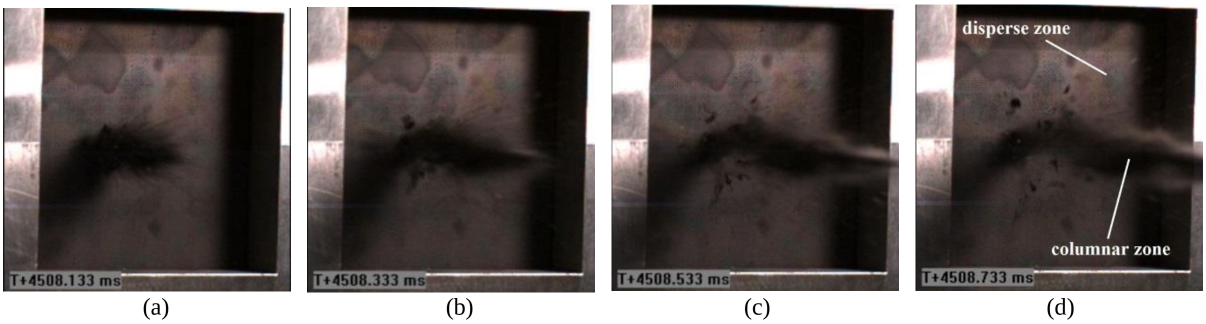
The experiments that the steel balls impact to 2D-C/SiC composite under the velocity of 79 m/s ~ 219m/s are investigated by using the air gun, and the development of the debris clouds are recorded by using the high-speed camera. The experimental scheme is shown in Table 1.

Table 1 Low-speed impact experimental scheme

Number	*Diameter(mm)*	*Velocity(m/s)*	*Energy(J)*	*Results*
1	5	79	1.61	No Penetration
2	5	92.7	2.22	No Penetration
3	5	98.5	2.51	No Penetration
4	5	130	4.37	Penetration
5	6	144	9.26	Penetration
6	6	147	9.65	Penetration
7	6	211	19.89	Penetration
8	6	218	21.23	Penetration
9	6	219	21.43	Penetration

2.2 Structure of the debris cloud

The screenshots of the records are shown in Fig.1. As can be seen from the figure, the development of debris cloud can be divided into two stages. First, cluster flyoff (Fig 1(a)). When the projectile contactes the target plate, lots of fiber fracture and matrix crushing occurr in the local area of the impact point, and a large amount of solid particles fly out in the form of cluster.



(a) (b) (c) (d)

Fig.1 Expansion of the debris cloud

Second, two regions form. As the development of debris cloud, it can be clearly found that the structure of 2D-C/SiC debris cloud could be divided into two parts, i.e. the columnar zone and the disperse zone. In the columnar zone, fragments have smaller size and move along the axis. While in the disperse zone, fragments have bigger size and move along some angles. This is the special damage characteristic of 2D-C/SiC under impact load, which need to be described by an reasonable constitutive model.

3 Numerical simulation and analysis

3.1 Material model and calculation model

The mechanical response process of composites under impact load is very complex, which is usually coupled response of material anisotropy, phase change materials and other factors. In the numerical calculation, equation of state and constitutive equation are two highly coupled sub-models. In the traditional methods, these two sub-models were calculated separately, but this process is very complex. A new methodology was firstly proposed by Anderson to solve anisotropic materials coupled problem with multiple response[5-10]. Based on this, an orthotropic constitutive material model is realized in Autodyn to describe 2D-C/SiC response under impact load.

2D-C/SiC is typical orthotropic composite materials, the total strain can be decomposed into the spherical strain ε_0 associated with the volume change and the deviatoric stain ε_{ij}^d associated with the change in shape. Therefore, the constitutive relation of 2D-C/SiC can be described by using the following symmetric stress-strain relation:

$$\begin{bmatrix}\sigma_{11}\\\sigma_{22}\\\sigma_{33}\\\sigma_{23}\\\sigma_{31}\\\sigma_{12}\end{bmatrix}=\begin{bmatrix}C_{11}&C_{12}&C_{13}&0&0&0\\C_{12}&C_{22}&C_{23}&0&0&0\\C_{13}&C_{23}&C_{33}&0&0&0\\0&0&0&C_{44}&0&0\\0&0&0&0&C_{55}&0\\0&0&0&0&0&C_{66}\end{bmatrix}\begin{bmatrix}\varepsilon_0+\varepsilon_{11}^d\\\varepsilon_0+\varepsilon_{22}^d\\\varepsilon_0+\varepsilon_{33}^d\\\varepsilon_{23}\\\varepsilon_{31}\\\varepsilon_{12}\end{bmatrix}$$

Since the isotropic pressure P is the opposite of the average of three normal stress, and therefore the following expression can be deduced based on the above equation:

$$P=-\frac{1}{3}(C_{11}+C_{22}+C_{33}+2C_{12}+2C_{13}+2C_{23})\varepsilon_0-\sum_{i=1}^{3}\frac{1}{3}[C_{1i}+C_{2i}+C_{3i}]\varepsilon_{ii}^d \tag{1}$$

The body strain item shown in (1) can also be replaced by a common equation of state (such as the Mie-Grüneisen EOS), and the following general form can be reached. Here the back item can be considered as a numerical correction to the conventional equation of state.

$$P=P_{\mathrm{EOS}}(\varepsilon_0,e)-\sum_{i=1}^{3}\frac{1}{3}[C_{1i}+C_{2i}+C_{3i}]\varepsilon_{ii}^d$$

Failure model includes failure initialization and post-failure response. The maximum stress criterion is used in the failure initialization stage. In the post-failure stage, the calculation is based on the following criteria. When the failure occurs in any direction of material, the carrying capacity in this direction loss instantaneously, and However, the carrying capacity remain unchanged in the other direction; while the shear carrying capacity decreases in three directions. Assuming direction 1 is the thickness direction of the target plate, and direction 2,3 are two orthogonal directions. For instance, stiffness matrix should be amended as follows if failure occurs in direction 1, where α is the stiffness degradation factor.

$$\begin{bmatrix}0\\\sigma_{22}\\\sigma_{33}\\\sigma_{23}\\\sigma_{31}\\\sigma_{12}\end{bmatrix}=\begin{bmatrix}0&0&0&0&0&0\\0&C_{22}&C_{23}&0&0&0\\0&C_{23}&C_{33}&0&0&0\\0&0&0&\alpha C_{44}&0&0\\0&0&0&0&\alpha C_{55}&0\\0&0&0&0&0&\alpha C_{66}\end{bmatrix}\begin{bmatrix}\varepsilon_{11}\\\varepsilon_{22}\\\varepsilon_{33}\\\varepsilon_{23}\\\varepsilon_{31}\\\varepsilon_{12}\end{bmatrix}$$

When failure occurs in other material directions, the corresponding response mode and stiffness degradation matrix could be obtained similar to the above.

Due to the symmetry of the positive impact, a half mode shown in Fig 2 is established in order to save the compute cost. SPHsolver is chosen for 2D-C/SiC and FEM is chosen for the steel projectile. Contact is set between the projectile and target plate and the contact spacing is 0.01mm. Fixed boundary conditions is imposed on the edge of target plate.

3.2 Comparison between experiment and numerical simulation

Numerical simulations corresponding to experimental conditions are carried out in Autodyn. Calculation results and the experimental data are compared to validate that this model can well describe the brittle characteristics and the softening behaviour of 2D-C/SiC under the impact load from the following 3 aspects:

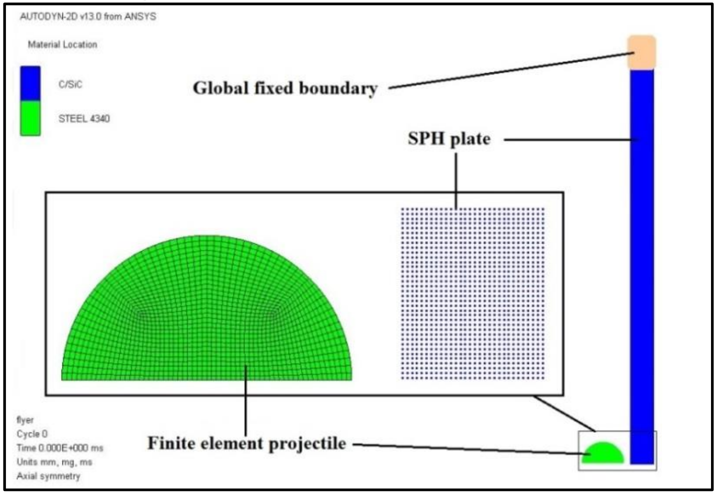


Fig.2 Computational model in Autodyn

(1) Debris cloud structure. It is shown in Fig.3 that, (a) the two parts structure of debris cloud can be found in both the experimental and the numerical results. (b) The velocity directions of fragments in these two parts shown in numerical results are consistent with that in experimental results. (c) The central cavity and the big fragments at the bottom of the debris cloud can be also found in the numerical results.

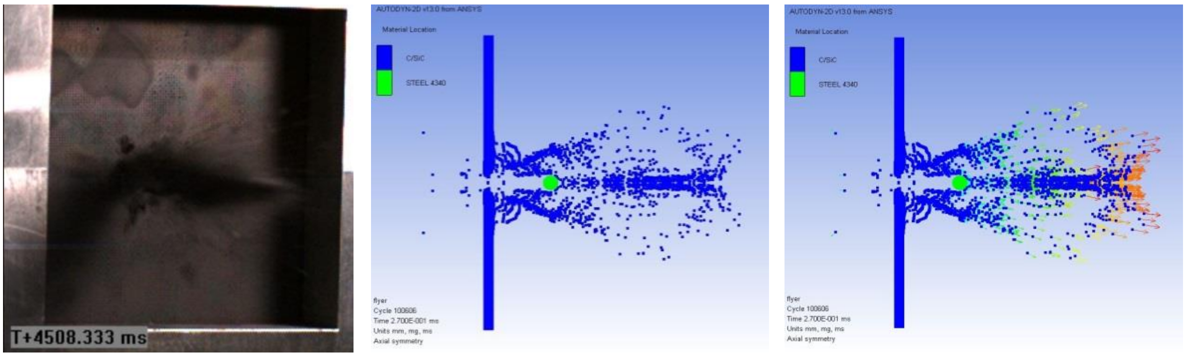
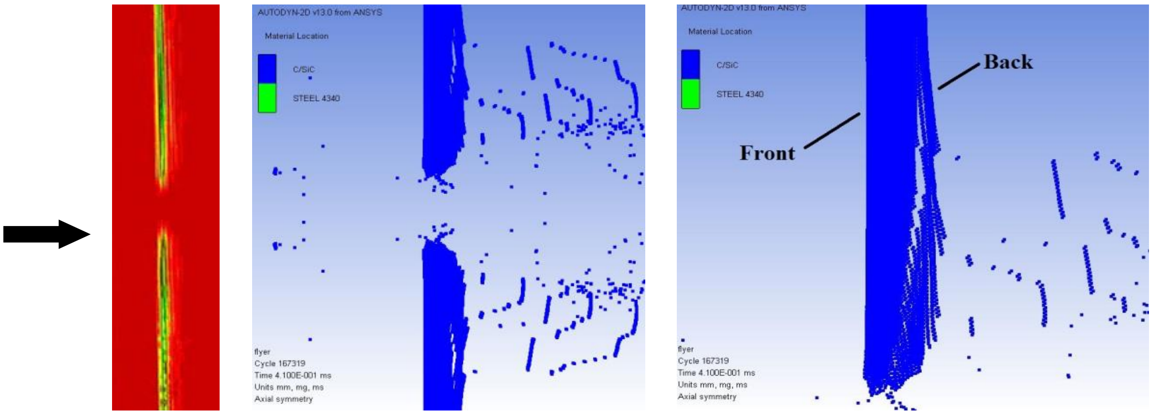


Fig.3 The simulation results of No.8 experiment

(2) B scan results. It can be found in Fig.4 that, (a) the perforation shape shown in the numerical results are similar with the B scan results. (b) The yellow area near the back surface is lighter than that near the front surface, which means the damage near the back surface is more serious than front surface. From the numerical results, the delamination and fragments spalling can be clearly found near the back surface corresponding to the B scan results.



(a) (b) (c)

Fig.4 Comparison between B-scan and simulation results

(3) Axis velocity of debris cloud. This is an important parameter to describe the development of debris cloud. The history of axis velocity of debris cloud under different impact velocities are shown in Fig.5, and the results of the axis velocity are compared and shown in Fig.6, which shows good agreement and the error is just 2.25% when the impact velocity is 219m/s.

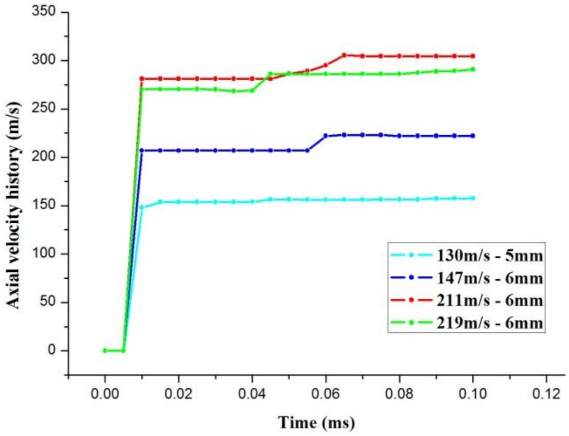


Fig.5 Axial velocity history under different impact velocities

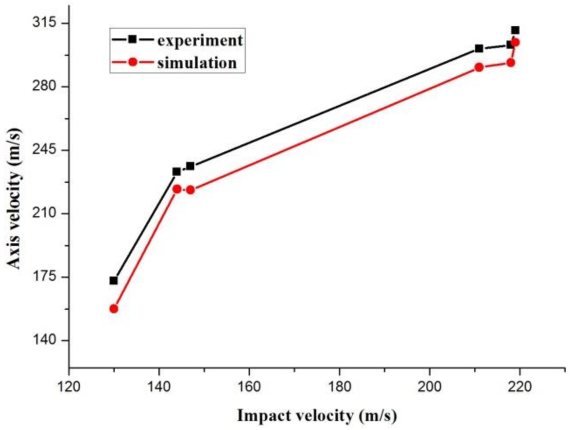


Fig.6 Comparison of the axial velocity

3.3 Limit penetration depth of 2D-C/SiC

Finally, the limit penetration depth of 2D-C/SiC under the impact load by steel ball is predicted based on the numerical results. The variation of residual velocity with different impact velocities as 50m/s,100m/s,…,400m/s and different plate thicknesses as 1mm, 2mm…5mm is studied, which is shown in Fig 7 and indicates the residual velocity of the projectile increases with the impact velocity and decreases with the plate thickness. However, it is very hard to get the fitting surface of the residual velocity directly due to the irregular oscillating changes near the critical penetration state, which can be clearly found in the distribution figure of the change rate on the residual velocity value shown in Fig.8.

Therefore, a two-steps fitting method is used to get the limit penetration depth formula. Firstly, the curve fitting on the variation of residual velocity with the plate thickness is carried out for the fixed impact velocity, and the limit penetration depth under this impact velocity can be obtained; Secondly, the curve fitting on the limit penetration depth with the impact velocity is carried out, and the following formula can be derived:

$$T=0.0005362\ln(1+0.756v^{2})$$

At this point, if the plate thickness has been determined in engineering, the ballistic limit velocity can be predicted as the inverse solution of the above formula.

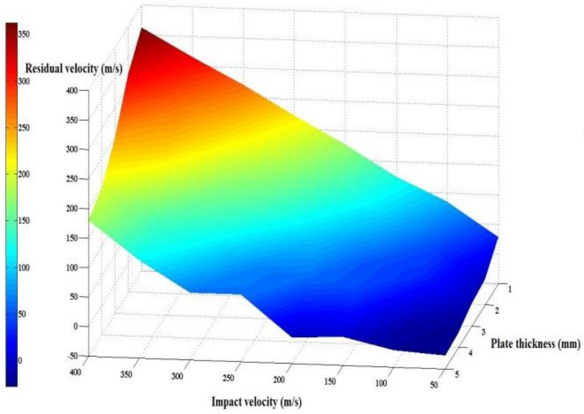


Fig.7 Variation of the residual velocity with different impact velocities and different plate thicknesses

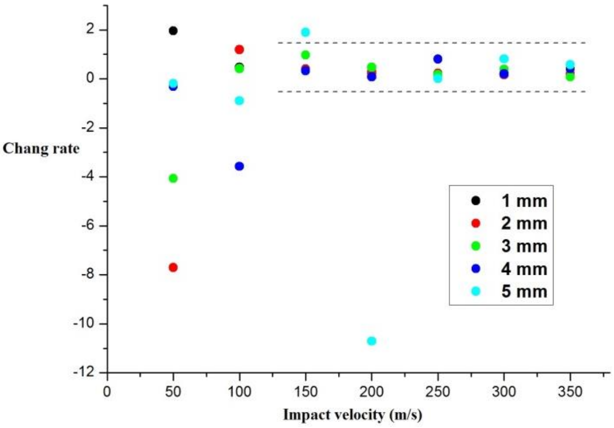


Fig.8 Distribution figure of the change rate of the residual velocity

4 Conclusions

2D-C/SiC low-speed impact experimental results were summarized and analyzed, and its impact performance under low-speed impact load were studied in Autodyn software. Based on the comparison from debris cloud structure, B-scan results and axial velocity, the rationality of the material model and parameters was validated. Finally the limit penetration depth formula of 2D-C/SiC was derived, which is valuable in engineering.

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