Mechanical model and numerical simulation of composite laminates subjected to low velocity impact

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Abstract. A mechanical model of laminated plates subjected to low velocity impact is proposed in this paper. The model studies the attenuation of impactor velocity affected by air resistance, intra-laminar damage initiation based strain, intra-laminar damage evolution based on damage parameters and delamination damage. Based on this mechanical model and ABAQUS platform, the experiment of Shi is numerically simulated. It is found that the predicted contact force, energy absorption and delamination damage of laminates are in good agreement with the experimental results, indicating that the established mechanical model can be used to predict the mechanical response and damage characteristics of composite laminates subjected to low velocity impact.

1. Introduction
Because of its light weight, high strength, high stiffness and good designability, composites are widely used in the field of aerospace[1]. However, the flight vehicle will inevitably be impacted by outside objects[2]. More seriously, the composites are sensitive to impact load and are prone to delamination and other damage[3]. Many scholars have established mechanical models to study composite laminates subjected to low-speed impact.

At present, most scholars default the velocity at the contact time to the initial velocity of the impactor, ignoring the influence of air resistance. Many scholars propose different methods to study the intra-laminar damage initiation. Xu Yutong[4] adopted the Hashin criterion, Liu Xiangmin[5] and Shi[6] adopted the Puck criterion, and Hongkarnjanakul[7] adopted the maximum strain criterion and Hashin criterion for matrix and fiber respectively. Most of these criteria take stress as a parameter. When damage occurs in the material, the stress distribution in the local damage area changes sharply, so it is not appropriate to adopt the damage initiation criterion based on stress[8]. For the intra-laminar damage evolution, some scholars use the elastic modulus reduction method, and others use the stiffness linear softening method based on fracture toughness. The former has high calculation efficiency, but it reduces the elastic modulus, which does not reflect the impact of damage on the stiffness matrix, resulting in the inaccurate degradation of the stiffness matrix. The latter directly degrades the stiffness matrix through the calculated damage variables, but the calculation of damage variables is too complex and slow and the debugging cycle is long, which is not conducive to practical application.

Based on the above considerations, a relatively perfect mechanical model of composite laminates subjected to low-speed impact is proposed in this paper. Firstly, the attenuation to the velocity of impact object is calculated. Considering that the strain is continuous before and after damage, damage initiation criterion based on strain is derived. Because the above two intra-laminar damage evolution criteria have their own advantages and disadvantages, this paper combines the two to form a
damage evolution criterion based on damage parameters. Based on this mechanical model and ABAQUS platform, Shi’s experiment is numerically simulated. Finally, the simulation results and experimental results are compared and analyzed from three aspects: contact force, energy absorption and delamination damage.

2. Impact mechanics model
Before the impactor contacts the laminate, the velocity will be attenuated due to air resistance. The whole damage process needs to consider the constitutive relationship, damage initiation and damage evolution.

2.1. Velocity attenuation
The velocity attenuation formula is deduced according to the basic mechanical knowledge.

The relationship between the velocity at the contact time and the initial velocity can be obtained:

\[ v = v_0 e^{-\frac{C_{\text{px}} x}{2m}} \]  

(1)

Where \( x \) is the moving distance of the impactor, \( s \) is the windward area, \( m \) is the mass of the impactor, \( C \) is the air resistance coefficient and \( \rho \) is the air density.

2.2. Constitutive relation
The constitutive relationship of undamaged unidirectional plates can be described by a stiffness matrix containing 9 independent constants. The stiffness matrix is as follows:

\[
\begin{bmatrix}
\sigma_{11} & \sigma_{12} & \sigma_{13} & C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\
\sigma_{22} & \sigma_{23} & C_{21} & C_{22} & C_{23} & 0 & 0 & 0 & \varepsilon_{22} \\
\sigma_{33} & C_{31} & C_{32} & C_{33} & 0 & 0 & 0 & \varepsilon_{33} & 0 \\
\tau_{23} & 0 & 0 & C_{44} & 0 & 0 & \gamma_{23} & 0 & 0 \\
t_{31} & 0 & 0 & 0 & C_{55} & 0 & \gamma_{31} & 0 & 0 \\
t_{12} & 0 & 0 & 0 & 0 & C_{66} & \gamma_{12} & 0 & 0
\end{bmatrix}
\]  

(2)

Where \( C_{ij} \) is the element of the stiffness matrix.

By introducing the damage parameters of different damage modes to reduce the element factors of the stiffness matrix, the stiffness matrix with damage parameters is as follows:

\[
\begin{bmatrix}
\sigma_{11} & \sigma_{12} & \sigma_{13} & \bar{d}C_{11} & \bar{d}C_{12} & \bar{d}C_{13} & 0 & 0 & 0 \\
\sigma_{22} & \sigma_{23} & \bar{d}C_{21} & \bar{d}C_{22} & \bar{d}C_{23} & 0 & 0 & 0 & \varepsilon_{22} \\
\sigma_{33} & \bar{d}C_{31} & \bar{d}C_{32} & \bar{d}C_{33} & 0 & 0 & 0 & \varepsilon_{33} & 0 \\
\tau_{23} & 0 & 0 & dC_{44} & 0 & 0 & \gamma_{23} & 0 & 0 \\
t_{31} & 0 & 0 & 0 & dC_{55} & 0 & \gamma_{31} & 0 & 0 \\
t_{12} & 0 & 0 & 0 & 0 & dC_{66} & \gamma_{12} & 0 & 0
\end{bmatrix}
\]  

(3)

Where \( \bar{d}C_{ij} \) and \( dC_{ij} \) are the combination of the damage parameters and material performance parameters.

2.3. Damage initiation
Considering that it is not suitable to describe the intra-laminar damage initiation criterion by stress, Hashin damage initiation criterion based on strain is derived based on the stress-strain relationship and 3D Hashin criterion.

Fiber tension:
\[
\left( \frac{\epsilon_{11}}{\epsilon_{11}^T} \right)^2 + \left( \frac{\epsilon_{12}}{\gamma_{12}} \right)^2 + \left( \frac{\epsilon_{31}}{\gamma_{31}} \right)^2 \geq 1(\epsilon_{11} > 0) 
\]  
(4)

Fiber compression:

\[
\left( \frac{\epsilon_{11}}{\epsilon_{11}^T} \right)^2 \geq 1(\epsilon_{11} < 0) 
\]  
(5)

Matrix tension:

\[
\left( \frac{\epsilon_{22}}{\epsilon_{22}^T} \right)^2 + \left( \frac{\epsilon_{12}}{\gamma_{12}} \right)^2 + \left( \frac{\epsilon_{23}}{\gamma_{23}} \right)^2 \geq 1(\epsilon_{22} > 0) 
\]  
(6)

Matrix compression:

\[
\left( \frac{\epsilon_{11}}{2\epsilon_{11}} \right)^2 + \left( \frac{\epsilon_{22}}{\epsilon_{22}^T} \right)^2 \left( \frac{\epsilon_{12}}{\gamma_{12}} \right)^2 + \epsilon_{22} \left( \frac{1}{\epsilon_{22}^T} + \frac{1}{\epsilon_{22}^C} \right) \geq 1(\epsilon_{22} < 0) 
\]  
(7)

For inter-laminar damage, secondary stress criterion is usually used to judge the initiation of delamination damage, and the expression is as follows:

\[
\frac{\langle t_n \rangle^2}{N^2} + \frac{t_x^2}{S^2} + \frac{t_y^2}{T^2} = 1 
\]  
(8)

The symbol \( \langle \cdot \rangle \) means that when the value in the bracket is positive, it takes itself, and when the value in the bracket is negative, it takes zero.

2.4. Damage evolution

After the damage initiation of composites, the properties of composites need to be degraded according to the corresponding damage mode.

For unidirectional plates, the degradation of stiffness matrix is realized by damage parameters. The damage parameters of different modes refer to the CAMANHO material performance reduction scheme, as shown in table 1. The damage evolution is instantaneous.

Table 1. Damage parameters of different damage modes.

| Damage Mode         | Fiber tensile | Fiber compression | Matrix tensile | Matrix compression |
|---------------------|---------------|-------------------|----------------|-------------------|
| \( d_{ft} \)        | 0.93          | \( d_{fc} \)     | 0.86          | \( d_{mt} \)     |
| \( d_{mc} \)        | 0.8           |                   | 0.6           |                   |

The degradation form is simple and will not cause the singularity of the matrix or reverse deformation. It is convenient to be used in finite element calculation.

For the interface layer, when the damage initiation criterion is satisfied, the B-K energy criterion is used to describe the damage evolution process. The specific expression of the B-K criterion is as follows:

\[
G^C = G_n^C + \left( G_q^C - G_n^C \right) \left( \frac{G_n}{G_T} \right)^\eta 
\]  
(9)

3. Numerical simulation

According to the established mechanical model, this paper establishes the finite element model based on ABAQUS/CAE platform for Shi’s test, and then compiles VUMAT user material subroutine to calculate the damage initiation and damage evolution of composites. The whole process is shown in figure 1.
Figure 1. Simulation process.

3.1. Analysis object
Shi[6] carried out low velocity impact test on carbon fiber epoxy composite laminates. The size of laminate is 100mm × 100mm × 2mm, the ply is [0/90]_{2S}, and the material parameters of unidirectional plate and interface layer are shown in table 2 and table 3. The laminate is tightened by two steel plates with circular holes with a diameter of 75mm. The steel impactor has a diameter of 15mm, a mass of 2kg and an impact energy of 14.7J. It falls freely from a height of 0.75m to impact the laminated plate.

Table 2. Material properties of unidirectional laminate.

| Property | Value |
|----------|-------|
| $\rho$ (kg/m$^3$) | 1600 |
| $E_1$ (GPa) | 153 |
| $E_2$ (GPa) | 10.3 |
| $\nu_{12}$ | 0.3 |
| $\nu_{23}$ | 0.4 |
| $G_{12}$ (GPa) | 6 |
| $G_{23}$ (GPa) | 3.7 |
| $X_I$ (MPa) | 2537 |
| $X_C$ (MPa) | 1580 |
| $Y_I$ (MPa) | 82 |
| $Y_C$ (MPa) | 236 |
| $S_{12}$ (MPa) | 90 |
| $S_{23}$ (MPa) | 40 |

Table 3. Material properties of interface cohesive element.

| Property | Value |
|----------|-------|
| $K_{nn}$ (GPa/mm) | 1373.3 |
| $K_{ss}$ (GPa/mm) | 493.3 |
| $N$ (MPa) | 62.3 |
| $S$ | 92.3 |
| $G_{1C}$ (J/m$^2$) | 280 |
| $G_{2C}$ (J/m$^2$) | 790 |
| $\eta$ | 1.45 |

3.2. Finite element model
The test object is transformed into finite element model, as shown in figure 2. The laminated plate is simplified as a circular plate with a diameter of 75mm and fixed on four sides. The thickness of unidirectional plate is 0.25mm, which is simulated by explicit C3D8R element. The thickness of the interface layer is 0.0075 mm, which is simulated by explicit COHESIVE element. The impactor is simulated with a three-dimensional analytical rigid and the inertial mass 2kg. The contact between the impactor and the laminate is general contact. The friction coefficient of tangential behavior is set to 0.3, and the normal behavior is set to hard contact.

According to the established mechanical model, the attenuation effect of air resistance on the velocity of impactor is investigated, which has only 0.02% effect on the analysis object in this paper. Therefore, 3834mm/s is still used as the contact velocity in the finite element model.
4. Results and discussion

The established mechanical model is verified by comparing experimental results and simulated results from contact force, energy absorption and delamination damage.

4.1. Contact force

The contact force-time curve is shown in the figure 3. Compared with the test, the simulated contact force is close to the test. In the initial stage of impact, the simulated contact force is slightly lower than the test value. In the intermediate stage, the simulated value reaches the peak value and is slightly lower than the test value. After the contact force reaches the peak value, the impactor rebounds and the simulated contact force is slightly higher than the test value, which will lead to recover to zero more slowly. This is probably caused by the contact force of adjacent layers after some interface layers are deleted in the numerical simulation.

The contact force-displacement curve is shown in the figure 4. Comparing the experimental and simulated values, the slopes of the two curves are similar in the initial stage of impact. When the impact velocity becomes zero, the centre of the composite laminate reaches the maximum displacement, and the maximum displacement predicted by the simulation is slightly larger than the test value. When the impactor rebounds, compared with the test, the simulated composite laminate returns to the original state faster and the recovered deformation is also large. In the experiment, the measured displacement corresponds to the displacement of the impactor, and the simulation value is obtained from the midpoint on the back of the plate. This difference and friction coefficient may lead to the recovery deviation between the simulated laminate and the test.
4.2. Energy absorption

The energy–time curve is shown in the figure 5. Compared with the test, the energy absorption can be accurately simulated in the initial stage of impact. However, there is inaccuracy in the simulation of the rebound stage of the impact, which leads to the inaccuracy of the final value of energy absorption. The final energy absorption predicted by numerical simulation is lower than the experimental results.

The main reasons for the small calculation deviation are as follows:

- The impactor is equivalent to a rigid body in this paper, but in practice, the impactor itself will also deform and lead to energy dissipation, which is included in the impact energy absorption value measured in the test, so that the simulation value is lower than the test value.
- In this model, the friction between unidirectional plate and interface layer is ignored, and then the energy dissipation caused by this friction is ignored, which will also lead to less impact energy absorption than the experimental.
- The friction dissipation between the laminate and the fixture of the test piece and the heat energy generated in the impact process are ignored, which will also lead to the impact energy absorption value being smaller than the test value.

4.3. Delamination damage

At the end of impact simulation, there is slight indentation on the surface of the laminate, but delamination damage occurs inside the laminate. The delamination damage from the front to the back of the laminate is given in turn, as shown in figure 6. The delamination shape of each interface layer is approximately oval, and the long axis direction of the damage shape is consistent with the laying direction of the fiber in the lower layer of the interface layer. After all layered damage images are superimposed and binarized by MATLAB, the overall contour of delamination damage of laminate is obtained, as shown in the figure 7. The overall contour of delamination damage is oval, and the long axis is along the direction of 0°.
Figure 6. Predicted delamination area at each interface.

The delamination damage image obtained by enhanced X-ray imaging technology is shown in figure 8. The damage shape is basically oval. The long axis of the damage shape is basically in the direction of 0° and the short axis is basically in the direction of 90°. Comparing the size and shape of delamination damage, the simulation results are basically consistent with the experimental results.

Figure 7. Superposition of simulated delamination area.

Figure 8. X-ray radiographs delamination area.

5. Conclusion

- A mechanical model of composite laminates subjected to low velocity impact is established. According to the established mechanical model, the low-speed impact behaviour of composite laminates is simulated with the help of ABAQUS/CAE and VUMAT subroutine, and the mechanical response and damage characteristics after impact are predicted.

- From the three aspects of contact force, absorbed energy and delamination damage, it is found that the mechanical response and damage characteristics predicted by the model are in good agreement with the experimental results, which verifies the availability of the model.

- From the above three aspects, the differences between simulation and experiment are explained to verify the rationality of the model.

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