Damage Behavior Prediction of Repaired Composite Laminates Subjected to Oblique Penetrate Loading

Lingling Yang¹, Tao Ran², Zhihui Liu² and Yiru Ren²

¹ China North Vehicle Research Institute, Beijing 100072, China
² College of Mechanical and Vehicle Engineering, Hunan University, Changsha 410082, China

Abstract. To predict the effect of oblique impact on the damage and performance of perforation resistance of repaired composite laminates, a three-dimensional continuum damage model (CDM) is used to simulate and calculate the low-velocity impact process of repaired laminates. In the established finite element model, several different types of failure modes are considered. The damage model is based on the modified 3D-Hashin failure criterion to predict the initial damage of the fiber and matrix. The linear-exponential law and the exponential law are used to simulate the tensile and compressive softening process of the material. The triangle traction-separation law and mixed-mode fracture energy method are applied to simulate interface debonding damage between patch/lamina, patch/patch and lamina/lamina. A comparison of the numerical results of several different offsets with the experimental results shows that the simulated failure modes and impact responses are very close to the experiment, which verifies the validation of the finite element model (FEM). The increase of the impact angle can enhance the residual velocity of the projectile in the laminate and reduces the energy absorption. At the same time, it has a great influence on the failure modes, especially the interface debonding damage of the patch.

1. Introduction

Composite laminates have been significantly increased in applications in various industries, especially in aerospace engineering, due to that light weight, high specific strength and energy absorption capacity[1-2]. However, the composite laminates are easy to be damaged by low impact, which will lead to a significant decrease in strength and greatly reduce the service life of the structure. Therefore, it is of vital importance to repair or reinforce damaged parts of composite laminates to improve their service life[3-4]. Ballistic impact load is one of the key conditions that composite laminates may experience during their service life, in which projectile impact incidence angle is variable. Therefore, perforation resistance of laminated plate structure is an important parameter to ensure its performance under different impact angles[5-6]. In previous studies, many scholars have evaluated the impact response and energy absorption of the projectile at oblique angle penetrating the laminates, but few reported evaluated the perforation resistance characteristics of the laminates with patches at different impact angles.

The repair of composite laminates is mainly carried out in the damaged area to achieve the original mechanical properties and enhance the seismic resistance of the structure. In the past few decades, a lot of research has been done on the development of adhesive repair technology. The repair techniques for composite laminates under low-speed impact mainly include bonding repair and embedding repair[7]. Andrew and Jefferson studied the residual compression characteristics of repaired composite laminates under low-speed impact load, the results showed that the adoption of repair method could improve the
bearing capacity\textsuperscript{[8-9]}. In addition, Balaganesan and Khan studied the perforation-resistant properties of the bonding and scarf repair composite laminates under projectile impact loads of different offsets, but the authors did not fully analyze the perforation-resistance mechanism and the interface stripping mechanism\textsuperscript{[10]}. Coelho studied the influence of single-patch and double-patch on the failure behavior of laminates repaired under impact load, the results showed that the use of double-patch made laminates have better impact characteristics\textsuperscript{[11]}

The purpose of this paper is to study the perforation resistance performance of the patch and repaired composite board with different impact incident angles \( (0^\circ, 15^\circ, 30^\circ, 45^\circ) \). Based on threedimensional continuum damage model, the improved 3D-Hashin failure criterion is proposed. To simulate tensile and compression softening, the triangle traction-separation law and the mixed fracture energy method are used to establish the damage of the debonding interface. All numerical simulations in this study were carried out in the finite element software ABAQUS.

2. Numerical simulation model

The main damage modes of composite laminates and composite patches under projectile impact load are intramolecular damage (matrix cracking, matrix buckling, fiber fracture and fiber compression failure). These damage mechanisms are caused by longitudinal tensile and compression loads, transverse tensile and compression loads as well as coupling effects\textsuperscript{[12]}. In addition, the stress in the thickness direction can cause local material intra-layer effects, which may be followed by delamination failures.

2.1. Failure criteria

Based on the improved 3D-Hashin failure criterion, a failure criterion which can be used for the initial failure of anisotropic composites is established. The failure modes of this criterion are independent of each other, including longitudinal and transverse tensile and compression failures. In order to predict the mechanical behavior of laminates more accurately, delamination failure caused by stress along the thickness direction is also considered. The various failure initiation criteria are shown in Equations (1) ~ (6).

Longitudinal tensile failure \( (\sigma_{11} \geq 0) \)

\[
FI_{L+} = \frac{\sigma_{11}}{\sigma_{c}}^2 + \frac{\sigma_{12}^2 + \sigma_{13}^2}{S_{12}^2} \tag{1}
\]

Longitudinal compression failure \( (\sigma_{11}<0) \)

\[
FI_{L-} = \left( \frac{\sigma_{11}}{\sigma_{c}} \right)^2 \tag{2}
\]

Transverse tensile failure \( (\sigma_{22} \geq 0) \)

\[
FI_{T+} = \frac{\sigma_{22}}{\sigma_T}^2 + \frac{\sigma_{12}^2}{S_{12}^2} + \frac{\sigma_{23}^2}{S_{23}^2} \tag{3}
\]

Transverse compression failure \( (\sigma_{22} < 0) \)

\[
FI_{T-} = \left( \frac{\sigma_{22}}{\sigma_T} \right)^2 \tag{4}
\]

Delamination failure (failure in the thickness direction)

\[
FI_{H+} = \left( \frac{\sigma_{33}}{\sigma_T} \right)^2 + \frac{\sigma_{13}^2}{S_{13}^2} + \frac{\sigma_{23}^2}{S_{23}^2} (\sigma_{33} \geq 0) \tag{5}
\]
\[ F_I = \left( \frac{\sigma_{33}}{Z_C} \right)^2 + \frac{\sigma_{12}^2}{S_{12}^2} + \frac{\sigma_{23}^2}{S_{23}^2} (\sigma_{33} < 0) \] (6)

Where \( F_I \) represents various damage variables. \( X_T \) and \( X_C \), \( Y_T \) and \( Y_C \), \( Y_T \) and \( Z_C \) are the longitudinal tensile and compression strengths, the transverse tensile and compression strengths, and the tensile and compression strengths in the thickness direction respectively, \( S_{12}, S_{23} \) and \( S_{13} \) are shear strength.

2.2. Damage evolution

When the damage variables meet the conditions, the mechanical properties of the material will be updated immediately according to the material reduction model until the complete failure. Due to the complex damage mechanism of fiber and matrix, different evolution rules are adopted for tensile failure and compression failure.

2.2.1. Fiber tensile failure

The linear-exponential reduction scheme is used to simulate material damage in longitudinal and transverse tensile failure [13]. The evolution form of damage variable is described by the following formula.

\[
\Omega_{L+/T+} = 1 + \frac{K}{E_{11/22}} \left( \frac{K}{E_{11/22}} + 1 \right) \frac{1}{r_{L+/T+}} (r_{L+/T+} \leq r_C^{L+/T+}) \] (7)

\[
\Omega_{L+/T+} = 1 - \frac{\sigma_{p0}}{\sigma_{XT/T}} \left( A_{L+/T+} r_{L+/T+}^{E_{L+/T+}} - C_{L+/T+} \right) (r_{L+/T+} > r_C^{L+/T+}) \] (8)

Where, \( \sigma_{p0} \) represents the ultimate stress corresponding to point B. \( L_C \) is the characteristic length of the element. \( K \) is the slope of the linear softening criterion, \( r_{L+/T+}^{E_{L+/T+}} \) and \( \Omega_{L+/T+}^{E_{L+/T+}} \) are damage threshold function and damage variable respectively, \( A_{L+/T+} \) is the parameter defining the exponential softening criterion.

2.2.2. Fiber compression failure

In the transverse compression failure, the softening process will be affected by compression and tensile damage, and the exponential reduction scheme is adopted here to simulate the damage [14]. The evolution form of damage variable is described by Equation (9).

\[
\Omega_{L-/T-} = 1 - (1 - \Omega_{L-/T-}^E) (1 - A \pm \Omega_{L+/T+}^E) \] (9)

Where, \( \Omega_{L-/T-}^E \) is the exponential damage variable of longitudinal or transverse compression damage.

2.2.3. Delamination failure

In order to improve the accuracy of damage evolution, delamination damage adopts exponential damage evolution [15], which is defined by Equation (10).

\[
\begin{align*}
\Omega_{H+} &= 1 - \frac{1}{e^{(\Omega_{H+}^m - m)S_{33}}} \geq 0 \\
\Omega_{H-} &= 1 - \frac{1}{e^{(\Omega_{H-}^m - m)S_{33}}} < 0
\end{align*}
\] (10)

Where, \( \Omega_{H+} \) and \( \Omega_{H-} \) are the damage variables in the direction of thickness. \( m \) is used to control profit-the shape of the strain response.
2.3. Interface peeling damage model

The bonding behavior of adjacent layers can be simulated by the interface peeling damage model, which is composed of elastic constitutive relations, failure initiation and progressive damage evolution. The linear elastic constitutive relation and the linear softening law constitute the bilinear tractor-separation response, as shown in Fig.1. Stress-displacement criterion is used to describe the constitutive relation, as shown in Equation (11).

\[
[t] = \begin{pmatrix}
\ell_N \\
\ell_S \\
\ell_T
\end{pmatrix} = \begin{pmatrix}
K_N & K_S & 0 \\
0 & K_S & 0 \\
0 & 0 & K_T
\end{pmatrix}
\begin{pmatrix}
\delta_N \\
\delta_S \\
\delta_T
\end{pmatrix} = [K][\delta]
\]

Where \([t]\) and \([\delta]\) are traction stress and separation displacement respectively, \([K]\) is the stiffness matrix, \([\delta]\) is the displacement matrix.

The initiation of debonding damage is determined by the quadratic nominal stress failure criterion. Its failure criterion is

\[
\left(\frac{\ell_N}{N}\right)^2 + \left(\frac{\ell_S}{S}\right)^2 + \left(\frac{\ell_T}{T}\right)^2 \geq 1
\]

Where, \(\ell_N\) is the normal traction stress, \(\ell_S\) and \(\ell_T\) are tangential traction stresses, \(N\), \(S\) are \(T\) the normal strength and two shear strength, respectively.

\[
\ell_N = \begin{cases}
(1 - D_d)\ell_N \\
\ell_N & \text{otherwise}
\end{cases}
\]

\[
\ell_S = (1 - D_d)\ell_S \\
\ell_T = (1 - D_d)\ell_T
\]

Where \(\ell_N, \ell_S, \\ell_T\) are the traction stress components, \(D_d\) is the delamination damage variable, which is defined by Equation (16).

\[
D_d = \frac{\delta^f_m \delta^{\text{max}}_m}{\delta^{\text{max}}_m}
\]

Where \(\delta^{\text{max}}_m\) is the maximum displacement obtained by the mixed mode in the loading process, \(\delta^f_m\) is the displacement obtained in the mixed mode when the failure is complete, \(\delta^0_m\) is the effective displacement at the initial damage.
When the damage has not started, \( D_d = 0 \), after the damage has started, it will continue to increase to 1, which means complete damage. The damage model is established using the mixed mode energy method of Benzeggagh-Kenane (BK) criterion\[^{16}\], as shown in Equation (17).

\[
G^C = G^C_n + \left( G^C_s - G^C_n \right) \left( \frac{G^C_s}{G^C_n} \right)^n
\]  

(17)

Where \( G_s = G_s + G_n \), \( G_T = G_s + G_n \), \( G_n \), and \( G_t \) are the work done by the normal stress and the two shear stresses on the surface, \( G^C_n \), \( G^C_n \) is the critical fracture energy of normal direction and tangential direction, \( \eta (\eta = 2.284) \) is the viscosity parameter\[^{16}\].

3. Model and Validation

3.1. Finite element model

The laminates are glass fiber epoxy resin matrix composites (material performance parameters are shown in Table 1). Relevant data in simulation and comparative experimental data come from literature\[^{10}\]. The size of the laminates is 150×150 mm\(^2\), and the three-layer fibers are 0/90 braided in warp and weft direction. The punch is a steel projectile with a front diameter of 9.5mm and a mass of 7.60g. The meshing of the central region is dense to improve the accuracy of simulation. The finite element model is shown in Figure 2. The laminar and patch models are established by using a linear 8-node body unit (C3D8R). The rigid projectile is modeled as a discrete rigid body (R3D4), the simulation study was conducted on the four test results that were 0mm, 5mm, 10mm, and 15mm away from the center of the patch.

| Table 1. Mechanical properties of laminate and interfacial adhesive |
|---------------------------------------------------------------|
| \( \rho = 1.87g/cm^3 \)                                       |
| \( E_{11} = 18.31GPa \)                                      |
| \( E_{22} = 18.31GPa \)                                      |
| \( E_{33} = 3GPa \)                                          |
| \( G_{12} = 3.49GPa \)                                       |
| \( G_{23} = 3.49GPa \)                                       |
| \( G_{31} = 3.22GPa \)                                       |
| \( U_{12} = 0.26 \)                                          |
| \( U_{23} = 0.35 \)                                          |
| \( U_{31} = 0.09 \)                                          |
| \( X_T = 604MPa \)                                          |
| \( X_C = 219MPa \)                                          |
| \( G_L+ = G_L+ = 12.5N/mm \)                                 |
| \( G_T+ = G_T- = 12.5N/mm \)                                 |
| \( N = 207.2MPa \)                                          |
| \( T = 50MPa \)                                              |
| \( S = 30MPa \)                                              |
| \( G_{IC} = 0.43kJ/m^2 \)                                    |

Figure 2. FEM of repairing laminated plate
3.2. Model validation

The impact damage under different impact angles, as shown in Figure 3, fiber damage, matrix damage and patch degumming damage were all found in perforation damage, the damage area is oval, and with the increase of the offset, serious damage to the area away from the patch center, the other side of the patch fiber, matrix and degummed damage does not occur, which is consistent with the conclusions drawn from the experiment in the literature[10].

Table 2 shows the comparison between the predicted residual velocity of the projectile and the experimental value under the four offsets, it can be seen that predict the residual velocity of projectile's very close to the experimental results, the biggest difference is that for 15 mm deviation, the simulated residual speed is 7.3% smaller than the experimental residual speed, but the corresponding error of the residual speed is still within 10%.

Table 2. Comparisons between numerical for the residual velocities at different offset values

| Offset(mm) | Initial velocity (m/s) | Experimental residual velocity(m/s) | Simulation residual velocity(m/s) | error(%) |
|------------|------------------------|------------------------------------|----------------------------------|----------|
| 0          | 124                    | 80                                 | 81.3                             | +1.6     |
| 5          | 136                    | 100                                | 98.1                             | -1.9     |
| 10         | 140                    | 110                                | 107.2                            | -2.5     |
| 15         | 136                    | 110                                | 102                              | -7.3     |

4. Study on influence of typical parameters

4.1. Effect of incident angle on perforation resistance of repaired laminates during low speed impact process

In order to study the influence of incident angle on the perforation resistance of composite laminates during low-speed impact process, four different incident angles (0°, 15°, 30° and 45°) were analyzed and compared for damage characteristics of composite laminates. Figure 4(a) describes the relationship between projectile velocity and time. It can be seen from this figure that under projectile impact with an incident velocity of 140 m/s, the whole impact contact process of the repaired laminated plate is short. When the incident angle is 45 degrees, the residual velocity of the projectile is the maximum, and when the incident angle is 0 degrees, the residual velocity of the projectile is the minimum, but the residual velocity of the projectile does not show a strict law relationship with the incident angle.
Figure 3. Comparison of final failure modes of laminate patch

Figure 4(b) shows the curve of impact energy absorption with the displacement of the projectile. It can be seen that the energy absorption of the three oblique impact projectiles is all smaller than that of the positive impact (0° incident angle). Therefore, the greater the incident angle of impact, the lower the energy absorption of the laminated plate. Figure 3 shows the final failure mode of the repair patch under different incident angles. It can be seen that the difference from the 0° incident angle is that the last layer of the repair patch of the three oblique impact repair laminates has obvious degumming phenomenon, indicating its contribution to the impact load is small, which is the reason why the residual velocity of the projectile in the oblique impact is higher than that in the forward impact, and the energy absorption of the laminate is low.

Figure 4. Comparison of residual velocity of projectile (a), and energy absorption (b) under different impact angles

5. Conclusions
(1) The failure modes predicted by the numerical simulation including fiber fracture, matrix cracking, delamination and interface debonding, which are similar to the experimental observation. The predicted residual velocity of the projectile is very close to the experimental results, indicating the rationality of the damage model.
(2) When the incident angle is 45 degrees, the residual velocity of the projectile is the maximum, and when the incident angle is 0 degrees, the residual velocity of the projectile is the minimum, but the residual velocity of the projectile does not show a strict law relationship with the incident angle. The energy absorption of the three oblique impact projectiles is all smaller than that of the positive impact.
(3) Under the impact of oblique incidence angle, the degumming phenomenon of the patch is more obvious, especially the obvious separation phenomenon of the last layer of patch.

6. References:
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