Failure Analysis of Composite Laminate under Low-Velocity Impact

Based on Micromechanics of Failure

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Abstract:

Previous researches on the impacted composite laminates were mainly carried out according to the macromechanics-based homogenous strength theories, which ignore the local stress nonuniformity and strength difference between the fiber and matrix. In this paper, a new multiscale analysis method which combines the micromechanics of failure (MMF) theory for intralaminar damage and cohesive model for interlaminar failure is proposed. This approach is able to identify the failure modes of fiber and matrix in microscale as well as delamination between laminas. The finite element model of the multidirectional carbon fiber reinforced plastic (CFRP) laminate subjected to low-velocity impact is built on ABAQUS/Explicit platform. User material subroutine VUMAT is developed to analyze the micro stresses and determine the possible failure modes of fiber and matrix. Cohesive elements with bi-linear traction-separation law are employed to capture the onset and propagation of delamination. Finally, the structure response, fiber and matrix failure mode and delamination area are compared with experimental data under different impact energies, and the good agreements validate the effectiveness and accuracy of the novel method.

Key words: multiscale, micromechanics of failure, failure criteria, low-velocity impact, cohesive model

1. Introduction

Carbon fiber reinforced plastic (CFRP) composite has been widely used in airplanes and automobiles by the virtues of high strength and light weight, however its sensibility to alien impact is a widespread issue to the structure designers and users. Compared with high energy impact, the low-velocity impact appears more frequently during the manufacturing or maintenance processes of composite structure^[1], in addition, the damage caused by low-velocity impact is more covert and even invisible which causes huge threat to the structure safety. Therefore, the research works on failure mode and evolution mechanism are crucial important to the structure design and safety analysis. Due to the high cost and impossibility to study each situation by experiment, numerical method has been gradually adopted to assist the research of composite subjected to impact. The damage mechanisms of CFRP composite can be classified into intralaminar damages such as fiber breakage, matrix crack and interlaminar damage namely delamination, the complexity of which results in difficulties during simulation.

In previous research works of intralaminar damage various strength theories were proposed, among which, Hashin^[2] and Puck^[3] criteria and their modified theories are frequently adopted, this can be seen in the works of Pinho^[4], Donadon^[5], Falzon^[6], Liu^[7] and Li^[8]. These theories are capable to determine the damage mode of constituents based on physical failure mechanism, however, both of them are macromechanics theory, which treat composite as homogeneous material and have not considered the influence of local stress difference in various area caused by the different properties of fiber and matrix.

Besides the macromechanics method, micromechanics method which studies the composite properties by repeating unit cell (RUC) or representative volume element (RVE) has also been used, the detail of which can be found in the review of Drago^[9]. The micromechanics methods existed can be classified as analytical, semi-analytical and numerical methods, and the detail description of various micromechanics theories is given by Aboudi^[10]. In principle it is more precise to analyze in micromechanics model, however, its impossibility to be implemented in the whole composite structure restricts its application. Therefore, multiscale method which combines the efficiency of macromechanics and accuracy of micromechanics was proposed^[11].

Previous multiscale researches focus on the strain or stress analysis of structure^[9], however, the failure mechanism of constituent has not been fully discussed. The micromechanics of failure (MMF) theory proposed by Ha^[12] firstly considered the failure of fiber and matrix based on physical mechanism in microscale, and stress amplification factors were introduced to realize the multiscale analysis. Combining MMF theory and accelerated testing methodology (ATM) Cai^[13] researched the long term failure behavior of multidirectional laminate under arbitrary frequency, load ratio and temperature. Li^[14] proposed a non-interactive failure criteria based on MMF and researched the progressive failure of open-hole composite structure.

Dealing with delamination Virtual Crack Closure (VCC) technique and Cohesive Zone Models (CZM) are often used. VCC technique is very sensitive to the size and density of finite element mesh, in addition, pre-existed crack and re-mesh technique are needed during the movement of crack tip, which will cause heavy computation cost. CZM is based on uniform constitutive relation to describe the crack initiation and propagation, which can avoid the stress singularity of crack tip in the linear elastic mechanics and is widely used in the delamination analysis of composite^[15].

In this paper, a multiscale analysis model of composite subjected to low-velocity impact was established based on the combination of MMF theory and cohesive model. On the commercial finite element software ABAQUS/Explicit platform, the finite model of composite under low-velocity impact was built through Python script language, user material subroutine VUMAT was developed to realize micromechanics calculation, the constituents failure judgement and the progressive damage analysis. The delamination evolution mechanism was researched through the cohesive elements embedded between the layers with different fiber directions. Finally, the structure response such as force, displacement and energy of the composite under various impact energies were obtained, the fiber and matrix failure area in each layer and the delamination between different layers were studied. Corresponding experiments were carried out, the structure responses were recorded and the impacted laminates were inspected by ultrasonic C scan device. The numerical and experimental results were compared to judge the accuracy of the FE model.

2. Multiscale analysis based on MMF

2.1 The calculation of micro stress

Distinct from earlier analytical method, to describe the relationship between macro stress and micro stress MMF theory developed by Ha^[12] adopts a new method which is called stress amplification factors, the procedure of which is well presented in his papers. For the better understanding of the MMF theory, a brief description is given in the following part. Firstly, the following assumptions are needed^[16]:

1. Carbon fiber is linear elastic, transversely isotropic and with uniform distribution;
2. Matrix is linear elastic, isotropic and without voids;
3. Every micro strain/stress component at any point within a fiber or matrix is linearly dependent on macro strains/stresses, as well as on temperature increment.

To analyze the micro stress of fiber and matrix, a unit cell mode is adopted as illustrated in Fig.1. By imposing

the boundary condition to the unit cell, the stress and strain status of the fiber and matrix can be obtained. In consideration of efficiency, 35 key points distributed in the unit cell are selected to describe the whole stress status, in which 17 key points are in the fiber and 19 key points in the matrix.

After the setup of key points, the micromechanics analysis of unit cell turns into the stress and strain analysis of 35 key points. Based on previous assumption, the stress of arbitrary point i in the 35 points can be explicitly expressed by:

$$\sigma_i = M_{\sigma}^i \bar{\sigma} + A_{\sigma}^i \Delta T \quad (1)$$

where σ_i is the micro stress of the point i , $\bar{\sigma}$ is the macro stress of unit cell, ΔT is the difference between zero-stress temperature and ambient temperature, M_{σ}^i is the mechanical stress amplification factor of point i , A_{σ}^i is the thermal stress amplification factor of point i , σ_i and $\bar{\sigma}$ are composed of six stress components, M_{σ}^i is 6×6 matrix, A_{σ}^i is 6×1 column vector.

The calculation of each components of M_{σ}^i and A_{σ}^i is based on finite element analysis of unit cell under 6 mechanical loadings and 1 thermal loading as illustrated in Fig.2. Take $\bar{\sigma}_{11}$ for example, macro stress $\bar{\sigma}$ equal to $[1 \ 0 \ 0 \ 0 \ 0 \ 0]^T$ is imposed to the unit cell and the exact value of stress in the i point σ_i can be obtained. By substituting the σ_i , $\bar{\sigma}$ and ΔT into Equation (1) the first column of M_{σ}^i can be obtained. Other columns of M_{σ}^i can be obtained through the same method by imposing $\bar{\sigma}_{22}, \bar{\sigma}_{33}, \bar{\tau}_{12}, \bar{\tau}_{13}, \bar{\tau}_{23}$ to the unit cell. In the calculation of A_{σ}^i , set $\bar{\sigma}$ equal to $[0 \ 0 \ 0 \ 0 \ 0 \ 0]^T$ and increase the temperature by 1 then the σ_i is obtained, by substituting the $\sigma_i, \bar{\sigma}$ and ΔT , then A_{σ}^i can be obtained.

Before the finite element analysis of unit cell, periodic boundary conditions must be applied in order to avoid separation or overlap between the neighboring unit cells during deformation^[17]. The boundary conditions used in this paper to calculate the stress amplification factors are same with the setting of Jin^[16]. To validate the boundary conditions, multi-cell model and unit cell model are built and the stress contours of the two models under shear loading $\bar{\tau}_{12}$ and $\bar{\tau}_{23}$ are compared as shown in Fig.3. The stress distributions in the multi-cell model and unit cell model are coincident, and the differences between the maximal stress values are less than 1%. For the reason that finite element analysis is a numeric technique for the approximate solution and the mesh strategies in the multi-cell and unit cell model are kind of different, it is suggested that the stress in the multi-cell and unit cell are consistent and the boundary conditions are validated in this paper.

2.2 Failure criteria of constituents

The intralaminar failure mechanisms of CFRP composite can be classified into fiber breakage, matrix crack and matrix-fiber debonding. Different failure modes can be judged by failure criteria of different strength theories. In previous theory homogenous stress is analyzed and the property differences between fiber and matrix are neglected. However, in MMF theory the local stress status of fiber and matrix are taken into account, based on which the failure mechanisms are identified. For the reason that the fiber-matrix interface strength is difficult to be obtained by experiments, the fiber and matrix are assumed to bond perfectly in this paper. A set of non-interactive failure criteria used to judge the fiber and matrix failure mechanism are as follows:

2.2.1. Fiber failure criteria

Fiber acts as the main load-bearing component and its damage is the primary indicator of the failure of composite when subjected to longitudinal tension or compression.

In the situation of longitudinal tension, the stress component σ_{11}^f of each key point in the fiber is chosen as the

parameter to judge the failure of fiber. The tensile failure criterion is shown as follows:

$$\frac{\sigma_{11}^f}{T_f} = 1 \quad (2)$$

The compressive failure criteria of fiber takes equivalent stress σ_{eq}^f into account, which considers the damage caused by shear deformation, as shown in expression (3):

$$\frac{\sigma_{eq}^f}{C_f} = 1 \quad (3)$$

where $\sigma_{eq}^f = \sqrt{0.5[(\sigma_{11} - \sigma_{22})^2 + (\sigma_{11} - \sigma_{33})^2 + (\sigma_{22} - \sigma_{33})^2 + 6(\tau_{12}^2 + \tau_{23}^2 + \tau_{13}^2)]}$, T_f and C_f are the critical values of σ_{11}^f and σ_{eq}^f when fiber failure occurs under tensile and compressive loading. To calculate the value of T_f , $\bar{\sigma}$ equal to $[X \ 0 \ 0 \ 0 \ 0 \ 0]^T$ and ΔT equal to -105 are taken into equation (1), then the stresses of 17 key points in fiber are obtained and the maximum σ_{11}^f is the T_f . Similarly, by taking $\bar{\sigma}$ equal to $[-X' \ 0 \ 0 \ 0 \ 0 \ 0]^T$ and ΔT equal to -105 into equation (1) the stress of 17 key points in fiber are obtained and the maximum σ_{eq}^f is the C_f (X and X' are the longitudinal tensile strength and compressive strength of unidirectional composite laminate).

2.2.2. Matrix failure criteria

In the situation of transverse tension the first invariant of stress I_1^m of key points in matrix is taken into account, which considers the damage caused by volume increment. In the situation of transverse compression the equivalent stress σ_{eq}^m of key points in matrix is adopted, which judges the damage caused by shear deformation. The tensile and compressive failure criteria of matrix are shown in expression (4) and (5) respectively.

$$\frac{I_1^m}{T_m} = 1 \quad (4)$$

$$\frac{\sigma_{eq}^m}{C_m} = 1 \quad (5)$$

where $I_1^m = \sigma_{11} + \sigma_{22} + \sigma_{33}$, $\sigma_{eq}^m = \sqrt{0.5[(\sigma_{11} - \sigma_{22})^2 + (\sigma_{11} - \sigma_{33})^2 + (\sigma_{22} - \sigma_{33})^2 + 6(\tau_{12}^2 + \tau_{23}^2 + \tau_{13}^2)]}$.

When calculating T_m and C_m , the same method is used as calculating T_f and C_f , the only differences are that the macro loading was transversely tensile strength Y and transversely compressive strength Y' of unidirectional laminate, and the parameters considered was I_1^m and σ_{eq}^m . The uniaxial strengths of unidirectional laminate are list in Table 1. The critical MMF parameters of constituents are shown in Table 2. The mechanical and thermal properties used in the finite element model are list in Table 3.

2.3 Multiscale analysis

The multiscale analysis sketch is illustrated in Fig.4. In macro scale the stress and strain of composite structure is analyzed though finite element method and the stress of each integration point of elements are then obtained. In micro scale each integration point can be seen as a unit cell, the micro stress of fiber and matrix can be calculated by Equation(1) and the failure mode can be decided by Equation(2)-(5). In this paper the finite element analysis was carried out on ABAQUS/ Explicit platform and the micromechanics analysis and failure criteria were realized by writing user material subroutine VUMAT.

2.4 Progressive damage model

The failure criteria in section 2.2 can be used to judge the initial damage of composite constituents. Once the local damage occurs the load-bearing capacity of composite will decrease and with the damage growing the load-bearing capacity will gradually decrease to zero, which is a progressive damage process. **The material stiffness degradation strategy used in this paper is based on the damage model proposed by McCarthy^[18].** The expressions are as follows:

$$\begin{aligned}
C_{11} &= E_1(1-d_f)[1-(1-d_m)^2\nu_{23}^2]/A \\
C_{22} &= E_2(1-d_m)[1-(1-d_m)(1-d_f)\nu_{13}\nu_{31}]/A \\
C_{33} &= E_2(1-d_m)[1-(1-d_m)(1-d_f)\nu_{12}\nu_{21}]/A \\
C_{12} &= E_2(1-d_m)(1-d_f)[(1-d_m)\nu_{13}\nu_{23} + \nu_{12}]/A \\
C_{13} &= E_2(1-d_m)(1-d_f)[(1-d_m)\nu_{12}\nu_{23} + \nu_{13}]/A \\
C_{23} &= E_2(1-d_m)^2[(1-d_f)\nu_{12}\nu_{31} + \nu_{23}]/A \\
C_{44} &= G_{12}(1-d_m)(1-d_f) \\
C_{55} &= G_{13}(1-d_m)(1-d_f) \\
C_{66} &= G_{23}(1-d_m)(1-d_f) \\
A &= 1 - (1-d_m)(1-d_f)\nu_{12}\nu_{21} - (1-d_m)^2\nu_{23}\nu_{32} \\
&\quad - (1-d_m)(1-d_f)\nu_{13}\nu_{31} - 2(1-d_m)^2(1-d_f)\nu_{12}\nu_{31}\nu_{23}
\end{aligned} \tag{6}$$

where d_f and d_m are the damage indexes of fiber and matrix, which are used to describe the failure status of fiber and matrix in a material point. Once one of key points in fiber or matrix satisfy the failure criteria (2)-(5), it is considered that the corresponding failure has occurred in the material point. The initial value of d_f and d_m is set as zero, and once the following criteria (7) and (8) are satisfied the values of d_f and d_m will change.

$$\text{If } \max \left\{ \frac{\sigma_{11}^{f,i}}{T_f} \right\} = 1 \text{ or } \max \left\{ \frac{\sigma_{eq}^{f,i}}{C_f} \right\} = 1, \quad i = 1, \dots, 17 \tag{7}$$

the damage index of fiber d_f will be set as 0.99.

$$\text{If } \max \left\{ \frac{I_{11}^{m,i}}{T_m} \right\} = 1 \text{ or } \max \left\{ \frac{\sigma_{eq}^{m,i}}{C_m} \right\} = 1, \quad i = 1, \dots, 19 \tag{8}$$

the damage index of matrix d_m will be set as 0.5. In previous papers the value of d_m is set as 0.99, however the matrix including cracks is still able to afford the compression perpendicular to the crack and tension parallel with the crack, so the d_m here is set as 0.5 as a compromise.

2.5 Cohesive model

To research the delamination occurs between layers with different directions, a cohesive model based on bilinear traction-separation constitutive relationship as shown in Fig.5 is adopted. The top and bottom nodes are hold together using penalty stiffness K_N (Mode I) and K_S , K_T (Mode II and Mode III) in linear elastic range (Point 1). In pure Mode I, II or III loading situation, once the interfacial normal or shear tractions attain their respective interlayer tensile (N) or shear strengths (S , T) (Point 2), the stiffness of cohesive element will decrease. At this moment, if unloading happens the force and displacement will act as the line through point 3 , in contrast if

continuing the loading the force and displacement will act as line through point 4 until final damage in point 5. The areas under the traction-separation curves are equal to corresponding fracture toughness of each mode.

The selection of cohesive model parameters plays a vital role in the analysis and improper choice will lead to compliance difficulties and wrong results. The fracture toughness is the material property of composite and can be obtained by corresponding experiment tests. The value of penalty stiffness K_N , K_S , K_T should be large enough to avoid affecting the overall compliance. The interface strength (N , S , T) of each mode will decide the maximum value of tensile or shear loading that the cohesive model can afford.

To obtain the fracture toughness of composite material used in this paper, DCB and ENF specimens were made and the test according to ASTM D5528 standard (Mode I) and ASTM D7905 standard (Mode II) were performed. Thin (0.03 mm) Teflon film was implanted in the specimens to create initial crack. The dimension of DCB specimens are $130 \times 25 \times 3.2 \text{ mm}^3$ with initial crack length of 30 mm, and the ENF specimens are $180 \times 25 \times 3.2 \text{ mm}^3$ with initial crack length of 60 mm. The tension and 3 points bending test are implemented at INSTRON1195 test machine and the force-displacement data was record, based on which the fracture toughness G_{IC} and G_{IIC} were calculated.

In order to determine the value of penalty stiffness (K_N , K_S , K_T) and interface strengths (N , S , T) 2-D finite element models of DCB and ENF specimens were built on ABAQUS/Standard platform as shown in Fig.6. **The force-displacement relationship calculated by FE model varies with different parameters selections of cohesive model, and by compared with experiment results (Fig.7) the parameters were finally confirmed as shown in Table 4.**

The stress status of composite under low velocity impact is complex and the delamination often occurs in mixed mode. A quadratic nominal stress criterion was adopted to judge the initiation of delamination:

$$\left(\frac{\langle \sigma_n \rangle}{N} \right)^2 + \left(\frac{\sigma_s}{S} \right)^2 + \left(\frac{\sigma_t}{T} \right)^2 = 1 \quad (9)$$

where $\langle \rangle$ represents Macaulay bracket and signify that a pure compressive deformation or stress state does not initiate delamination.

The criteria used to predict delamination propagation under mixed-mode loading conditions are usually established in terms of the energy release rate and fracture toughness. The mixed-mode criterion proposed by Benzeggagh and Kenane^[19] (B-K criterion) is able to account for the variation of fracture toughness as a function of mode ratio in epoxy composites and is adopted in this paper, whose expression is as follows:

$$G_{IC} + (G_{IIC} - G_{IC}) \left(\frac{G_{shear}}{G_T} \right)^\eta = G_{TC} \quad (10)$$

where

$$\begin{aligned} G_{shear} &= G_{II} + G_{III} \\ G_T &= G_I + G_{II} + G_{III} \end{aligned} \quad (11)$$

The parameter η can be obtained from MMB tests at different mode ratios, and in this paper it is set as 1.6.

3. Finite element modeling and experiment

3.1 Finite element modeling

The finite model to analyze structural response and damage propagation of composite subjected to low-velocity impact was built on ABAQUS/Explicit platform using Python script language as illustrated in Fig.8, user material

subroutine VUMAT was written using FORTRAN language to calculate the micro stress status and describe the progressive damage. Thin thickness (0.01mm) cohesive elements were placed between layers with different fiber directions.

The mass of impactor is set as 2.41Kg with a hemispheric head of 20 mm diameter. The impactor is consisted of C3D8R elements and coupled to be a rigid body. The dimension of the laminate is $150 \times 100 \times 1.6 \text{ mm}^3$, and the single layer is 0.1mm thick with the stacking sequence of $[-45/90/45/0]_{2S}$ (Fig.9). In order to improve the computation efficiency special mesh strategy is used, the dimension of the mesh in the center area is fine ($0.5 \times 0.5 \text{ mm}^2$) and the outer area is coarse. To reduce the hourglass effect of the model the element in the center area is set as C3D8 and to improve the computing efficiency the outer side area is set as C3D8R. Thin COH3D8 elements are embedded between each layer and the cohesive parameters are selected by the method in section 2.5.

The laminate is supported by a rigid plate within which there is a $125 \times 75 \text{ mm}^2$ groove. Four rigid cylinders are fixed on the top of the laminate. General contact property is set in the whole model. The Coulomb friction coefficient is set as 0.3. Mass scaling technique is not adopted in this model to avoid the influence on the precision. Different impact energies of 3.40 J, 5.36 J, 7.35 J are imposed on the impactor by changing its velocity before contacting with laminate.

3.2 Experiment

Composite laminate specimens were produced with UTS50/E51 carbon fiber/epoxy resin prepreg by hot pressing process with stacking sequence of $[-45/90/45/0]_{2S}$. The impact experiments were carried out according to ASTM D7136 standard on INSTRON 9350HV machine. By changing the height of impactor the experiments with different impact energies of 3.40 J, 5.36 J and 7.35 J were performed, during which the contact force, displacement and velocity of impactor were recorded with the frequency of 1K Hz. After the impact test, the specimens were visually examined and inspected by VEO1664 ultrasonic C-scan equipment, by which the delamination images were acquired.

4. Results and discussion

The structure response of laminate including the contact force, impactor displacement and kinetic energy show the entire process of impact and can be used to validate the accuracy of the FE model, therefore, these numerical data were extracted to compare with the experimental data. FE model which only include intralaminar model (MMF) was used to calculate the structure response of laminate, for the reason that cohesive model contains penalty stiffness (K_N , K_S , K_T) which is different from the stiffness of composite layer by order of magnitude, and once large amount of these stiffer cohesive elements were introduced into the model, the composite will be much stiffer and the structure response will be significantly affected. In the study of both intralaminar damage and interlaminar damage in section 4.2 and 4.3, the MMF model and cohesive model are adopted in union.

4.1. Structure Response

The impactor displacement history during the impact process under different energies K are illustrated in Fig.10, the numerical curves show the same trend of displacement and are quite precise in the value of time when the velocity of impactor reduces to zero.

The contact force-time curves are shown in Fig 11, it can be found that the numerical maximal force of 3.40 J situation is larger than experimental data by 11.8%, however the 5.36 J and 7.35 J model are much more accurate with the error of 2.1% and 3.0%. The force-displacement data are illustrated in Fig.12, which shows same tendency in simulation and experiment. Fig.13 shows the kinetic energy of impactor varies with time, the numerical data match with experimental data quite well except the ending part where the kinetic energy calculated by FE model is

larger than experiment. It is supposed that these differences D are caused by the lack of consideration of delamination. Delamination is a kind of matrix fracture and its fracture energy is originated from the kinetic energy of impactor, with the growth of impact energy the delamination area increases as shown in Fig.16, which can also be discovered through the value of D .

4.2 Intralaminar damage

4.2.1 Fiber breakage

The fiber failure area predicted by FE model under different impact energies are illustrated in Fig.14, there is no fiber failure found in 3.40 J situation, however, tiny tensile fiber failure area are founded in Layer 3(45°) under impact energies of 5.36 J and 7.35 J. Because the damage area of fiber is so small that it has little effect on the whole strength of composite laminate.

4.2.2 Matrix damage

Compared with fiber failure the damage area of matrix is larger and more complicated. The trend of matrix failure area in different layers under impact energies of 3.40 J, 5.36 J and 7.35 J are alike as shown in Fig.15 (taken 5.36 J for example). The tensile matrix failure decreased from the bottom layer to the top layer (Layer 1 to layer 16). The compressive matrix failure increased from the bottom layer to the top layer. These two trends suggest that the matrix damage mechanism in the bottom layers are mainly tensile failure and in the top layers are mainly compressive failure. In addition, matrix tensile failure and compressive failure often occur in the same layer, which are mutually complementary.

The matrix damage areas caused by different failure mechanisms under different impact energies are illustrated in Fig.17, it can be found that the matrix tensile failure plays a main role in the whole laminate, however the matrix compressive failure only affect several top layers.

4.3 Delamination

The delamination between different layers under impact energies K of 3.40 J, 5.36 J and 7.35 J are shown in Fig. 16(1a), (2a) and (3a). The interlayers which include delamination are interlayer 3, 5, 7 and 11 in 3.40 J situation, when the impact energy increases to 5.36 J delamination occurs in interlayer 9. By stacking the delamination of each interlayer the delamination contour of whole composite is obtained as shown in Fig 16(1b), (2b) and (3b). Compared with the C scan results in Fig 16(1c), (2c) and (3c), it is found that the numerical results agree with the experiment quite well. First, no delamination occurs in the center area under the impactor, it is suggested that the stress in the center area is mainly normal compressive stress and will not cause delamination, however the stress in the area around the center is mainly shear stress and will result in delamination. Second, the contours of delamination under each impact energy are ellipse, the damage in the 90° direction are more serious than the 0° direction despite the difference of impact energy. It is suggested that the rectangle groove in the supporting plate makes the boundary restriction in the 90° direction more serious and cause larger shear effect and lead to larger delamination. The delamination areas of each interlayer under different impact energies obtained by FE model are illustrated in Fig.17.

5. Conclusion

In this paper, a new method combining micromechanics of failure (MMF) theory and cohesive model was proposed to study the failure mechanism and structure response of carbon fiber reinforced plastic (CFRP) laminate subjected to low-velocity impact loading. The MMF theory was used to study the fiber and matrix failure mechanism, as well as the force, displacement and kinetic energy of impactor. The cohesive model was employed

to capture the onset and propagation of delamination.

Various impact processes with energies of 3.40 J, 5.36 J and 7.35 J were analyzed. The numerical data of structure response, fiber and matrix failure as well as delamination draw the following conclusions:

(1) In low-velocity impact condition, the fiber breakage is very limited, while the matrix crack and delamination are the main failure mechanism. In the top layers matrix damage are mainly caused by compressive stress and the bottom layers are mainly caused by tensile stress.

(2) The low-velocity impact results in the delamination only in several interlayers. There is no delamination in the center area due to the normal compressive stress applied by the impactor. The contour of delamination looks like an ellipse due to the asymmetrical boundary condition.

(3) The structure response and failure mechanism predicted by the FE model agree with experimental results quite well, which validate this novel micromechanic-based method for the research of impacted composite.

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Fig.1. Unit cell model and key points location in fiber and matrix.

Fig.2. Mechanical and thermal loading in the calculation of M_σ^i and A_σ^i .

Fig.3. Stress contour of multi-cell and unit cell under different loadings.

Fig.4. Schematic diagram of multiscale analysis.

Figure.5. Traction-separation constitutive relationship of cohesive model.

Fig.6. FE model of DCB and ENF specimens.

Fig.7. Force-displacement curves of DCB and ENF obtained by simulation and experiment.

Fig.8. The FE model of laminate subjected to impact.

Fig.9. The layer stacking sequence of laminate.

(a) $K = 3.40 \text{ J}$

(b) $K = 5.36 \text{ J}$

(c) $K = 7.35 \text{ J}$

Fig.10. Displacement-time curves of impactor with different energies K .

(a) $K = 3.40 \text{ J}$

(b) $K = 5.36 \text{ J}$

(c) $K = 7.35 \text{ J}$

Fig.11. Force-time curves of impactor with different energies K .

(a) $K = 3.40 \text{ J}$

(b) $K = 5.36 \text{ J}$

(c) $K = 7.35 \text{ J}$

Fig.12. Force-displacement curves of impactor with different energies K .

Fig.13 Force-displacement curves of impactor with different energies K .

Fig.14. Tensile fiber failure area of layer 3 predicted by FE model under impact energy K of 5.36 J (a) and 7.35 J (b).

Fig.15. Matrix failure predicted by FE model under impact energy K of 5.36 J.

Fig.16. Delamination area of laminate under different impact energy K obtained by simulation and C-scan of specimens.

(1) $K=3.40$ J (2) $K=5.36$ J (3) $K=7.35$ J.

Fig.17. Area of matrix failure and delamination predicted by FE model under different impact energy K .

Table 1The uniaxial strengths of unidirectional UTSS50/E51 laminate ^[14]

The uniaxial strength of unidirectional laminate		
Longitudinal tensile strength X	/Mpa	2100
Longitudinal compressive strength X'	/Mpa	1932
Transverse tensile strength Y	/Mpa	54
Transverse compressive strength Y'	/Mpa	179

Table 2MMF parameters of UTSS50/E51 laminate ^[14]

Critical parameters of constituents		
Fiber tensile strength T_f	/Mpa	3170
Fiber compressive strength C_f	/Mpa	3400
Matrix tensile strength T_m	/Mpa	155
Matrix compressive strength C_m	/Mpa	207

Table 3Mechanical and thermal properties used in the FE model^[14].

Materials properties	Ply	Fiber	Matrix
Fiber volume fraction V_f	0.56	1.0	0.0
Longitudinal modulus E_1 /GPa	136	240	3
Transverse modulus $E_2=E_3$ /GPa	10	42	3
Shear modulus $G_{12}=G_{13}$ /GPa	4.7	23	1.06
Shear modulus G_{23} /GPa	3.2	12	1.09
Poisson's ration $\mu_{12}=\mu_{13}$	0.35	0.33	0.38
Poisson's ration μ_{23}	0.56	0.71	0.38
Longitudinal coefficient of thermal expansion $\alpha_1/10^{-6}K^{-1}$	-0.34	-0.87	60
Transverse coefficient of thermal expansion $\alpha_2=\alpha_3/10^{-6}K^{-1}$	75	40	60

Table 4

Cohesive parameters used in this paper

Cohesive properties	Value
K_n /GPa·m ⁻¹	3.2×10^4
K_t /GPa·m ⁻¹	3.5×10^4
K_s /GPa·m ⁻¹	3.5×10^4
N /MPa	10
T /MPa	15
S /MPa	15
G_{IC} /J·m ⁻²	190
G_{IIIC} /J·m ⁻²	635
G_{IIIIC} /J·m ⁻²	635