Numerical Analysis on Low-Velocity Impact Damage of Laminated Composites by Combining Continuum Damage Mechanics with Cohesive Zone Model

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1 Introduction

When laminated composites are applied in the aircraft, they may suffer from tool dropping, stone hitting, bird impact and so on. These impactors can be summarized as drop-weight (high mass, low velocity) or gas-gun (low mass, high velocity) [1]. It is known that the plate-shell structure of fiber reinforced composites is sensitive to transverse impact, even slight lateral impact may lead to intraply and interlaminar damage. Thus, the ability of laminated composites to resist impact has been the focus of attention. Focusing on the low-velocity impact damage, the mainstream explanations for its damage mechanism have the following two ways. Choi and Chang [2] put forward that the top delaminations were mainly induced by inner shear cracking whereas the bottom delaminations were mainly induced by surface bending cracking. Renault [3] proposed to give matrix cracking a precursor role regarding the development of specific delamination. This idea has been globally admitted in literatures [4-6].

Currently, there has been much work on carrying out the relevant researches on drop-weight by experimental and simulated methods [7-10]. These studies include the response of laminated composites to low-velocity impact as well as the initiation, propagation and extent of damage in the structure. Also, the influences of such factors as thickness, curvature, stacking sequence and boundary conditions on the structural behavior under low-velocity impact are discussed. Considering that the experimental methods are time and labor consuming and costly, more and more scholars start to use numerical simulation technology for correlative research work.

Sun and Chen [11] studied the impact on laminates under initial stress using the finite element method, but its computational demands can be exorbitant. Then some simple but efficient theories and methods have been presented to deal with this problem. Choi et al. [12] used the dynamic finite element method coupled with failure analysis to predict the threshold of impact damage and initiation of delamination. Aslan et al. [13] used 3DIMPACT transient dynamic finite element analysis code for calculating stresses and contact forces of the composite plates during impact along with a failure analysis for predicting the threshold of impact damage and initiation of delamination. Raimondo et al. [14] adopted a progressive failure model for mesh-size-independent finite element analysis. According to the proposed method, the accurate modeling of composites impact damage using a relatively coarse mesh can obviously reduce the computational cost. Yokoyama et al. [15] proposed an energy based failure model in ABAQUS FE code to study the impact resistance of composite shells accounting for the pressure, curvature, lay-up and thickness effects. They used a newly developed in-plane damage model for plane stress elements. The model formulation also incorporated an objectivity algorithm which avoided strain localization problems and ensured constant energy dissipation for each failure mode regardless of mesh refinement, element topology and cracking direction. The proposed formulation also used the Second Piola-Kirchhoff stress tensor in order to avoid excessive material deformation, such as trellising. Bouvet et al. [16] used interface type elements to describe matrix cracking. Delaminations were described with interface elements similar to the ones used to represent matrix cracking and the coupling between these two damages were established.
However, most of the approaches are restricted to using a simple constitutive model to get rich data such as impact dynamics, damage morphologies and so on with a relatively low modeling accuracy. Therefore a continuum damage mechanics constitutive relation is used for the prediction of the intraply damage of Hexply AS4/8552 laminated composites under low-velocity impact in this paper. Meanwhile a ‘tiebreak’ contact, which contains the traction-separation rule by a cohesive zone model, is presented to simulate the delamination and ordinary contact between two adjacent plies after delamination, and then the impact dynamics and damage morphologies are visualized vividly. In addition, the computational demands of this work are compared with the ones of Lopes et al. [17].

2 Damage Model

As shown in Fig. 1, a continuum damage mechanics (CDM) is used for the numerical model to characterize the intraply damage, and a cohesive zone model (CZM) is used to represent interlaminar damage.

Recently the researches based on CDM modeling the damage of composite laminates subjected to impact have been reported [18-20]. In this paper, based on the Hashin’s failure criterion [21, 22], the CDM contains the longitudinal (fiber) failure and transverse matrix cracking. The \( \omega_{11} \), \( \omega_{22} \) are the damage variables associated with longitudinal (fiber) failure, transverse matrix cracking, respectively, and are assumed to be different values for tension (\( \omega_{11t} \) and \( \omega_{22t} \)) and compression (\( \omega_{11c} \) and \( \omega_{22c} \)) in order to account for the phenomenon of one-sidedness. The damage parameter for shear \( \omega_{12} \) is independent on the sign of the shear stress \( \tau \). \( E_1 \), \( E_2 \) and \( G \) denote longitudinal Young’s modulus, transversal Young’s modulus and shear modulus, respectively. \( \nu \) denotes Poisson’s ratio. The shape of the loading surface is:

for fiber damage

\[
f_1 = \frac{\sigma_{11}^2}{(1-\omega_{11c,t})^2} X_{c,t}^2 - r_{c,t} = 0 \tag{1}
\]

for matrix damage

\[
f_2 = \frac{\sigma_{22}^2}{(1-\omega_{22c,t})^2} Z_{c,t}^2 + \frac{r^2}{(1-\omega_{22c,t})^2 S^2} - r = 0 \tag{2}
\]

where \( X_{c,t} \), \( Z_{c,t} \) and \( S \) denote longitudinal, transversal and shear strength, respectively. \( r \) denotes damage threshold, subscript \( c \) denotes compression, and \( t \) denotes tension [23, 24].

The CZM is a powerful tool to analyze nonlinear fracture problems, and has been widely applied in the field of composites [25-28]. In this paper, a CZM [29], based on the energy dissipation mechanisms, is introduced to correlate traction force with displacement at the interface between plies, as shown in Fig. 2. Both the normal crack and the tangential slip are taken into account. The damage initiation is related to the interfacial strength, i.e., the maximum traction in the traction-displacement relation. When the area under the traction-displacement relation curve is equal to the traction toughness, the traction is reduced to zero and a new crack surface is formed. In bilinear CZM, for the normal delamination, the fracture toughness is:

\[
G_{IC}=0.5T\delta_1. \tag{3}
\]

Here \( T \) is the peak tractions in normal and tangential direction, and \( T=Z_\nu \). \( \delta_1 \) and \( \delta_\parallel \) denote the ultimate displacements in normal and tangential direction, respectively.

In this cohesive material model, the total mixed-mode relative displacement \( \delta_m \) is defined as:

\[
\delta_m = \sqrt{\delta_1^2 + \delta_\parallel^2} \tag{4}
\]

\( \delta_m \), \( \delta_1 \) and \( \delta_\parallel \) are defined as the corresponding interlaminar normal and two shear displacements, respectively.

The mixed-mode damage initiation displacement \( \delta^0 \) is given by:

\[
\delta^0 = \delta_1^0 \delta_\parallel^0 \sqrt{\frac{1 + \beta^2}{(\delta_1^0)^2 + (\beta \delta_\parallel^0)^2}} \tag{5}
\]

where \( \delta_1^0=T/E_\nu \) and \( \delta_\parallel^0=S/E_t \) are the single mode damage initiation separations, and \( \beta=\delta_1^0/\delta_\parallel^0 \) is the mode-mixity. \( E_\nu \) and \( E_t \) denote the longitudinal and transversal stiffness, respectively. The ultimate mixed-mode displacement \( \delta^m \) for the Benzeggagh-Kenane law [30] is:


\[
\delta^F = \frac{2}{\delta} \left(1 + \frac{\beta^2}{T + \beta^2} \right) \left[ \delta_{\text{IC}} + \delta_{\text{NC}} \left( \frac{S \beta^2}{T + \beta^2} \right)^\eta \right]
\]

(6)

where \( \eta \) is defined by the mixed-mode bending (MMB) test, and the value used here is \( \eta = 1.45 \) [31,32].

### 3 Numerical Model

The ASTM D7136 test standard is adopted in this paper. The test specimen of 150x100x4.368 mm³, contains 24 layers. The configuration of carbon fiber reinforced plastics (CFRP) laminates is ±45/0/45/0/90/-45/0/90. Between the adjacent plies exists a resin area which is regard as a interface. The delamination between adjacent plies with different fiber directions is taken into account, and the plies with same fiber direction are regarded as a sub-plate. So there are 15 sub-plates and 14 interfaces in the model as shown in Fig. 3. The ply material parameters are shown in Tab. 1. According to the ASTM D7136 test standard, the specimen is fixed between a steel support and a steel plate, which have rectangular cuts of 125x75 mm². The impactor is simplified as a sphere with a diameter of 16 mm. In this paper the shell element is used to discretize plies with CDM constitutive relation. A 'tiebreak' contact, which contains the traction- separation rule by CZM, is used to simulate the delamination and ordinary surface to surface contact after delamination. Through constraining the surfaces of steel support and plate, the boundary conditions are simulated, as shown in Fig. 4.

The impact responses and damage of laminated composites resulted from impact energy of 29.7 J, 19.6 J and 9.1 J are simulated by FEM and compared with the experimental results [16]. The impactor is modelled as a rigid body with the mass 2.44 kg (29.7 J, 19.6 J) or 1.33 kg (9.1 J) [33]. Each run of these examples takes about 48 hours to complete using a cluster of 8 CPUs.

### 4 Results and Discussion

#### 4.1 Contact Force and Displacement

The oscillatory behavior due to the dynamic coupling between specimen and supports is not considered in the simulation. Comparing the simulated results with experimental results after smooth fitting, the values of contact force and displacement are well predicted, as shown in Fig. 5. The simulated response times are delayed, compared with the experimental ones, however this has little influence on the damage evolution. The two important parameters, namely the extreme value of contact force corresponding to the first drop and the maximum value of contact force, are accordant with the experiment. The contact force between impactor and laminated composites rises rapidly with the increase of displacement. When the impact energy is 29.7 J and time is 0.97 ms, the contact force reaches to 5574 N, being in agreement with the experimental extreme value 5510 N at 0.7 ms. After obvious reduction, the contact force begins to increase to the maximum value 5858 N. Compared with the peak value 5800 N from experiment, the error is just about 1%. Then the impactor achieves the maximum displacement 6.54 mm in the finite element simulation, basically fitting with the experimental value 6.2 mm. Meanwhile the velocity of impactor whose kinetic energy has been transformed to the elastic strain energy and internal dissipated energy of laminates reaches to zero. Hereafter due to the elastic deformation recovery, the specimen starts backstepping the impactor and transforms its elastic strain energy into the kinetic energy of the impactor.

#### 4.2 Impact Energy

As shown in Fig. 6, with the impact energy increasing, both the energy dissipated by the specimen (total dissipated energy) and the maximum displacement of the impactor increase nearly linearly.

#### 4.3 Impact Damage

During the impact process, various kinds of damages occur in the laminated composites. This paper takes the 29.7 J impact energy for example to carry out the study.

##### 4.3.1 Delamination

The damage morphology is acquired through the simulation and compared with the experimental result. The delaminations of five representative interfaces are shown in Fig. 7. It can be seen that the simulated result and the C-scan image of a delamination contain mostly the fiber orientation information of the two neighboring plies, but the lower ply often shows more prominently than the upper one. Generally, the simulated results are slightly less than the experimental results.

The simulated results are used to calculate the delamination area from the 6th interface to the 10th
interface, then they are fitted by linear curve and quadratic curve, as show in Fig. 8. The further an interfacial position from the impact site is, the greater a damage area is. Here, the linear fitting equation is \( y = 57.561x + 312.91 \) with a correlation coefficient \( R^2 = 0.9660 \), and the quadratic fitting equation is \( y = -7.5746x^2 + 103.01x + 259.89 \) with a correlation coefficient \( R^2 = 0.9894 \). Thus the growth trend of delamination area is more consistent with the quadratic relationship than the linear one.

### 4.3.2 Matrix Cracking

The simulated results of the matrix cracking in six plies (from No. 5 to No. 10) are depicted in Fig. 9. The dark shadows in the middle of specimens are representative for matrix damage. The results show that the matrix damage direction is mainly parallel to the fiber orientation of the ply which the matrix belongs to, and also is affected by the fiber orientation of adjacent plies.

The above damage characteristics can be interpreted as follows. The damage begins with the development of matrix cracking in the impact zone below the impactor. The cracks in tangential direction (in (1, 2) plane, where 1 denotes the longitudinal or fiber direction and 2 is the transverse one) grow up during the loading following the fiber direction. Finally, in each ply, a strip of fibers and resin disjoints and slides in the normal direction of this ply. This disjointed strip creates an interlaminar zone of tension stress between two adjacent plies and is susceptible to induce delamination in this zone, as shown in Fig. 10. In this paper a schematic of this process is proposed with a [-45/0/45] stacking sequence, where -45° is the upper ply and 45° is the lower ply. This stacking sequence represents only a part of a real stacking. Take the section A-A and section B-B for example to illustrate the disjointed strips of the first two plies and the interlaminar zone of tension stress. This interlaminar zone, limited by the disjointed strips of the two adjacent plies, has a triangular shape with a size which grows from the impacted side to the non-impacted side. The consensus of this explanation has been broadly achieved [3-6].

The total damages including delamination and matrix cracking predicted by the finite element simulation are compared with the experimental results. As shown in Fig. 11, the position and morphology of total damages under different impact energies are well predicted. At higher energy level, the damage area is obviously larger. It can be seen that the simulated damage areas are smaller than the experimental ones. On the one hand, this is because that the actual damages of laminated composites under low-velocity impact are more complicated than those considered in the simulation. Based on a homogenized numerical model, the simulation adopts the macroscopic mechanics without considering the damage of mesoscopic structures, such as the fracture of single fiber and the interface de-bonding between fiber and resin. Thus the failure criteria of concerned damages which contain fiber fracture, matrix cracking and delamination cannot fully reflect all the damages, which lead to the lessening of the simulated results. On the other hand, the errors of the input parameters may result in the errors of the simulated results. However the differences are not so considerable. Therefore by means of the numerical method presented in this paper, the concerned damages are well characterized and the results are credible.

### Summary

A continuum damage mechanics (CDM) and a cohesive zone model (CZM) are used for the numerical model to characterize the low-velocity impact damage of laminated composites. At high energy levels, especially at 29.7J, the simulated results of impact dynamics and impact footprint are remarkably consistent with the experimental results. For the low-velocity impact on Hexply AS4/8552 laminated composites, both the total dissipated energy and the maximum displacement of impactor increase with the increase of impact energy. The directions of delamination and matrix cracking are both related to the fiber orientation of the two neighboring plies, and the damage area increases along with the increase of the distance between the impact site and damage position. Although due to the restriction of current simulated technology the results is slightly small, the type, location and extent of important damage forms can be well predicted by this numerical method. The present work will be beneficial to further research on the damage extension in laminated composites with different designs under low-velocity impact.

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Table 1 Hexply AS4/8552 ply material parameters [16]

<table>
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<tr>
<th>$E_1$</th>
<th>$E_2$</th>
<th>$G_{12}$</th>
<th>$\nu_{12}$</th>
<th>$X_t$</th>
<th>$X_c$</th>
<th>$Z_t$</th>
<th>$Z_c$</th>
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<td>114.5</td>
<td>0.28</td>
<td>0.79</td>
<td>1590</td>
</tr>
</tbody>
</table>

Note: $X_t$ is the longitudinal tensile strength; $X_c$ is the longitudinal compressive strength; $Z_t$ is the transversal tensile strength; $Z_c$ is the transversal compressive strength; $\rho$ is the density.

Fig. 1. Technology roadmap

Fig. 2. Mixed-mode traction-separation law

Fig. 3. Distribution and numbering of laminae and interfaces

Fig. 4. Finite element model

Fig. 5. Contact force-time relations and contact force-displacement relations for three impacts
Fig. 6. Curves of two key parameters versus impact energy

Fig. 8. Distribution of delamination area

Fig. 7. Major delaminations

Fig. 9. Simulated contour map of matrix cracking

a. Main view of damage
Fig. 10. Schematic diagram of formation mechanism of delamination [6]

Fig. 11. Impact footprints of numerical result and C-scan experimental result

29.7 J 19.6 J 9.1 J

References


