[Technical Paper]

Impact Response and Energy Distribution of Low Velocity Impact on Composite Laminates

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Abstract: The dynamic characteristics of composite laminates are very complex because many concurrent phenomena occur with laminate failure under impact load. In order to research impact response and energy distribution of composite laminates in different low-impacted energies, Hashin failure criteria was taken based on the finite element software of ABAQUS, combined progressive damage stiffness reduction scheme with viscous regularization. The impact response was analyzed from the points of impact energy, contact pressure, internal energy and damage dissipation energy. The result showed that the peak of contact pressure moved forward and the different value of internal energy and damage dissipation energy became bigger with the increase of impact energy. Furthermore, impact energy would be transformed into many types of energies and the distribution of impact energy was discussed.

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1. Introduction

Composites have been widely used in the manufacturing of aerospace, vehicle, sports equipment, pressure vessel, etc. because of theirs good properties. In many conditions, composite structures may be influenced by impact, especially transverse impact. Under the effect of impacting loads, complex damages such as matrix cracking, delamination, fiber breakage and debonding could occur, and the composite structures would have a high complex impact behavior, which are sensitive to non-visual damages, so the residual load bearing capability will be strongly influenced.

The performance of composite materials has been widely concerned in advanced engineering, and many researchers have tried to analyze the impact dynamics of the structures. In the process of low speed impact, the mechanism of composite materials is studied. Davies and Zhang X [1] found that the curves of contact pressure and time were fitted close with sinusoid under the low-velocity impact energy; Schoeppne et al. [2] summarized the connection between the threshold of delamination and other parameters; Ferabol et al. [3-5] had approved that the peak of contact pressure was closely relevant to the impact energy under the low energy impact and elasticity process. With the increase of energy, the damage dissipation energy appeared and increased and the contact pressure would not increase; Jung-Seok Kim et al. [3] conducted low velocity impact on laminates at three impact energy levels, by which the impact force, damaged area and absorbed energy were researched.

Recently, numerical simulation of the experiments is carried out through finite element (FE) tools. Kumar et al. [7] employed 3D finite element formulation to investigate the influence of impactor and laminate parameters on the impact response and damages in the graphite/epoxy laminated cylindrical shells. Lopez C S et al. [8] used the ABAQUS finite element software to simulate the impact process, and contrast the impact connected pressure curves of test results and numerical results, and discussed the damage dissipation energy. Kim et al. [9] designed a 3D FE program to describe impact behaviors and

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predict damages of the shell-shaped structures. Tarfaoui et al. [10] tested and predicted the elastic behavior of static and dynamic loadings on thick filament wound glass/epoxy tubes and then, an impact model was designed for damage prediction. Volnei Tita et al. [11] simulated the failure mechanisms by using Hill’s and material models, and the influence of stacking sequence and impact energy level on composite plates was verified. A.R. Setoodeh et al. [12] designed a FE code for the analysis of thick composite laminates, which gave the evidence for the faster spreading of flexural waves in the direction with the greatest stiffness. Wang Y F et al. [13] tested three composite laminates with different layups under low-velocity impact via dropping weight method. The results showed that damage evolution rested theoretically with the absorbed energy but was more closely relevant to the total impact energy and the maximum contact force was only a threshold and if the peak contact force reached the threshold, a plateau emerged.

In recent years, considerable amount of work on the impact response of low velocity impact on composite laminates has been carried out by many researchers. However, the research on the energy distribution of low velocity impact is lacking. In this paper, a new point of sight in impact response of low velocity impact on composite laminates has been discussed. Furthermore, the energy distribution during the impact process has been researched in depth, and the software of ABAQUUS is used as a tool to verify the final conclusion.

2. Impact damage models

2.1 Impact dynamics and contact law

It is known that contact law is defined as a relation between contact force and indentation. The maximum contact force and displacement are obtained by energy conservation equation. And the fundamental assumption is that all of the impact energy converts into the internal energy of the panel at the maximum contact force or maximum displacement. Energy dissipation and the damp of material and the vibration of panel are ignored. So

\[ \frac{1}{2} M V^2 = \int_0^{\delta_m} F_d \, d\delta + \int_0^{\alpha_m} F_c \, d\alpha \]  

(1)

where \( M \), \( V \) are the mass and velocity of the impactor; \( \delta \) is the deflection at the impact point; \( \alpha \) is the dent depth; \( F \) is contact force. The first item on the right side of the equation is bending distortion energy and the other is contact energy.

\[ F_1(t) = k \delta(t) \]  

(2)

where is the stiffness at the impact point. Apparently, it is the parameter of panel sizes, boundary condition, laminate material and so on. They are considered when calculated by finite element method.

With the modified Hertz contact law, the contact force \( F \) can be evaluated as

\[ F_2(t) = k \alpha^{1/2}(t) \]  

(3)

where \( \alpha \) is the indentation, which can show the difference between impactor tip displacement (\( \delta' \)) and plate displacement (\( \delta' \)) at impact point (Fig. 1), and \( k \) is the modified Hertz contact stiffness. In order to find the elastic contact stiffness, Sun and Chen [14] proposed the following equation for laminated plate with orthotropic layers.

\[ k_c = \frac{4}{3} \frac{1}{\alpha^{1/2}} E_z \]  

(4)

or

\[ n = \frac{4}{3} \frac{1}{\alpha^{1/2}} \left( \frac{1 - v_1^2}{E_1} - \frac{1 - v_2^2}{E_2} \right) \]  

(5)

where \( E \) is the transverse Young’s modulus of the target composite lamina, \( r \) is the radius of the indentation, \( E \) and \( \nu \) are the Young’s modulus and poisson’s ratio of the impactor respectively, \( \nu \) is the poisson’s ratio of lamina; \( n \) is hertz contact rigidity. From Eq.(2) and Eq.(3), Eq.(1) can be written as follows:

\[ \frac{1}{2} M V^2 = \frac{1}{2} F_{\text{max}}^2 + \frac{2}{5} \frac{F_{\text{max}}^{5/3}}{n^{3/3}} \]  

(6)

Fig. 1 Composite laminate before and after impact

2.2 Failure criteria

Hashin’s damage criteria [15–17] can be applied into analysis of the composites damage preferably.
Based on Hashin’s theory, the damage initiation criteria for fiber reinforced composites is proposed. The Hashin’s initiation criteria are used to predict the onset of damage. The expression can be written as follows:

Fiber cracking failure \( (\sigma_0 \geq 0) \)

\[
e_f = \left( \frac{\sigma_{11}}{X_t} \right)^2 + \left( \frac{\sigma_{12}}{S_{12}} \right)^2 + \left( \frac{\sigma_{13}}{S_{13}} \right)^2 \tag{7}
\]

Fiber buckling failure \( (\sigma_0 < 0) \)

\[
e_f = \left( \frac{\sigma_{11}}{X_t} \right)^2 \tag{8}
\]

Matrix Compression failure \( (\sigma_{23} + \sigma_{33} < 0) \)

\[
e_m = \frac{1}{Y_e} \left[ \left( \frac{Y_e}{2S_{12}} \right)^2 - 1 \right] \left( \sigma_{23} + \sigma_{33} \right) + \left( \frac{\sigma_{23} + \sigma_{33}}{2S_{12}} \right)^2 \\
+ \frac{1}{S_{13}^2} \left( \sigma_{13}^2 - \sigma_{23}^2 \sigma_{33} \right) + \left( \sigma_{13} \right)^2 \tag{9}
\]

Matrix Tension failure \( (\sigma_0 + \sigma_{11} \geq 0) \)

\[
e_m = \left( \frac{\sigma_{23} + \sigma_{33}}{Y_e} \right)^2 + \left( \frac{\sigma_{13}}{S_{13}} \right)^2 \tag{10}
\]

Tension delamination failure \( (\sigma_0 \geq 0) \)

\[
e_d = \left( \frac{\sigma_{33}}{Z_t} \right)^2 + \left( \frac{\sigma_{23}}{S_{23}} \right)^2 \tag{11}
\]

Shear delamination failure \( (\sigma_0 < 0) \)

\[
e_d = \left( \frac{r_{13}}{S_{13}} \right)^2 + \left( \frac{r_{23}}{S_{23}} \right)^2 \tag{12}
\]

where 1 is the direction of fiber, 2 is the direction of transverse fiber, 3 is the direction of thickness; \( X_t \) is tensile strength on the direction 1; \( Y_e \) is compression strength on the direction 1; \( X_t \) is tensile strength on the direction 2; \( Y_e \) is compression strength on the direction 2; \( S_{ij} \) (\( i, j = 1, 2, 3 \)) is shear strength; \( \sigma_{ij}, \epsilon_{ij} \) are normal stress and shear stress; \( e_s, e_{sw}, e_{cw} \) are damage factors. When \( e_s \geq 1, (i = f, m, d) \) the materials are failed. Eq.(7)-Eq.(12) are used for the criterion to judge whether the material is damaged during the impact process in the FEA model, and it is not used to calculate the impact response.

2.3 Damage evolution

Post damage-initiation material behavior is defined by damage evolution. Presently, there are three methods of stiffness reduction and they are stress updating, degradation of elastic constant and progressive damage. In the impact process of composites, the stresses of panel in the damage area change severely and the method of progressive damage evolution can characterize the material damage preferably [18], so the progressive damage evolution method is used in this paper.

In the impact process, when met the Hashin’s damage criteria, the material begins to damage and the stiffness matrix begin to be degradation. The parameter of fiber damage \( d_f \) and the parameter of matrix damage \( d_m \) can be written as follows [19]:

\[
d_f = 1 - \frac{\epsilon_{fs}(f_i) - \epsilon_{fs}(f_j)}{f_f}, \tag{13}
\]

\[
d_m = 1 - \frac{\epsilon_{ms}(m_i) - \epsilon_{ms}(m_j)}{f_m},
\]

where \( f_f = \sqrt{e_s}, f_m = \sqrt{e_s} \); \( \epsilon_f \) is the strain on the direction \( i \); \( L \) is characteristic length at the material integral point; \( G \) is the shear modulus; the subscript \( f, m, d \) represent the same with 1, 2, 3; the superscript \( t, c \) represent the stress state of a material is under tension or pressure. The stiffness matrix will be degradation with the parameter of fiber damage \( d_f \) and the parameter of matrix damage \( d_m \) in the impact process. The two parameters are used to characterize the damage degree of fibers and matrices, and their value ranges are 0-1, where 1 represents complete damage. The form of material response after damage initiation is: \( \sigma = C(d) : \epsilon \), where \( C(d) \) is the damaged elasticity matrix.

\[
C_i = \begin{bmatrix}
(\epsilon_{fs})(c_{ij}) & (\epsilon_{fs})(c_{ij}) & 0 & 0 & 0 \\
(\epsilon_{ms})(c_{ij}) & (\epsilon_{ms})(c_{ij}) & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
(\epsilon_{ms})(c_{ij}) & (\epsilon_{ms})(c_{ij}) & 0 & 0 & 0
\end{bmatrix}_{\text{symmetric}}
\tag{14}
\]

After differentiating the above equation, Jacobian matrix can be obtained as

\[
\frac{\partial \sigma}{\partial \epsilon} = \frac{\partial C_d}{\partial C_d} : \epsilon = C_d + \left( \frac{\partial C_d}{\partial d_f} : \epsilon \right) \tag{15}
\]

As Eq.(15) is not symmetric, unsymmetrical equation solution is recommended when convergence rate is slow.

2.4 Viscous regularization

For convergence, a damage variable viscous regularization based technique is proposed. Thus, the damage variables can be “regularized” by [20]
\[ d^x = \frac{1}{\eta}(d_m - d^x), \quad d^y = \frac{1}{\eta}(d_f - d^y) \]  \hspace{1cm} (16)

where \( d_m \) and \( d_f \) are the matrix and fiber damage variables, \( d^x \) and \( d^y \) are the “regularized” data for the real calculations, and \( \eta \) is a viscosity parameter at which \( d^x \), \( d^y \) approach to \( d_m \), \( d_f \). As the stiffness degradation scheme is included in the model, it is difficult for calculation convergence due to the large reduction of stiffness, and it is often shown that the excessive distortion of the unit under large deformation leads to the suspension of the explicit analysis process. Thus, in order to improve the convergence, the technology based on the law of viscosity is introduced [20], and the choice of viscosity component depends on the requirement of the precision of the result. When the viscosity component is large, the stiffness reduction process of the material will be significantly delayed. The regularized damage parameter in Eq.(16) is adopted for easier convergence in the calculation process [20], and the relationship between the viscosity component and impact response can be used as a follow-up study to analyze the response by changing the viscosity component.

For the “regularized” updating values at time \( t_0+\Delta t \), the above equations can be discretized as

\[ d_{v(0+\Delta t)} = \frac{\Delta t}{\eta + \Delta t} d_{v(0+\Delta t)} + \frac{\eta}{\eta + \Delta t} d_{v(0)} \]  \hspace{1cm} (17)

Therefore, the Jacobian matrix can be further formulated as follows:

\[ \frac{\partial \Delta \sigma}{\partial \Delta \epsilon} = C_d + \left[ \begin{array}{c} \frac{\partial d_m}{\partial d^x} \epsilon \\ \frac{\partial d_f}{\partial d^x} \epsilon \\ \frac{\partial d_m}{\partial d^y} \epsilon \\ \frac{\partial d_f}{\partial d^y} \epsilon \end{array} \right] \left[ \begin{array}{c} \frac{\partial d_m}{\partial d^x} \epsilon \\ \frac{\partial d_f}{\partial d^x} \epsilon \\ \frac{\partial d_m}{\partial d^y} \epsilon \\ \frac{\partial d_f}{\partial d^y} \epsilon \end{array} \right] \frac{\Delta t}{\eta + \Delta t} \]  \hspace{1cm} (18)

3. Impact experimentation and Finite element models

3.1 Vertical drop-weight low-velocity impact experimentation

Composite laminate low-velocity impact tests are usually conducted by vertical drop-weight type impact test systems, which has a track guiding the impactor into the target drop position. In this paper, tests were carried out to study the impact response at four different impact energy levels, and the test sample is selected with medium temperature curing epoxy carbon fiber CCF 300, epoxy resin base BA 9916-II, volume fraction 64%. The diameter of the impactor is 16 mm and the mass of the impactor is 5.275 kg. The impact test equipment is shown in Fig. 2. The impact point is at the center of the test specimen. After impact test, the dent depth of impact point is measured. In order to investigate the damage zones of laminates, the nondestructive ultrasonic C-scanning method is adopted, and the C-scan images can be obtained with a pulse-reflection technique.

3.2 Finite element model

In this section, ABAQUS/Explicit is employed for impact simulation. The laminates model was created using continuum shell elements (SC8R) with eight integration points in order to simulate the plane stress at the laminate. According to the sample information, the stacking sequence adopted is [(45/−45/0/90)/0]/45−45]. The laminates contain 22 plies and the thickness of every ply is 0.125 mm. The specimens of 100 mm×100 mm are used for the tests. And the impactor, which was set to rigid body, was created using solid elements. And the FE model of the test specimen is shown in Fig. 3.
Table 1  The material properties of T 300/QY 8911

<table>
<thead>
<tr>
<th>$E_1$/MPa</th>
<th>$E_2$/MPa</th>
<th>$E_3$/MPa</th>
<th>$v_{12}$</th>
<th>$v_{13}$</th>
<th>$v_{23}$</th>
<th>$G_{12}$/MPa</th>
<th>$G_{13}$/MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>135000</td>
<td>8800</td>
<td>8800</td>
<td>0.328</td>
<td>0.328</td>
<td>0.45</td>
<td>4470</td>
<td>4470</td>
</tr>
<tr>
<td>$G_{13}$/MPa</td>
<td>$X'_1$/MPa</td>
<td>$Y'_1$/MPa</td>
<td>$X'_3$/MPa</td>
<td>$Y'_3$/MPa</td>
<td>$S_{11}$/MPa</td>
<td>$S_{12}$/MPa</td>
<td>$S_{13}$/MPa</td>
</tr>
<tr>
<td>3260</td>
<td>1548</td>
<td>55.5</td>
<td>1226</td>
<td>218</td>
<td>89.9</td>
<td>110.5</td>
<td>110.5</td>
</tr>
</tbody>
</table>

according to the sample information.

where $E$, $v$ and $G$ have been explained in Sec.2.1, and all the subscripts of the symbols are the directions. The focus of this paper is to study the impact response and energy distribution of laminar composite materials, and the influence of anisotropy effect (laminar effect) on each layer can be further studied.

4. Results and discussion

4.1 Contrast between FEA and tests of damage area

The damage evolution is simulated in impact process by the finite element model established in this paper. And the area of damage is computed. Fig. 4 show the damage area by the two methods. Because the impact energy of 10 J is small to produce damage, the simulation and C-scan images are not shown in this energy level.

Fig. 4 Images of damage area by FEA and C-scan under different impact energies

Fig. 4 shows that the shape of damage area obtained by FEA is similar by C-scan. The length and width of damage area obtained by FEA are close to them obtained by C-scan. Table 2 shows the results of damage area obtained by FEA and tests.

Table 2  Contrast between FEA and tests

<table>
<thead>
<tr>
<th>Impact energy</th>
<th>FEA result</th>
<th>Test result</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>10J</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>15J</td>
<td>203 mm$^2$</td>
<td>235 mm$^2$</td>
<td>13.6%</td>
</tr>
<tr>
<td>20J</td>
<td>1136 mm$^2$</td>
<td>984 mm$^2$</td>
<td>13.3%</td>
</tr>
<tr>
<td>25J</td>
<td>1568 mm$^2$</td>
<td>1376 mm$^2$</td>
<td>12.2%</td>
</tr>
</tbody>
</table>

The test result in Table 2 is the average value of the three effective experimental data, while the C-scan image in Fig. 4 is the result of one of the experimental data, and the standard error values are 24,860, 28,249, 32,342. From the Table 2, the conclusion is shown that the results obtained by FEA are close to the results obtained by tests. And the errors between FEA and tests are smaller. These results prove that the established model is reasonable and effective.

4.2 Dynamic response in the impact process

The curves of contact pressure, absorbed internal energy of composite laminates and damage dissipation energy are obtained through finite element method under different impact energy levels. They are shown in Fig. 5.

Fig. 5 Contact pressure histories under different impact energies

In the primeval impact process, contact pressure increases linearly with time. Because of progressive damage evolution, stiffness matrix begins to be
degradation and contact pressure begins to vibrate slightly. When met the damage initiation criteria, damage begin to appear in the laminate. Then stiffness matrix is attenuated further and contact pressure begins to vibrate severely. When damage is appeared with increased energy, damage will dissipate energy. The contact pressure is no longer increasing and a platform is emergence. When impact velocity comes to 0, the absorbed internal energy of composite laminate reaches the maximum. Because of laminate’s vibrating, the vibrating of contact pressure will exist in the recession process.

Meanwhile, impact energy will change into laminate’s internal energy with the time passage of contact between impactor and laminate. When the velocity of impactor is 0, the impact energy becomes 0 and the most of impact energy change into internal energy of laminate (a small quantity of energy change into other energy because of friction). Subsequently, the most of internal energy will disappear with the elastic deformation and vibrating of laminate. Because of the actions of impact loads, the damage dissipation energy appears on the composite laminate. This part of energy becomes a part of internal energy permanently with the emergence of damage.

At the different impact energy levels, the curves of contact pressure, internal energy and damage dissipation energy are different. These Figs (Fig. 4-Fig. 6) show that with the increase of impact energy, the internal energy absorption is greater when impact velocity is 0. For different impact energy, the emergence time of the peak of contact pressure is different. The emergence time of the peak of contact pressure is consistent with the emergence of the peak of internal energy for impact energy of 10 J. But for the impact energy of 15 J, 20 J, 25 J, the emergence time of the peak of contact pressure is prior to the emergence of the peak of internal energy. The greater of impact energy, the sooner of the emergence time of the peak of contact pressure. For the phenomenon, this paper argues that the degree of damage is different under different impact energy. For impact energy of 10 J, there is rarely damage on the laminate and the structure deformation is elastic. Seen by the Hooke’s law, when the impact velocity is 0, the deformation of the laminate is the maximum and the contact pressure is the maximum; because of damage emergence, the stiffness matrix degradation appears. Therefore, contact pressure is not proportional relationship to deformation of laminate. For the impact energy of 25 J, the area of damage is large and the stiffness matrix descends severely, so the emergence of the peak of contact pressure is the earliest in these impact energies. This paper also argues that the internal energy absorption is incomplete to damage dissipation energy after the impact process. Part of the absorbed energy is used for plasticity deformation energy which is existed permanently. This is reflected in that the absorption of laminate’s internal energy is not completely coincided with damage dissipation energy. Furthermore, the different value between internal energy and damage dissipation energy is larger when the impact energy is greater. The different value is shown in Table 3.

4.3 Distribution of impact energy

In the impact process, a little of impact energy will be dissipated because of friction. However, because of elastic deformation of composite laminate, a lot of impact energy will transformed into elastic deformation energy which will be dissipated with the laminate’s oscillation. The other of the energy will be absorbed by composite laminate and they are the internal energy of the laminate. The distribution of impact energy is shown in Fig. 8 (impact energy is
Table 3  Different value between internal energy and damage dissipation energy

<table>
<thead>
<tr>
<th>Impact energy</th>
<th>Internal energy</th>
<th>Damage dissipation energy</th>
<th>Different value</th>
</tr>
</thead>
<tbody>
<tr>
<td>10J</td>
<td>462.36mJ</td>
<td>143.26mJ</td>
<td>319.10mJ</td>
</tr>
<tr>
<td>15J</td>
<td>959.07mJ</td>
<td>538.26mJ</td>
<td>420.81mJ</td>
</tr>
<tr>
<td>20J</td>
<td>1631.27mJ</td>
<td>1110.44mJ</td>
<td>520.83mJ</td>
</tr>
<tr>
<td>25J</td>
<td>2279.19mJ</td>
<td>1637.43mJ</td>
<td>641.76mJ</td>
</tr>
</tbody>
</table>

Fig. 8  Results of FEA: elastic deformation energy and damage dissipation energy

Not all of the internal energy will be transformed into damage dissipation energy. The different value between internal energy and damage dissipation energy contain plasticity deformation energy and vibrated energy. The vibrated energy transformed into thermal energy in the vibrating process. The damage dissipation energy contains two types of energy. The one is the energy which is transformed by the friable damage. The other is the energy which is transformed by the plasticity damage which is emerged after plasticity deformation. The plasticity deformation is comprised by pit deformation, flexure deformation and compaction deformation (see Fig. 9).

Fig. 9  Plasticity deformation

The distribution of impact energy can be described as Fig. 10, which is obtained according to Fig. 8 and the results and analysis of the previous data.

Fig. 10  Distribution of impact energy
distribution. The FEA results of damage area are fitted to tests results. The error between FEA and tests is about 13%. Therefore, the model is effective.

The impact responses of low velocity impact on composite laminates are investigated. Contact pressure increases linearly with time in the primeval impact process. When the damage of composite laminates appears, the damage will dissipate energy and contact pressure will not increase and a platform appears. Meanwhile, the stiffness matrix will be degradation and contact pressure will vibrate at the same time. With the increase of impact energy, the emergence time of the peak of contact pressure will move ahead. The different value between internal energy and damage dissipation energy will be larger. Moreover, the impact energy will be transformed into elastic deformation energy, internal energy and dissipated energy. Furthermore, the internal energy is composed by plasticity deformation energy, damage dissipation energy and vibrated energy.

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5. Conclusion

In this paper, it was analyzed on the composite laminate to assess their impact response. A reasonable ABAQUS based model was established to analyze impact response and impact energy

References