1 Introduction

Composite materials are now being used in primary aircraft structures, particularly in helicopters, light aircrafts, commercial planes and sailplanes, because of their numerous advantages including low weight, high modulus and strengths and the possibility of manufacturing large integral shell structures. However, a well-known problem with composite laminates is their poor resistance to accidental impact by foreign objects. The resulting damage due to impacts, often in the form of delamination, matrix cracking and fiber failures, may severely reduce the structural strength and stability[1]. Therefore, considerable amount of research has been done in the area of impact of composite structures.

The relationship between the indentation and impact energy has been studied by many investigators[2]. It is proved to be an effective method to evaluate the internal damage by observing the indentation. Laminated composite panels with BVID (Barely Visible Impact Damage) are required to endure the full DUL (Design Ultimate Load) in the strength criteria usually adopted in composite wing structure design in civil aviation. BVID primarily considers the depth of the permanent indentation. More exactly the depth of indentation after impact is measured, more accurate evaluation of composite can be made, which provides a reference to the design of composite structure.

With the development of computer, many calculative methods were raised to study the formation of the indentation, which made it possible to gain an insight into the damage theory of composites. In the simulation of the impact, Hertzian contact law has been widely used to calculate the contact force between the impactor and the laminates. In 1977, C.T. Sun proposed a modified Hertzian contact law [3]. In 1981, Yang and Sun experimentally investigated indentation phenomena through static indentation tests on composite laminated specimens and they presented the experimental static indentation law[4]. In order to follow the approach, researchers needed to develop their own finite element method (FEM) program. Many new damage theories and analytical methods were established to simulate the damage evolution process during the impact.

At present, the dynamic process of the indentation growth has been studied a lot by the simulation but rarely by experiment, because it was impossible to observe the details between the impactor and the laminates during impact test. Most contact laws are based on Hertzian/modified Hertzian contact law, which was generalized from the static indentation test. It is necessary to measure the dynamic changes of the indentation during the impact test to understand the damage evolution process better.

In the present study, firstly, a simplified method was introduced to measure the thickness changes of the laminates at the impact point during the experiment. Secondly, a modified Hertzian contact law was raised based on the dynamic indentation. Thirdly, a calculative method was developed to predict the permanent indentation.

2 Experiment

The dynamic indentation is defined as the changes of the thickness where the specimen is impacted. In order to acquire the dynamic indentation, the displacements of the impact side and backside of the specimen should be measured. In the experiment, the Polytec PSV-400 Vibrometer was used. The PSV-400 can record the velocity history of the detected point, then the displacements can be calculated from the integration of the velocities. The measuring system is shown in Fig. 1. The test equipment has a high degree of accuracy to ensure the repeatability among different specimens.
The specimens were T700/5428A laminates with the stacking sequence $[45/0/-45/90]_{4S}$. Several of them were used to detect the velocity of the impact side and the others were used to detect that of the backside. The velocity of impactor before contact was detected by the flag (shown in Fig. 1) using a high speed data acquisition system. A comparison of the impactor’s velocity between the experimental result and the integration of the contact force was made which showed the correctness of the method. The velocities of the impactor and backside of the specimen are shown in Fig. 2 and Fig. 3. From the Figures, the velocities of both sides have a high accordance except that the backside has some vibrations in the earlier stage of impact.

The histories of dynamic indentation with different impact energies were obtained by the displacements of both sides, which were calculated by integration of the velocities recorded by the PSV-400. The relationship of the dynamic indentation and contact force are shown in Fig. 4 and Fig. 5. As we can see, the dynamic indentation histories are similar to the contact force before large damage occurred.
3 Computation

In the computation, a modified Hertzian contact law has been used to analyze the relationship of the contact force and dynamic indentation:

\[ f = k \alpha^n \]  \hspace{1cm} (1)

Where \( f \) is contact force, \( \alpha \) is indentation shown in Fig.6, \( k \) is the contact coefficient, obtained from experiments, but can also be approximately calculated as

\[ k = \frac{4}{3} \sqrt{R_i} \frac{1}{(1 - \nu_i^2) / E_i + 1 / E_i} \]  \hspace{1cm} (2)

Where \( R_i \) is the radius of the impactor, \( \nu_i \) and \( E_i \) are respectively the Poisson's ratio and the Young's modulus of the impactor, and \( E_t \) is the transverse out-of-plane Young's modulus of the laminated composite.

Fig. 6 Quasi-static indentation with the bottom clamped

Modified unloading \[ f = f_m \left( \frac{\alpha - \alpha_0}{\alpha_m - \alpha_0} \right)^n \]  \hspace{1cm} (3)

Where \( n \) equals 2.5 during the unloading period and equals 1.5 during the loading period, \( f_m \) and \( \alpha_m \) are respectively the max contact force and the max indentation during one loading-unloading cycle, \( \alpha_0 \) is the depth of the permanent indentation caused by the max contact force \( f_m \). \( \alpha_0 \) is given by

\[ \alpha_0 = \begin{cases} 0 & \alpha_m \leq \alpha_{cr} \\ \alpha_m \left( 1 - \left( \frac{\alpha_{cr}}{\alpha_m} \right)^{2/5} \right) & \alpha_m > \alpha_{cr} \end{cases} \]  \hspace{1cm} (4)

Where \( \alpha_m \) is the maximum indentation, and \( \alpha_{cr} \) is the critical indentation and it can be estimated by the following equation [7].

\[ \alpha_{cr} = \frac{Z_i h}{E_i} \]  \hspace{1cm} (5)

In order to acquire the relationship between the contact force and dynamic indentation, a new contact law was introduced from eq. (1), in which \( n \) equals 1.4, \( k \) is \( 0.9 \times 10^9 \text{N/m}^{1.5} \) calculated by eq. (2). The test and fitting curves are shown in Fig.7 and Fig.8.

Fig.7 Fitting curve with the impact energy of 17J

Fig.8 Fitting curve with the impact energy of 26J

The fitting curves are similar with the test results in the vibration mode and maximum force. Therefore it could be used in the dynamic analysis of laminates subjected to low-velocity impact.

A simple computational method was summarized to estimate the permanent indentation through the maximum contact force which could be obtained from a finite element analysis, in which the modified Hertzian contact law was incorporated in the FEM program CIMPACT written in FORTRAN. The permanent indentation can be obtained from eq. (4), in which the maximum indentation and critical
indentation can be calculated by eq. (1) and eq. (5), respectively. The examples are shown as follows.

4 Calculation examples

Carbon/epoxy composite T700/5428 is used in this study. The laminates is a 150mm × 100mm × 4mm plate, with stacking sequence [45/90/-45/0]_R4S_R4S. Two common energy levels, 4.45J/mm and 6.67J/mm, are applied in the calculation and impact tests. The detailed properties of the material are shown in the table 1.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Symbol</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-plane longitudinal modulus</td>
<td>E₁ (GPa)</td>
<td></td>
<td>125</td>
</tr>
<tr>
<td>In-plane transverse modulus</td>
<td>E₂ (GPa)</td>
<td></td>
<td>7.8</td>
</tr>
<tr>
<td>Out-of-plane transverse modulus</td>
<td>E₃ (GPa)</td>
<td></td>
<td>7.8</td>
</tr>
<tr>
<td>In-plane shear modulus</td>
<td>G₁₂ (GPa)</td>
<td></td>
<td>5.6</td>
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<tr>
<td>In-plane Poisson’s ratio</td>
<td>V₁₂</td>
<td></td>
<td>0.28</td>
</tr>
<tr>
<td>Density</td>
<td>ρ</td>
<td>kg/m³</td>
<td>1540</td>
</tr>
<tr>
<td>Longitudinal tension</td>
<td>Xₜ(MPa)</td>
<td></td>
<td>2150</td>
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<tr>
<td>Longitudinal compression</td>
<td>Xₑ(MPa)</td>
<td></td>
<td>1200</td>
</tr>
<tr>
<td>Transverse tension</td>
<td>Yₜ(MPa)</td>
<td></td>
<td>65</td>
</tr>
<tr>
<td>Transverse compression</td>
<td>Yₑ(MPa)</td>
<td></td>
<td>220</td>
</tr>
<tr>
<td>Ply longitudinal shear</td>
<td>S₁₂(MPa)</td>
<td></td>
<td>110</td>
</tr>
</tbody>
</table>

Table 1 Material Properties of T700/5428 carbon/epoxy

First, the finite element model is built, and the simulation is carried out by the program CIMPACT. The program uses the Hertzian contact law, adopting eq. (1) during loading period and eq. (3) during local unloading and reloading period. The contact force histories are shown in Fig.9 and Fig.10.

Second, calculate the depth of the permanent indentation as follows:

(1) Calculate the contact coefficient $k$

According to eq. (2) and the material properties in the table 1, the contact coefficient can be calculated, and its value is $0.9 \times 10^9$ N/m$^{1.5}$.

(2) By eq. (1), the max indentation $\alpha_m$ can be calculated from the max contact force $f_m$ produced from the finite element simulation. The values with the two impact energy levels can be seen in Table 2.

(3) Calculate the depth of the permanent indentation $\alpha_0$ using eq. (7) and $\alpha_m$.

Table 2 Calculation results

<table>
<thead>
<tr>
<th>Impact Energy</th>
<th>$f_m$ /N</th>
<th>$\alpha_m$ /mm</th>
<th>$\alpha_0$ /mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.45J/mm</td>
<td>7000</td>
<td>0.393</td>
<td>0.185</td>
</tr>
<tr>
<td>6.67J/mm</td>
<td>9100</td>
<td>0.468</td>
<td>0.237</td>
</tr>
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</table>

Table 3 shows the comparison of the analytical and experimental results. As we can see, the calculation results are almost the same as test results with the error no more than five percent. The result shows that it is effective to calculate the depth of the permanent indentation using the method based on Hertzian contact law.

Table 3 Comparison of the calculation and impact tests

<table>
<thead>
<tr>
<th>Impact Energy</th>
<th>Calculation</th>
<th>Tests</th>
<th>error</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.45J/mm</td>
<td>0.185mm</td>
<td>0.18mm</td>
<td>2.7%</td>
</tr>
<tr>
<td>6.67J/mm</td>
<td>0.237mm</td>
<td>0.24mm</td>
<td>1.8%</td>
</tr>
</tbody>
</table>

5 Conclusion

1. The variation of dynamic indentation with time is similar to that of contact force before significant damage occurred. After large damage appeared, dynamic indentation increases quite slowly. Fig.4 and Fig.5 show the relationship between dynamic indentation and contact force with the impact energy of 17J and 26J respectively.

2. A modified Hertzian contact law is raised based on the dynamic indentation. Fig.7 and Fig.8 show the relationship between contact force and dynamic indentation. In eq. (1), $n$ can be set as 1.4 when using the dynamic indentation.
3. A new computational method is developed to predict the permanent indentation using the modified Hertzian contact law. It proved to be very effective.

References