Original Article

Microscopic Damage Modes and Physical Mechanisms of CFRP Laminates Impacted by Ice projectile at High Velocity

Enling Tang *, Junru Wang, Yafei Han, Chuang Chen

School of Equipment Engineering, Shenyang Ligong University, Shenyang, 110159, China

A R T I C L E   I N F O

Article history:
Received 23 August 2019
Accepted 12 September 2019
Available online 29 October 2019

Keywords:
CFRP laminates
Cohesion model of ice projectiles
Microscopic damage model
Microscopic damage mechanism
Delamination failure prediction

A B S T R A C T

In order to deeply reveal the microscopic damage mode and microscopic damage mechanism of Carbon Fiber Reinforced Plastic laminates (CFRP laminates) impacted vertically by the ice projectile at high velocity. In this paper, the loading system of the one-stage light gas gun, the liquid nitrogen circulating cooling system, the impact pressure measuring system and the high speed camera acquisition system are used, and the experiments of the spherical ice projectile (simulated hail ice, SHI) with diameter of 11 mm impacting CFRP laminates vertically at the velocity of 50-200 m/s were carried out. The impact pressure of the SHI impacting the target, the strain of X-Y in the two main directions at the impact point were measured, and the deflection/ time history curve at the impact point during the impact process was obtained. By using ABAQUS/Explicit finite element software, the numerical simulation of high-velocity vertical impact of SHI on CFRP laminates was compared with the image acquisition results of the high speed camera at different moments during the impact process, and the failure morphology and process of SHI was analyzed. At the same time, the delamination of the target obtained by numerical simulation is compared with the cracking of the CFRP fiber reinforcement and the delamination of the epoxy resin interface obtained by microscopic SEM observation, the correctness of using cohesion model to describe the micro-damage of CFRP laminates induced by SHI impacting vertically at high speed was verified. The damage failure threshold of CFRP laminates under the impact load of SHI under given experimental conditions was obtained. By establishing a three-point simply supported physical model, the ultimate deflection of laminated plates subjected to delamination failure was analyzed. Based on the measurement of strain and deflection at impact point, the valuable reference for the prediction of delamination failure in CFRP laminates can be provided, then the detection of the micro-damage to the surface composite part of the aircraft will be realized by the control of the sensor.

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* Corresponding author.

E-mails: tangenling@126.com (E. Tang), jrwang1993@126.com (J. Wang), hanyafei1979@126.com (Y. Han), chenchuang198701@126.com (C. Chen).

https://doi.org/10.1016/j.jmrt.2019.09.035

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1. Introduction

Carbon Fiber Reinforced Plastic (CFRP) has gradually replaced the traditional metal panels (such as aluminium panels, steel panels) and become an ideal structural material in the field of aerospace because of its light weight, high specific strength, large specific modulus, energy absorption and easy to form in a large area. Usually metal structures will leave scars on the surface when they are impacted, while composite materials under impact loads may cause internal damage which is difficult to detect by naked eyes, such as delamination, fiber reinforced fracture, etc. This internal damage has a great influence on the overall properties of composite materials. With the further application of advanced CFRP materials in aircraft exterior structures, the impact of hail has become an important factor that must be considered in the design of aircraft structures. For the hail, the impact pressure produced by the impact velocity of 50-200 m/s is far greater than its own strength, so the impact under the experimental conditions in this paper can be called High Velocity impact. Therefore, the research of hail impact composite structures has attracted great attention of scholars and researchers all over the world. In 1999, Kim [1] et al. carried out the impact test of artificial ice ball on composite laminates by using aerodynamic gun, and measured the impact pressure during the impact process. On this basis, the finite element simulation of hail material was realized by using MAT13 elastic-plastic failure material model in DYNA-3D software for the first time. In 2006, Alastair F [2] studied the numerical simulation and prediction of the damage of composite structures impacted by soft materials such as birds and hail. In the simulation, the hail was modeled by smooth particle hydrodynamics (SPH). Through the numerical simulation of the high-speed impact of hail on composite structures, the delamination and bending damage phenomena were found. The dependence of the damage degree on the impact energy was analyzed, and the numerical simulation results were validated. The results were basically consistent with the experimental results. In 2013, Rhymr J et al. [3] carried out experimental and simulated studies on impact response of multidirectional laminated carbon fiber composite laminates under the load by hail. Based on the measurement of impact pressure and the C-mode ultrasonic scanning of target after experiment, the critical impact loads of composite laminates with different ply angles were obtained. The cohesive element of ABAQUS finite element software was introduced into the numerical simulation to simulate the resin matrix, and the failure modes such as CFRP delamination and crack growth were simulated. In 2018, Robin James et al. [4] has simulated the extreme deformation of the impactor (hailstone and bird) along with the composite plate by using the smoothed particle hydrodynamics (SPH) modeling. In 2018, Akhil Mehandiratta et al [5] conducted the experiment as ASTM Standard D 790 for flexural test by varying the span lengths to understand the behavior of the flexural strength and flexural modulus. Therefore, an optimum span length can be obtained for testing flexural strength, which will be useful to the designers and the composite manufacturers to accomplish better standard testing procedures.

At present, when researching hail impacting on composite materials, ice projectiles are mostly used to carry out impact experiments with high kinetic energy, but the research on the characteristics and mechanism of the load inside the laminate is still rare. In this paper, the SHI loaded by an one-stage light gas gun was used to impact CFRP laminates at high Velocity. Through real-time measurement of impact pressure and strain at the target surface, image acquisition of impact process by high speed camera and micro-observation of impacted CFRP laminates by scanning electron microscopy (SEM), the correctness of the simulation results was verified and the critical impact pressure of the debonding and delamination of the laminate under the impact of SHI was obtained. The impact model simply supported by three-point bending on both sides was established, the critical yield deflection and other key physical quantities of laminates were obtained, and the prediction of delamination failure of CFRP laminates impacted by SHI at high velocity was realized.

2. Experiment

2.1. Loading and testing system

The experiment was carried out on one-stage light gas gun at the Intense Dynamic Research Center of Shenyang Ligong University, China. The initial velocity of the projectile launched by the gun can be controlled between 50 and 1000 m/s. In experiment, the CFRP laminates are impacted by hail projectiles which can be launched by the gun at high velocity in order to ensure that the projectile is in a stable freezing state before launched, the liquid nitrogen circulation cooling system is established by the technical method of winding the copper tube along the direction of the barrel and covered by the heat insulating cotton. The liquid nitrogen is fed into the copper tube and flows to the outside ensuring the system always staying in low temperature. Based on the control of liquid nitrogen flow rate, the temperature of the gun-barrel is the same as that of freezing ice, so that the ice projectile remains intact in the barrel before launched. Laser velocimeter and PVDF pressure sensor are used to measure the launching velocity of SHI and the impact pressure of target respectively. Strain gauge/super dynamic strain gauge system is used to measure the strain in two main directions of target X-Y. And real-time acquisition of physical process of SHI impacting CFRP laminates is realized by using high speed camera. Fig.1 shows the schematic diagram of the loading, testing and liquid nitrogen cooling system of the one-stage light gas gun.

2.2. Experimental materials and parameters

The projectile is a solid spherical ice projectile with a diameter of 11 mm. In order to simulate the characteristics of formation and mechanical properties of hail, a suitable amount of medical cotton is added to the projectile. At the same time, to ensure that the projectile can still impact CFRP laminates in a complete state when it is subjected to high pressure gas, ultra-light clay is used to make the projectile sabot in experiment, and it can be dried for 48 hours after shaping. The advantages of the sabot are light weight, strong elasticit,
non-fragmentation and long storage time. The target is 3 K carbon fiber reinforced resin matrix composite plate produced by Shandong Intelligent New Materials Co. Ltd. The specification of carbon fibre sheet is 120 mm × 120 mm × 3 mm. T300 carbon fibers manufactured by Toray Company of Japan are made of 12 layers of 0°/90° staggered pavement. Fig. 2 shows the projectile and sabot. Fig. 3 is the real figure of CFRP laminates.

3. Experimental results and analysis

3.1. Experimental parameters and measurement results

To simulate the inside damage of composite laminates in the process of hail impacting on aircraft during flight, experiments of SHI impacting CFRP laminated targets vertically at different velocities were carried out. Table 1 shows the experimental parameters and measurement results.

Since CFRP has not been seriously damaged after impact, the target is cut at the impact point, the cuboid specimens of 10 mm × 10 mm × 3 mm shown in Figs. 4–6 are obtained for the purpose of SEM micro-damage morphology analysis.

Figs. 4–6 are the main and side view of the specimen which are magnified 5 times under the optical microscope. By observing the main view and side view of the specimens after cutting under three experimental conditions, it can be found that the surface of the specimens in experiment
No.1 is not damaged and macro-stratification is not seen in the direction of side thickness. In experimental No.2, there was slight damage on the target surface and slight delamination in the direction of lateral thickness. In experimental No.3, there were three parallel cracks on the target surface and serious delamination in the direction of lateral thickness.

3.2. Microscopic analysis of target at impact point

The micro failure modes of CFRP mainly include delamination, Inter Fibre Fracture (IFF) and Fibre Fracture (FF). The concept of IFF is different from that of FF. IFF refers to the cracks in the laminate that run parallel to the direction of the fibers through the whole thickness of the single layer. The FF is the simultaneous breakage of multiple bundles of fibers.

SEM was used to observe the micro-morphology of CFRP target at the experimental No.1–No.3 locations along the thickness direction. Fig. 7 is the SEM image of the impact point in experimental No.1.

As can be seen from Fig. 7 (a), when the magnification is 100, there was no micro-damage in the cutting sample in experimental No.1, and the geometric position of all the surfaces was not yet analyzed. As shown in Fig. 7 (b), when the magnification is 1000, the integrity of fiber bundles can be clearly seen, and the epoxy resin at the interlayer interface remained intact without cracking failure, and the properties of the specimens at the target were still in good condition. Therefore, it can be judged that the CFRP laminates have no delamination failure at the impact velocity of 56.65 m/s, and still maintain good structural and mechanical properties. Fig. 8 shows the SEM image of the impact point in experimental No.2.

Fig. 8 (a) is the SEM image of the sample at magnification of 100. The SHI impacts vertically (The direction of impact is shown in Fig.8(a)), and the delamination can be observed clearly, which is mainly due to the mismatch of bending stiffness of fat-rich zone between layers of fibers in different directions. Fig.8 (b) is the SEM image of the sample at magnification of 300. The micro-cracks through the whole layer can be clearly observed in the micro-topographic images. This is a typical IFF. In order to explain the failure better, the stress analysis model shown in Fig.5 is established. The transverse shear stress wave generated at the moment of impact of ice
projectiles form the shear stresses $\tau_{23}$ and $\tau_{32}$ in the vertical direction of fibers. Meanwhile, the stress wave is reflected through the interface to form the tension wave, which produces local tension stress $\sigma_t$. From the failure criterion of Puck’s action surface [6], when the three-dimensional stress multiplied by the minimum elongation factor ($f_{\text{min}}$) greater than 1 divided by the stress risk factor ($f_{\text{risk}}$) in laminates, IFF occurs on the 45 degree plane parallel to the direction of fibers in the fiber reinforced matrix of laminates. Fig. 9 shows the local stress diagram of IFF.

As shown in Fig. 8 (c), the debonding failure of epoxy resin and the wire drawing damage of a few carbon fibers can be clearly seen when the image of sample is magnified 1800 times. Fracture damage of fibers is mainly affected by high local stress concentration near impact point and indentation caused by shear stress. Fracture of fibers far from impact point is mainly caused by high bending stress. To sum up, when the SHI impacts the target vertically at a velocity of 115.31 m/s, IFF and serious delamination occur on the the CFRP laminates. It is considered that the CFRP laminate has failed at this moment. Fig. 10 is the SEM image of the impact point in experimental No.3.

In Fig. 10(a), the image of target sample in experimental No.3 is magnified 100 times. It can be seen that the delamination failure of CFRP laminates occurs at almost all the interfaces of the laminates in the field of view. The direction of vertical impact of ice projectiles is shown in Fig. 10(a). Typical IFF can be found in each layer of matrix in laminates. In order to further explain the internal damage of CFRP laminates, the specimen is further enlarged to 160 times to observe the failure morphology of IFF. As can be seen from Fig. 10(b), both IFF in the figure are invalidated along the oblique 45° direction. Combining with the observation of micro-SEM images in Fig. 8(b), it can be found that IFF exist in all layers. It can be inferred that the main reason of delamination is the high local stress caused by the stress concentration at the failure tip of IFF, which gradually expands, and then causes the local delamination phenomenon. The delamination position of the specimen was further enlarged to 700 and 3000 times, it can be seen from Figs. 10(c), (d) that a large number of matrix fracture and delamination failures occur, accompanied by more wire drawing damage, resulting in friction or wear between
fibers, and micro-damage and crack propagation occur at the weakest or stress concentration of a single fiber. In summary, more serious damage and failure of laminates occur at the impact velocity of 160.16 m/s, but no obvious FF occurred. At the same time, it can be observed that these CFRP plates are mainly delaminated along the direction of the fibers, because the structure delaminates unimpeded in this direction.

4. Numerical simulation

In order to obtain more effective key physical quantities and better reveal the internal micro-damage mechanism of CFRP laminates, it is of great significance to carry out numerical simulation on damage of CFRP laminates impacted by SHI at high velocity considering the limitation of experimental measurements and micro-analysis to obtain the mechanism of micro-damage in CFRP laminates. In this paper the impact dynamics simulation of SHI impacting CFRP laminates at high velocity is carried out based on Abaqus/Explicit finite element software because of its great advantages on simulation of composite materials under impact loading. The method of combining experiment with numerical simulation is adopted, based on the calibration of the accuracy of numerical simulation by the key physical quantities obtained from experiments, more effective key physical quantities were extracted by numerical simulation, and the micro-damage mechanism of SHI impacting CFRP laminates at high velocity was further revealed, and Fig. 11 is the ABAQUS numerical evaluation.

4.1 Establishment of model

4.1.1 Constitutive model of CFRP laminates

The 120 mm × 120 mm × 3 mm solid plate was defined as CFRP and divided into 12 layers, alternating with 0°/90°. Meanwhile a coordinate system corresponding to the weaving direction was established. The interface between CFRP laminates and
Table 2 – Mechanical properties of CFRP Laminates.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbols</th>
<th>Values</th>
<th>Parameters</th>
<th>Symbols</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>(\rho (kg \cdot m^{-3}))</td>
<td>1548</td>
<td>The strength in fiber direction</td>
<td>(X/I) MPa</td>
<td>1000</td>
</tr>
<tr>
<td>Elastic modulus</td>
<td>E11/GPa</td>
<td>118</td>
<td>The strength in vertical fiber direction</td>
<td>(Y/I) MPa</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>E22/GPa</td>
<td>8.8</td>
<td></td>
<td>(Y/C) MPa</td>
<td>132</td>
</tr>
<tr>
<td></td>
<td>E33/GPa</td>
<td>8.8</td>
<td></td>
<td>(Z/I) MPa</td>
<td>35</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>(\nu_{12})</td>
<td>0.31</td>
<td>The strength in thickness direction</td>
<td>(Z/C) MPa</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>(\nu_{13})</td>
<td>0.31</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(\nu_{14})</td>
<td>0.33</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shear modulus</td>
<td>G12/GPa</td>
<td>4</td>
<td>Shear strength</td>
<td>S12/MPa</td>
<td>58.3</td>
</tr>
<tr>
<td></td>
<td>G13/GPa</td>
<td>4</td>
<td></td>
<td>S13/MPa</td>
<td>58.3</td>
</tr>
<tr>
<td></td>
<td>G23/GPa</td>
<td>3</td>
<td></td>
<td>S23/MPa</td>
<td>40</td>
</tr>
</tbody>
</table>

Fig. 11 – Block diagram of numerical simulation steps.

Table 3 – Material parameters used in the interface cohesive element.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Normalised elastic modulus (MPa/mm)</th>
<th>Inter-laminar strength (MPa)</th>
<th>Inter-laminar fracture toughness (kJ/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>8000</td>
<td>80</td>
<td>0.15</td>
</tr>
<tr>
<td>II</td>
<td>4500</td>
<td>12</td>
<td>0.25</td>
</tr>
<tr>
<td>III</td>
<td>4500</td>
<td>12</td>
<td>0.25</td>
</tr>
</tbody>
</table>

4.1.2. Constitutive model of SHI

In order to simulate the high-velocity impact of Hail on aircraft, a spherical ice projectile model is established in this paper. Most of the original hail constitutive models were improved based on metal constitutive models. In 2007, Kim[11], Keune[12] used the simplest MAT13 model in LS-Dyna, the model was a metal material model, which can reflect the hydrostatic stress-like hydrodynamic behavior of ice after failure, but the strain rate dependence of ice is not taken into consideration in this model. In 2010, Park and Kim[13] et al. added the tension failure criterion on this basis. When the stress reached the set tension failure stress, the deviator stress component was set to zero, and the material can only bear compressive stress. The process of hail impact cracking was approximated to the hydrodynamic behavior. In 2012, Carney[14] et al. developed a constitutive model to describe ice under high strain rate load. In addition to post-failure behavior and state equation, Carney model also includes strain rate dependence and tensile-compressive failure mechanical behavior of ice. However, the yield stress of brittle materials is also affected by pressure, which is not included in the Carney model[15]. Based on the constitutive equation of Mazars elastic damage model, In 2014, Chuzel[16] et al. improved the material model of ice. Assuming that the material is in the linear elastic stage before failure, the law of exponential softening is used to describe the degradation and viscous properties of ice under compressive stress, and then to simulate the damage evolution and cracking behavior of hail. However, the above model can not be used to simulate the hail with a certain degree of plasticity and cracking. In this paper, a rate-dependent cohesion model is established by Langrange algorithm, i.e. cohesive elements with 0 thickness are randomly inserted into the hail model, the material properties of cohesive elements are defined as same as that of hail matrix materials, and the damage mode is defined as Quads damage. In 2007, according to the experimental results of fitting the compressive strength of ice under impact strain rate by Kim et al.[17], the nominal pressure of Quads damage was defined to set the cohesive force interface parameters at 0 thickness. The nominal pressure of Quads damage is defined to set the cohesive interface parameters at 0 thickness. The parameters of hail matrix model[18] are mainly set by density, mechanical properties, yield stress-strain, yield ratio related to strain rate, and so on. Finally, the rate-dependent hail projectile cohesion random cracking model is established. Table 4 shows the mechanical properties of SHI.

epoxy resin was established by building cohesive elements between the layers. The orthotropic constitutive model is used for the CFRP composite material [7]. The orthotropic constitutive model is defined in the elastic stage, and the stress and strain are satisfied with a linear relationship, which 9 elastic constants are included. For interlaminar damage, a bilinear cohesive zone model which can predict delamination and simulate delamination expansion is adopted[8,9]. The parameters of CFRP laminates are provided in reference [10]. Table 2 shows the mechanical properties of CFRP laminates.

Table 3 is the material parameters used in the interface cohesive element.
Table 4 – Mechanical properties of SHI.

<table>
<thead>
<tr>
<th>Density/kg m⁻³</th>
<th>Elastic modulus/MPa</th>
<th>Shear modulus/MPa</th>
<th>Poisson's ratio</th>
<th>Yield Strength/MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>900.5</td>
<td>9380</td>
<td>3526</td>
<td>0.33</td>
<td>5.2</td>
</tr>
</tbody>
</table>

Table 5 – Ice hardening rate parameter.

<table>
<thead>
<tr>
<th>Strain rate</th>
<th>0</th>
<th>1 \times 10⁻¹</th>
<th>5 \times 10⁻¹</th>
<th>1 \times 10⁰</th>
<th>5 \times 10⁵</th>
<th>1 \times 10¹</th>
<th>5 \times 10⁵</th>
<th>1 \times 10²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardening factor</td>
<td>1</td>
<td>1.01</td>
<td>1.5</td>
<td>1.71</td>
<td>2.2</td>
<td>2.42</td>
<td>2.91</td>
<td>3.13</td>
</tr>
<tr>
<td>Strain rate</td>
<td>5 \times 10²</td>
<td>1 \times 10³</td>
<td>5 \times 10³</td>
<td>1 \times 10⁴</td>
<td>5 \times 10⁴</td>
<td>1 \times 10⁵</td>
<td>5 \times 10⁵</td>
<td>1 \times 10⁶</td>
</tr>
<tr>
<td>Hardening factor</td>
<td>3.62</td>
<td>3.84</td>
<td>4.33</td>
<td>4.55</td>
<td>5.04</td>
<td>5.25</td>
<td>5.75</td>
<td>5.96</td>
</tr>
</tbody>
</table>

Table 6 – Material parameters used with free thickness cohesive element.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density/kg m⁻³</td>
<td>912.5</td>
</tr>
<tr>
<td>Normalised elastic modulus (MPa/mm)</td>
<td>E = 8380</td>
</tr>
<tr>
<td>Normalised shear modulus (MPa/mm)</td>
<td>G₁ = G₂ = 3526</td>
</tr>
<tr>
<td>Nominal stress/MPa</td>
<td>t₁ = t₂ = 10.3, t₃ = 5</td>
</tr>
</tbody>
</table>

Table 5 shows the hardening rate parameters of ice. Table 6 shows the material parameters of 0 thickness cohesive element.

4.2. Mesh generation

Mesh generation is an important part of numerical simulation process. Mesh generation of CFRP fiber reinforcement, CFRP laminates interlaminar cohesive element, hail matrix and 0-thickness cohesive element in hail is required for numerical simulation, respectively. In this paper, all the components are hexahedral meshes. Among them, the matrix of CFRP adopts three-dimensional stress, explicit and linear analysis C3D8R element, and element distortion and element deletion are set. For CFRP interlayer cohesive element, the mesh type is viscous, linear and explicit analysis COH3D8 element, and the element deletion is needed. Three-dimensional stress, explicit and linear analysis of C3D8R element are applied to spherical hail matrix, and the deletion option is set to No. The cohesive element with 0 thickness is set as COH3D8 element with viscous, linear and explicit analysis, and the element deletion is also needed.

4.3. Failure criteria of CFRP laminates

Hashin failure criterion [19] and partial Puck failure criterion are used as the initial failure criterion for composite laminates. The failure criterions of CFRP laminates in the process of collision, including tensile fracture of fibers, failure of fibers under compression and failure of matrix under tension and compression are defined Hashin failure criterion is expressed as follows:

(1) Criterion of fiber fracture : \( \frac{\sigma_{11}}{X_f} \geq 1 \) (1)

(2) Criterion of matrix cracking : \( \left( \frac{\sigma_{22}}{Y_1} \right)^2 + \left( \frac{\sigma_{12}}{S_{12}} \right)^2 \geq 1 \) (2)

(3) Criterion of matrix extrusion : \( \left( \frac{\sigma_{22}}{2S_{12}} \right)^2 + \left( \frac{Y_c}{\frac{\sigma_{22}}{2S_{12}}} - 1 \right) \left( \frac{\sigma_{22}}{Y_c} \right) + \left( \frac{\sigma_{12}}{S_{12}} \right)^2 \geq 1 \) (3)

ABAQUS/Explicit display solver is used, and the VUMAT subroutine is compiled based on the constitutive relation, initial damage criterion and damage extension criterion of single-layer plate. Finally, numerical simulation of multivariate under different experimental conditions is achieved by calling user materials.

4.4. Comparison between numerical simulation and experimental results

4.4.1. The process of SHI impacting target

The numerical simulation of the impact process of the SHI under the condition of experimental No.3 was compared with the record of the high speed camera on the impact of the SHI on the CFRP target. Fig. 12 is a comparison of numerical simulations and experimental results of impact on CFRP laminates at different impact moments.

It can be clearly seen from Fig.12 that a short plastic strain process happens at the moment that SHI contacts with the target due to a large interaction force, and then the hail cracks randomly under the action of tensile wave. The process of corresponding time between numerical simulation and high-speed camera shooting is highly consistent, which can preliminarily prove the reliability of the ice projectile and CFRP modeling.

4.5. Comparison between numerical simulation and experimental results

In order to further verify the accuracy of numerical simulation, the numerical simulation of high-velocity impact of SHI on CFRP laminates was carried out, the key physical quantities in the impact process were extracted, and the results of numerical simulation and experiment under corresponding conditions were compared.
(1) Comparison of impact pressure

The impact pressure on CFRP laminates impacted by SHI at high velocity in the simulation process of No.1~No.3 was extracted and compared with the experimental results. Fig. 13 shows the impact pressure-time curve at the impact point obtained by numerical simulation and experiment.

By comparing the experimental impact pressure measurements with the simulation results at different impact velocities in Fig.13, the accuracy of the simulation results is proved, and the correctness of the ice projectile model is verified again. From Fig. 13, it can be found that the peak value of impact pressure in the simulation results is higher than the measured ones, which is mainly due to: (1) There are still some cracks and bubbles in the ice projectile launched in the experiment, which lead to the inadequacy of the mechanical properties of the ice projectile compared with the ideal ones, while the parameters of the ice projectile have been set as the parameters of hail which has greater mechanical properties in simulation. (2) The determination of impact pressure in experiment involves the contact area between the ice projectile and the target. However, as a brittle material, the contact area of the ice projectile is difficult to be determined accurately, so there will be some errors.

(2) Comparison of damage modes

The results of numerical simulation and SEM at the impact point about the experimental No.2 and No.3 at 100 times magnification are compared, as shown in Figs.14 and 15. Fig. 14 is a comparison between numerical simulation and SEM results of resin interface failure under the condition of experimental No.2.

It can be seen from Fig.14(a), the red areas of the interface indicates that the resin has failed.

Comparing with the SEM images of CFRP laminates at the impact point after the experiment, there is a few local delamination. It is also found that the interface of 3th, 5th, 7th and 9th layers of epoxy resin in the simulation diagram is in a critical stiffness degradation state, while the interface of 2th, 4th, 6th and 8th layers is completely degraded, which results in more serious delamination. Fig.15 is a comparison between numerical simulation and microscopic SEM results of resin interface failure under the condition of experimental No.3.

As can be seen from Fig.15(a), the red areas of the interface indicates that the resin has failed, and the SHI impact has caused a large number of interface failures. The interface of the 2th, 4th and 6th layers of epoxy resin has a more serious degradation and element deletion, which can be seen from Fig.15 (a) that the spacing between these layers is larger. Combining with Figs.14 and 15, it is found that the delamination of laminates near the impact point is more serious, which is quite different from the damage mode of traditional homogeneous materials.

4.5.1. Simulation analysis

The numerical simulation results of high-velocity impact of SHI on CFRP laminates in experimental No.2 and No.3 are expanded as shown in Fig.13. Fig.16 is the schematic diagram of the damage results of each composite layer and interface of CFRP.

In Fig.16, Part1 is the diagram of the tensile failure (SDV3) of the 12 layers matrix in CFRP laminates. The red region represents the parts where the tensile failure has occurred. It is obvious that the direction of the tensile failure part of each layer is along the direction of 0° and 90°, respectively. In the process of simulation, it can be seen clearly that the tensile damage of the matrix occurs first in the last layer and the damage area is the largest, which is due to the effect of the tensile wave produced by the impact of SHI. Part2 is the diagram of the stiffness degradation (SDEG) of 11 adhesive layers in CFRP laminates. The red parts are the areas where the stiffness degradation have occurred and the adhesive layers have been debonded. When the stiffness degradation is more serious, the element is deleted by simulation settings. In Fig.16(b), element deletion occurs at the interfaces of layers 2th, 4th, 6th and 8th, and more serious delamination occurs between these layers of CFRP. It is evident from Part 1 in Fig.15 that the increase of tensile damage in each layer of these panels
occurs mainly in the direction of 90 degrees, because the damage can extend unimpeded along the direction of the fibers in the structure. Fig.17 is a schematic diagram of the debonding area of the laminate in the simulation process.

In Fig.17, the matrix parts of the CFRP laminates are hidden in the simulation results, leaving the interface between the SHI and the epoxy resin layers in the CFRP laminates. The degree and scope of the stiffness degradation of the interface at the impact point can be observed more clearly. Moreover, most of the laminates have no delamination failure just below the impact point. The bending deformation of the laminate is more obvious when the projectile impacts on the target under
the condition of experimental No.3, and the rigidity degradation of the epoxy resin interface is very serious, leading to the obvious local delamination phenomenon. Under the experimental No.2 condition, several interfacial positions in laminates are in critical delamination state. The shear stress of 4th, 6th and 8th layer where the stiffness degradation is higher in the crack arrest zone and the stiffness degradation occurs at the interface of the laminates extracted as shown in
Fig. 18 – The shear stress time history curve of the interface stiffness degradation region of laminates.

Figs. 18 and 19. Fig.18 is the shear stress time history curve of the interface stiffness degradation region of laminates. Fig.19 is the shear stress time history curve of the crack arrest area of the impact target.

Combining Figs. 17–19, it can be concluded that the critical shear stress of the degradation damage of the rigidity at the interface of epoxy resin is 15 MPa, while the tensile strength of the fibre wire is more than 1000 MPa, which results in the tensile failure of the matrix along the direction of 45° from the fibre during the impact on CFRP laminates. With the shear stress acting continuously, the interface of epoxy resin is destroyed leading to the debonding between fibre and matrix. And relative movement of them happens and fibre drawing damage occurs between the interface of each matrix layer.

5. Physical model of SHI impacting CFRP laminates

By measuring the deflection of CFRP around the contact point during the impacting process, the delamination prediction of CFRP laminates can be realized. Based on the measurement of impact load and strain of laminates at impact point in experiment, and combined with numerical simulation, the deflection time history curve at impact point is fitted. Then the critical deformation condition of the CFRP laminate is obtained. Finally, the physical model of ice projectile high-velocity impacting on CFRP laminate is established. Fig.20 is the numerical simulation cutaway view during SHI impacting on CFRP laminates at high velocity.

Fig. 19 – The shear stress time history curve of the crack arrest area of the impact target.

Fig. 20 – Cutaway view of numerical simulation of SHI impacting on CFRP laminates at high velocity.
The bending moment (maximum bending moment) of the middle section of the beam is set as \( dM^0 \) (\( 0.25 \text{d}P \)), and set the curvature increment at the neutral axis corresponding to the section \( dK^0 \). For laminates, the calculation of the above model in the width direction should be taken into account, so the relationship between the internal force increment, the bending moment increment and the strain increment can be expressed by formulas (4) and (5).

\[
\left\{ \begin{array}{l}
\frac{dN_x}{dz} \\
\frac{dN_y}{dz}
\end{array} \right\} = \left\{ \begin{array}{l}
\frac{d\sigma_x}{d\sigma_y}
\end{array} \right\} \text{bdz}
\]

\[
\frac{dM_x}{dz} = \int_{-h/2}^{h/2} \left\{ \begin{array}{l}
\frac{d\sigma_x}{d\sigma_y}
\end{array} \right\} bzdz
\]

\[
\frac{dM_y}{dz} = \int_{-h/2}^{h/2} \left\{ \begin{array}{l}
\frac{d\sigma_x}{d\sigma_y}
\end{array} \right\} dz
\]

Based on measurement of X and Y principal strain \((d\varepsilon_{xx}, d\varepsilon_{yy})\) of laminates under impact loading in experiments, the increment of internal force and bending moment \((dN, dM)\) is obtained.

Fig. 24 shows the strain-time curves obtained by experimental measurement and numerical simulation.

Based on the formulas of \(dN\) and \(dM\), the curvature increment \((dk^0)\) of arbitrary x-section at the neutral axis of a laminated beam can be obtained by using the formula (5). The load on the X-section can be expressed as

\[
\left\{ \begin{array}{l}
\frac{dN_{xx}}{dz} \\
\frac{dN_{yy}}{dz}
\end{array} \right\} = \left\{ \begin{array}{l}
Q_{11} \quad Q_{12} \quad Q_{11} \quad Q_{12} \quad Q_{11} \quad Q_{12} \quad Q_{11} \quad Q_{12} \quad Q_{11} \quad Q_{12} \\
Q_{21} \quad Q_{22} \quad Q_{21} \quad Q_{22} \quad Q_{21} \quad Q_{22} \quad Q_{21} \quad Q_{22} \quad Q_{21} \quad Q_{22}
\end{array} \right\} \text{bdz}
\]

\[
\left\{ \begin{array}{l}
\frac{dM_{xx}}{dz} \\
\frac{dM_{yy}}{dz}
\end{array} \right\} = \left\{ \begin{array}{l}
Q_{11} \quad Q_{12} \quad Q_{11} \quad Q_{12} \quad Q_{11} \quad Q_{12} \quad Q_{11} \quad Q_{12} \quad Q_{11} \quad Q_{12} \\
Q_{21} \quad Q_{22} \quad Q_{21} \quad Q_{22} \quad Q_{21} \quad Q_{22} \quad Q_{21} \quad Q_{22} \quad Q_{21} \quad Q_{22}
\end{array} \right\} \text{bdz}
\]

The matrix \(Q\) in formula (6) is called the global stiffness matrix of the laminate. The increments of strain, curvature and distortion in the middle plane of the laminate can be solved. The relationship between the curvature increment of arbitrary x-section at the neutral axis \((dk^0)\) and the curvature
increment at the middle section of the laminated beam \((dk_0, 0, 0)\) satisfies the following formulas (7)

\[
dk_{xx}^0 = \frac{2x}{l} dk_{xx}^{0,0}
\]

According to the two hypotheses of Kirchhoff about the static indefinite structure of classical laminate theory [21,22]:
1. The strain component along the thickness direction is neglected; 2. The straight normal line perpendicular to the middle surface remains linear after deformation. The relation between the curvature and the displacement increments in the mid-plane of the laminate is integrated to obtain the equation (8), where \(F\) is the two undetermined functions in the coordinate plane and can be obtained by solving with boundary conditions. When \(x = 0.5l, dk_{xx}^0 = dk_{xx}^{0,0}\).

Since the internal moment of X-section is the same as that of the middle section, and the stiffness of the beam remains unchanged throughout the span. Then formula (7) is substituted in formula (8) and the deflection time relationship of the middle surface of the laminate in the process of high-velocity impact of SHI shown in formula (9) is obtained by using the boundary conditions of simply supported two ends.

\[
dw^0 = -\int dk_{xx}^0 dx + F_1(y)x + F_2(y)
\]

\[
dw^0 = -\frac{1}{3l} \frac{y^3}{3} + \frac{1}{4} dk_{xx}^{0,0} 0 \leq x \leq 0.5l
\]

The deflection-time curves obtained by deducting from the expressions above with the principal strain along \(X\) and \(Y\) captured in experiments No.2 and No.3 are compared with those simulated Fig.25 is the deflection/time history curves obtained by numerical simulation and experiment.

Combining with the deflection-time history curves at the impact point in Fig.25, the bending moment time history curves at the impact point in Fig.24 and the impact pressure time history curves in Fig.14, it can be found that when the impact pressure of ice projectile reaches its peak value, the failure of CFRP laminates occurs, meanwhile the load-carrying capacity of composite materials will also decrease significantly with the bending moment reach its maximum value correspondingly. Reflected on the fitted deflection-time history curve, the deflection no longer increases monotonously after the critical deflection (that is the deflection of the corresponding laminate under the maximum load) is reached. The ultimate failure deflection (corresponding to the maximum bearing capacity) of CFRP laminates subjected to impact are predicted to be 0.7-0.8 mm, because the experimental No.2 is in critical delamination failure state after SHI impacting the CFRP laminates. When the deflection of CFRP target subjected to vertical impact of SHI exceeds its limit deflection, and no obvious surface damage, the degree of delamination failure in CFRP laminates can be predicted by measuring the strain and deflection at the impact location.

6. Conclusion

Based on one-stage light gas gun loading system, the liquid nitrogen cooling system, the impact pressure measurement system and the high-speed camera acquisition system, the experiment of the spherical ice projectile (simulated hail ice) impacting CFRP laminates vertically at the velocity of 50-200 m/s was carried out. The impact pressure, strain in the X and Y direction at the impact point were measured and the
process of high-velocity vertical impact of SHI on CFRP laminates was captured by high-speed camera. In addition, the numerical simulation under the corresponding experimental conditions was carried out by bringing in ABAQUS/Explicit finite element software. Meanwhile, the microscopic observation and morphological analysis of carbon fiber laminates at the impact point were finished by means of scanning electron microscopy (SEM), and the physical model of high-velocity vertical impact of SHI on CFRP laminates was established. The following conclusions can be drawn:

1. The velocity threshold of damage caused by SHI with diameter of 11 mm impacting carbon fiber laminates vertically is about 100 m/s, and the impact pressure threshold is between 130 and 140 MPa.

2. By acquiring experimental photographs at different impact moments in the physical process of CFRP laminates impacted vertically by SHI at high velocity, and extracting data of key physical quantities from experiment and numerical simulation, the reliability of using cohesion model to describe the random cracking of SHI in the process of high-speed impact on CFRP laminates is verified.

3. Microscopic observation of cutting specimens at impact point based on SEM and numerical simulation of high-speed vertical impact of SHI on laminate under corresponding experimental conditions show that: When the SHI impacts CFRP laminates vertically and at high velocity, the laminates begin to bear load and bend to a certain extent. The projectile contacts the target and generates stress wave transferring along the transverse and longitudinal of the target. Due to the combined action of tensile stress and transverse shear stress on the fiber reinforced body, the fiber reinforced body fail when the principal stress on the failure surface exceeds the ultimate strength. Along with the cracking of the fiber reinforced body, the local stress concentration at the crack of the 45° failure surface leads to the failure of the resin matrix at the interface. With the continuous action of the tensile wave, the cracking extends obviously and the debonding failure occurs at the interface. Moreover, the tensile damage of CFRP laminates occurs mainly along the 90° direction of the fibers.

4. Under the given experimental conditions, the ultimate deflection for delamination failure of CFRP laminates is 0.7–0.8 mm. Meanwhile, through the distribution and control of sensors, the detection of delamination damage for surface composite materials will be realized when aircraft is hit by hail.

Acknowledgments

The authors would like to acknowledge National Natural Science Foundation of China (Grant No.11472178; 11802182), Open Foundation of Hypervelocity Impact Research Center of CARDC(Grant No. 20190201) and Open Project of State Key Laboratory of Explosion Science and technology in Beijing Institute of Technology (Grant No. KFJJ18-04M) to provide fund for conducting experiments.

References

Enling Tang: Male he was born in 1971, who is a postgraduate/Doctor of Technical Science. He graduated from the Engineering Mechanics Major of the School of Aerospace Science and Technology in Beijing Institute of Technology. Currently, he is a professor and also a part-time doctoral supervisor of the First-Level Discipline of weapon science and technology of Nanjing University of Science and Technology. He is also a distinguished professor of Liaoning Province, and enjoying the special allowance from the State Council of the People’s Republic of China. He is now vice president of the school of equipment engineering and head of mechanics discipline.

He is mainly engaged in electromechanical effects of advanced materials and structures under strong dynamic loads, the effects of femtosecond pulsed laser irradiating on materials and structures; the electromechanical coupling mechanism of piezoelectric materials, the measurement and control technology of high dynamic aircraft near-space, electromagnetic launch technology, high voltage discharge testing technology of spacecraft, preparation and characterization of reactive materials and terminal trajectory and damage theory, etc. He has hosted four projects of the National Natural Science Foundation of China, two projects of high-end talents such as Liaoning distinguish Professors and excellent talents support plan of Colleges or Universities (Level 1) in Liaoning, one of the key projects of China weapons pre-research fund, one of the key projects of CAIT Foundation, two open funds of State Key Laboratories, and one of the scientific and technological projects of Liaoning Education Department, and 12 other horizontal items. He has won 6 Awards for academic achievements of Natural Science in Liaoning Province and 3 awards for academic achievements of Natural Science in Shenyang City. He has published 110 academic papers in high-level academic journals at home and abroad, of which 108 are retrieved by SCI and EI. He was authorized 4 invention patents and 1 software copyright. Current, he is editorial board of Defence technology, editorial board of Chinese core journal of Weapons and Equipment Engineering, and member of Explosion and Safety Committee of China ordance Society. He was awarded “The third Shenyang best technological innovation expert”, “the ninth excellent scientific and technological operator in Shenyang City”, and selected into the talent level of 100 people in Liaoning Province.