research Article

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Damage and failure analysis of composite stiffened panels under low-velocity impact and compression after impact with damp-heat aging

https://doi.org/10.1515/secm-2022-0159
received March 20, 2022; accepted September 12, 2022

Abstract: The low-velocity impact and compression after the impact of the composite stiffened panels were carried out after damp-heat aging. The experimental results show that reinforcing the ribs can enhance the impact resistance of test pieces after damp-heat aging. After impacting, the specimens were tested in an axial compression. The results show that the ultimate bearing capacity of the specimen is also affected by different located positions of the impact and different aging times. Compared with the intact specimen, the ultimate load-bearing capacity was reduced to 16.83, 12.10, and 17.10% with the specimen aging for 0, 45, and 90 days, respectively, while the impact position located at the intersection of longitudinal and transverse bars has the greatest influence on the damp-heat aging of specimens.

Keywords: damp-heat aging, composite stiffened panels, compression after impact

1 Introduction

Composite materials can be described as the combination of two or more materials, which have better properties than the individual components used alone [1]. Carbon fiber-reinforced composite material (carbon fiber-reinforced polymer [CFRP]) has been widely used in the aerospace industry due to its high specific strength and stiffness, performance design, corrosion resistance, and overall shape [2–7]. The advanced composite grid-reinforced structure with high strength, high rigidity, and damage resistance has been developed and applied to the structure of aircraft and spacecraft in recent years [8]. The failure of reinforced composite structures usually involves various failure mechanisms, such as fiber fracture, fiber buckling, matrix cracks, fiber matrix shear failure, delamination, stiffener debonding, or a combination of these mechanisms [9]. Among these failure mechanisms, rib–skin detachment can lead to catastrophic advanced composite grid-stiffened structure structural failure because the detached rib and skin are prone to flexing since the skin is usually thin and the rib bears most of the load. This fact has attracted the attention of many researchers [10]. Carbon fibers are widely used to enhance the performance of composite materials in high-performance structural applications. Carbon fiber/epoxy matrix composites have grown rapidly and have been manufactured as aircraft structural components [11]. For example, the Boeing 787 aircraft is 80% composite by volume and 50% by weight [12], and the Airbus A350 XWB aircraft is 52% composite by weight [13]. Composites are more susceptible to damage from localized impacts than metallic materials [14]. Damage can develop inside the material without significant changes to the impact surface, resulting in reduced material strength and structural failure. Furthermore, due to the heterogeneity and anisotropy of composites, their damage patterns can be diverse, which makes identification and quantification more difficult. The need for reliable damage detection in modern multilayer composite panels has led to the development of several non-destructive evaluation methods. Of all the suitable techniques, radiography, ultrasound, visual inspection, and acoustic emission are widely used. In particular, the ultrasonic method based on non-destructive testing has shown great prospects because of its high efficiency, safety, and flexibility, and it is very suitable [15–17].

The structure of carbon fiber-reinforced resin-based composite material is inevitably subjected to the influence

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of factors such as light, temperature, moisture, etc. during storage, transportation, and use. The material and structure will suffer from performance degradation or even failure because of aging. Damp-heat aging is the most important factor affecting the aging failure of composite materials. In a damp-heat environment, the effects of water molecules on composite materials mainly include the following: the swelling and plasticization of water molecules in the resin matrix; the capillary action of water molecules at the fiber-resin interface; the effects of water molecules in material defects, voids, and crack aggregation; and the combined effect of various influencing factors [18]. The damp-heat aging behavior of carbon fiber-reinforced resin matrix composites is a focus of our recent research. The damp-heat environment has a particularly obvious effect on fiber-reinforced resin matrix composites, which is the synergistic effect of humidity and temperature; the effect of the medium immersion environment on the material is the diffusion of water molecules [19–22]. Increasing temperature can speed up the rate of moisture absorption, increase the equilibrium moisture absorption of the material, and shorten the time to reach equilibrium. At the same time, the effect of water on the matrix and interface at high temperature is also more significant [23–25]. Tual et al. [26] reported the effect of damp-heat treatment on the tensile properties of epoxy-based composites. Although the tensile modulus does not seem to change with the wet heat-soaking aging, the tensile strength value is significantly reduced. Joshi reported that when the temperature was increased from 20 to 130°C, the tensile strength decreased from about 220 to 140 MPa, respectively. The tensile modulus is not affected by the increased water content of the composite material. In contrast to the tensile modulus, the compressive modulus decreases as the water content of the composite material increases [27]. The damp-heat aging of composite materials combines water ingress and thermally accelerated aging. The degree of influence of damp-heat aging on composite properties will depend on the water absorption, temperature and heat exposure time of the composite, the type of polymer used as the matrix material, the type of interface defects, and the type of interface defect. Although the damp-heat method is considered to have considerable benefits in the design of accelerated aging and immersion of composite materials, there is still no clear method to link the damp-heat aging temperature and time to the real-time aging year. This method is still very valuable because only by qualitative design in a short period of time can we truly understand and design composite materials that have been aging for a long time.

The damp-heat method can reduce the structural weight and has a great influence on the weight reduction of modern aircraft because of the material and structural form of the carbon fiber composite stiffened panels. Therefore, the carbon fiber composite stiffened panels are also a structural form widely used in the aviation field. Composite materials are anisotropic, and the shear strength between the plies is much lower than the longitudinal and transverse strengths, and it is easy to form delamination damage inside. Weak impact resistance is a shortcoming that cannot be ignored in composite materials [28]. Low-velocity impact damage has the greatest impact on the performance of composite materials. It is concealed and generally does not form visible damage on the surface of the structure. During the production, maintenance, and use of carbon fiber composite grid panels, when repair tools fall, equipment crashes, or runway debris splashes on the composite structure, invisible defects and damages will be formed inside the structure, including matrix cracks, fiber breakage, delamination, interface debonding, etc. [29].

These damages severely damage the structural integrity, resulting in a significant reduction in the load-bearing capacity of the structure during use. Therefore, it is particularly important to study the impact resistance of carbon fiber composite grid panels and the residual strength after impact. Mitrevski et al. [30] experimentally studied the effect of hemispherical, elliptical, and conical punches on the impact response of carbon fiber laminates. The study found that under the same energy impact, the conical punch impacted the specimen to absorb the most energy, resulting in a permanent indentation area, which is the largest. When the hemispherical punch impacts, the peak force generated is the largest and the impact time history is the shortest. Malhotra et al. [31] conducted a near-edge impact and edge impact on composite laminates of different thicknesses through experiments; they found that the impact caused more serious internal delamination on thinner laminates, and that the near-edge impact was caused inside the specimen. The damage is a single delamination, but the edge impact causes multiple delaminations inside. Artero-Guerrero et al. [32] studied the impact of different quality drop hammers on carbon fiber laminates. They used an ultrasonic C scanning system and phased array ultrasonic inspection system to perform non-destructive testing on the impacted specimens and analyzed the impact of punch quality. The impact law of laminate failure experiments shows that the impact load–displacement curve is only related to impact energy. The study also found that thicker laminates have a higher peak force.
and residual stiffness, less contact time, and shorter displacement when subjected to impact. Ostré et al. [33] conducted low-velocity edge impact and quasi-static tests on CFRPs. Four different unidirectional laminates were subjected to impact tests at 10, 20, and 35 J impact energies using the drop weight test and the quasi-static indentation test. The results show that under the impact, the fiber properties determine the initial stiffness of the impact, while in the quasi-static indentation test, the initial indentation stiffness is dominated by the performance of the matrix. Abir et al. [34,35] analyzed the effects of ply sequence, sub-layer buckling, and ply damage on the compressive strength after finite-element simulation, and established the relationship between the impact failure of laminates and the compressive strength after impact. The study found that the size, position, and shape of the impact damage are related to the order of the plies. Impact damage causes the overall and local buckling failure of the laminate during the compression process. The results show that there is a strong correlation between the impact failure mechanism and the compressive strength after impact. Tan et al. [36] studied the effect of impact damage on the compressive properties of a single T-shaped stiffener. The results show that the impact damage reduces the buckling load and the failure load. Therefore, the research in this article is particularly important. Fan et al. [37] carried out a comprehensive study on the mechanical efficiency transfer law of the composite interface in terms of experiments and theory, which is of great significance to the study of mechanics in the future.

The above scholars mainly studied the influence of an external condition on the resistance of the specimen. This experiment is mainly based on the experience of the above researchers, according to the American Society for Testing and Materials (ASTM) standard, so that the experimental materials are subjected to damp-heat aging, and then the 15 J low-velocity impact is carried out. Origin software is used to draw and fit a quadratic curve, and the ultrasonic C scan is used to determine the internal damage area of the test piece to explain the influence of damp-heat aging on the impact resistance of the specimen, while the strain is measured to determine the effect of damp-heat aging and impact damage on the compression of the specimen resistance effects. The research on the influence of damp-heat aging on the impact damage of the test piece in this experiment has paved the way for future research by scholars (Table 1).

2 Materials and methods

In this article, carbon fiber composites with different resin matrices and different weaving angles are used to conduct tests on relevant professional instruments.

2.1 Material details

The carbon fiber/epoxy composite was fabricated using MT300A/603 prepregs. The thickness of the single layer of the prepreg is 0.15 mm, and the order of the skin layer of the grid specimen is [±45°/0°/45°/0°/90°/−45°/0°]S; the length and width of the specimen are 272 and 140 mm, respectively, and the thickness of the specimen’s skin is 3 mm, as shown in Figure 1.

| Specimen number | Aging time (days) | Loading methods |
|-----------------|------------------|----------------|
| #1              | 0                | Compression    |
| #2              | 0                | Located at position 1 and compression |
| #3              | 0                | Located at position 2 and compression |
| #4              | 0                | Located at position 3 and compression |
| #5              | 45               | Compression    |
| #6              | 45               | Located at position 1 and compression |
| #7              | 45               | Located at position 2 and compression |
| #8              | 45               | Located at position 3 and compression |
| #9              | 90               | Compression    |
| #10             | 90               | Located at position 1 and compression |
| #11             | 90               | Located at position 2 and compression |
| #12             | 90               | Located at position 3 and compression |

Note: position 1 is under the impact without stiffeners; position 2 is the midpoint of a single stiffener under the impact; position 3 is the intersection of the transverse stiffeners and the longitudinal stiffeners.
2.2 Experimental equipment

Experimental equipment includes a constant-temperature water bath, a drop hammer impact testing machine, a universal testing machine, and an ultrasonic C-scan system. The test equipment is shown in Figure 2.

2.3 Experimental methods

The test parameter combinations of different damp-heat aging times and loading methods are shown in Table 2. The specimens are named #1–#12.

Specimens are numbered and subjected to group experiments. Specimens #1–#4 are aged 0 days, #5–#8 specimens 45 days, and #9–#12 specimens 90 days. Specimens #2, #6, #10; #3, #7, #11; and #4, #8, #12 were subjected to impact position 1, position 2, and position 3, respectively, after damp-heat aging. Then, compression test was done on all test pieces.

2.3.1 Moisture absorption rate calculation

After placing the specimens of the composite grid-reinforced structure in a constant-temperature water bath (temperature: 60°C) for 0, 45, and 90 days, respectively, the specimens are taken out, the moisture on the surface of the specimens is absorbed with a filter paper, and their mass is weighed. The formula for calculating the rate of the water absorption of the specimens is as follows:

\[ m_{px1} = \frac{M_{xi}}{M_{x0}} \]

where \( m_{px1} \) is the percentage of water absorption relative to the original mass of the specimen; \( M_{x0} \) is the original mass g of the specimen with the initial number \( x \); and \( M_{xi} \) is the growth mass of the specimen with the initial number \( x \) after damp-heat aging on the \( i \) day. The tests are carried out according to the ASTM test standard.

2.3.2 Impact test

The impact test was carried out using an Instron 9,250 Hv drop-weight tester, as shown in Figure 3(a). When carrying out the impact test, the impact energy is input into the computer, and the drop hammer tester uses the sensor to change the height of the drop weight to give the impact energy to the drop hammer. The impact energy is 15 J.

As shown in Figure 2, the composite stiffened panels are fixed on a special fixture for impact test, and the impact on different positions of the specimen is achieved by changing the position of the fixture support platform. The low-velocity impact position takes three positions (Figure 3). 15J impact energy is the most suitable impact

Figure 1: (a) The geometry dimension (mm); (b) the reinforced composite skin structure specimen.
energy for this experiment obtained through pre-experiment. The impact testing machine is equipped with a pneumatic clamp. When the first impact is completed, the pneumatic clamp pops up to prevent the specimen from being subjected to secondary impacts. The weight of the drop hammer is 8.765 kg, and the diameter of the hemispherical punch is 12.7 mm.

2.3.3 Compression test after impact (CAI)

CAI is one of the most commonly used methods to evaluate the effect of impact damage on the structure, which is used to measure the residual compression strength of the specimens. In this study, compression tests were performed on three intact specimens to compare with CAI specimens, which are named as #1. The axial compression test is carried out on a 100-ton universal testing machine (WAW-1000D). In order to prevent the specimen from being out-of-plane, the composite stiffened panels were fixed to a special fixture, while the three sides of the specimen were fixed by the slider on the fixture; the top of the specimen was fixed by the indenter of the fixture to prevent the specimen from instability and damage because of uneven force. A gap of about 4 mm is left between the indenter and the fixture to leave the specimen with downward displacement space. The platform above the compression testing machine remains stationary, and the upward movement of the lower platform is managed through programming control. In order to make the compression process more stable, the load is applied in the form of stress control, and the loading rate is 0.5 kN/s.

Table 2: Water absorption rate

| Time (days) | Water absorption rate (%) |
|------------|--------------------------|
| 45         | 1.12                     |
| 90         | 1.50                     |

Figure 2: (a) Impact testing machine; (b) impact fixture; (c) ultrasound C-scan; (d) strain detection system; (e) compression testing machine; and (f) compression fixture.
3 Results

3.1 Damp-heat test results

Water absorption rate of the composite stiffened panels under the damp-heat aging is shown in Table 2. The average water absorption rate of the specimen under damp-heat aging for 45 days is 1.12%, while the average for 90 days is 1.50%. As time proceeds, the rate first increases rapidly and then stabilizes (Figure 4).

3.2 Impact test results

3.2.1 Impact response

Figure 5(a)–(c) shows the load–displacement curves of the specimens of impacted position 1, impacted position 2, and impacted position 3 after damp-heat aging for 0, 45, and 90 days. The slope of the curves represents the impact resistance of the specimens; the greater the slope, the greater the impact resistance of the specimens. Damp-heat aging has little effect on the impact resistance.
of positions 2 and 3, but has a greater effect on position 1. The longer the damp-heat aging time, the greater the impact resistance. As shown in Figure 5(a), the red curve has two stages that first rise and then fall, with a clear peak; the blue curve first rises rapidly, then falls rapidly, reaches its peak in a wave-like rise, and then falls to 0, which has gone through four stages; the black curve rises slowly and then fluctuates around the peak until the load drops to 0. As shown in Figure 5(b), the red curve first rises rapidly, then slowly rises to a peak and then the load drops to 0; the blue curve first rises rapidly, then drops to 90 A, then rises to 90 B, and then the load drops to 0; the black curve first rises rapidly to the peak, then drops to 0 A, then slowly rises to 0 B, and finally drops to 0. As shown in Figure 5(c), the trends of the three curves are roughly the same, indicating that damp-heat aging has little effect on the impact position 3. Figure 5(d) is a histogram of the load peaks at different load positions under different damp-heat aging times, and it is shown that the bearing load of position 3 is the largest, and that of position 1 is the smallest; the bearing load of the specimen increases when the damp-heat aging time is longer.

3.2.2 External damage

As shown in Figure 5(a), when the impact head is located at position 1 of the specimen damp-heat aging for 0 days, the upper surface of the specimen has a pea-sized impact mark, and the depth of the dent is about 2 mm. As shown in Figure 5(b), when the impact head is located at position 2 of the specimen damp-heat aging for 0 days, the upper surface of the specimen has a green bean-sized impact mark, and the depth of the dent is about 0.8 mm. As shown in Figure 5(c), when the impact head is located
Figure 5: (a and d) External damage of #2 specimen; (b and e) external damage of #3 specimen; and (c and f) external damage of #4 specimen.

Figure 6: (a and d) External damage of #6 specimen; (b and e) external damage of #7 specimen; and (c and f) external damage of #8 specimen.
Figure 7: (a and d) External damage of #10 specimen; (b and e) external damage of #11 specimen; and (c and f) external damage of #12 specimen.

Figure 8: Internal impact damage: (a) 0d-P1; (b) 0d-P2; (c) 0d-P3; (d) 45d-P1; (e) 45d-P2; (f) 45d-P3; (g) 90d-P1; (h) 90d-P2; and (i) 90d-P3.
at position 3 of the specimen, damp-heat aging for 0 days, the upper surface of the specimen has a rice grain-sized impact mark, and the depth of the dent is about 0.3 mm.

As shown in Figure 5(d), when the impact head is located at position 1 of the specimen, damp-heat aging for 0 days, the lower surface of the specimen has a ply splitting along the 45° direction on the impacted position, and ply fracture at the junction of adjacent stiffeners and laminates. As shown in Figure 5(d) and (e), when the impact head is located at positions 2 and 3 of the specimen, damp-heat aging for 0 days, the lower surface of the specimen has a ply fracture at the junction of adjacent stiffeners and laminates (Figures 6 and 7).

### 3.2.3 Internal damage

As shown in Figure 8, the damage area of the impact located at position 1 is much larger than that of the impact located at positions 2 and 3. As the damp-heat aging time of the specimen increases, the damage area of the specimen under impact is also gradually reduced.

### 3.3 Compression test results

Figure 9(a)–(c) shows the load–displacement curves of specimens under CAI after aging for 0, 45, and 90 days,
and the slope of the curve represents the compression resistance of the specimens. The greater the slope, the greater the compression resistance of the specimens, and the trend of the curves is roughly the same; it first rises rapidly to the peak and then rapidly decreases. Figure 11(d) is a histogram of the ultimate load of specimens under CAI. It can be seen that the ultimate bearing capacity of the specimen decreases with the increase of aging time.

Table 3: Summary of experimental and simulation results

| Number | Aging time (days) | Loading method | Ultimate load (kN) |
|--------|-------------------|----------------|-------------------|
| #1     | 0                 | Compression    | 272.45            |
| #2     | 0                 | Located at position 1 and compression | 243.14 |
| #3     | 0                 | Located at position 2 and compression | 255.77 |
| #4     | 0                 | Located at position 3 and compression | 226.60 |
| #5     | 45                | Compression    | 252.91            |
| #6     | 45                | Located at position 1 and compression | 236.98 |
| #7     | 45                | Located at position 2 and compression | 244.29 |
| #8     | 45                | Located at position 3 and compression | 222.31 |
| #9     | 90                | Compression    | 243.83            |
| #10    | 90                | Located at position 1 and compression | 232.76 |
| #11    | 90                | Located at position 2 and compression | 239.01 |
| #12    | 90                | Located at position 3 and compression | 202.14 |

Figure 10: Compression damage of the specimen after aging for 0 days: (a and d) #2; (b and e) #3; and (c and f) #4.
damage and heat aging time; the impact damage can reduce the ultimate bearing capacity of the specimen, and the stiffener can increase the ultimate bearing capacity of the specimen.

As shown in Table 3, the ultimate bearing capacity of the unimpacted specimen is 272.45 kN. The ultimate bearing capacity of the specimen located at position 1 is 243.14 kN, and it is reduced by 10.59% compared with the unimpacted specimen; the ultimate bearing capacity of the specimen located at position 2 is 255.77 kN, and it is reduced by 6.12% compared with the unimpacted specimen; the ultimate bearing capacity of the specimen located at position 3 is 226.60 kN, and it is reduced by 16.09% compared with the unimpacted specimen.

As shown in Figures 10–12, the upper surface of the specimen was broken regardless of the impact position. At the impact position 1, there was a larger area of skin debonding than at the impact position 3 where it appeared on the lower surface of the specimen. At the impact position 2, it exhibited debonding of the skin and stiffeners fracture on the lower surface of the specimen.

4 Discussion

4.1 Analysis of water absorption rate

As shown in Figure 13, the black dot is the water absorption rate of the specimen after damp-heat aging calculated every day, and the red curve is the fitted mean curve. The fitted formula is as follows:

\[
y = (-1.60639 \times 10^{-4} \pm 1.0495 \times 10^{-5})x^2 \\
+ (0.02841 \pm 9.85675 \times 10^{-6})x \\
+ (0.23872 \pm 0.01943).
\]
Note: Use Origin software to fit the quadratic function according to the test data scatter plot.

The curve first increases rapidly and then stabilizes. The growth rate of the moisture absorption rate of 45 days of damp-heat aging is higher than that of 90 days of damp-heat aging. The specimen is surrounded by pure water, and the water is easier to diffuse into the composite material. The moisture absorption state of the material can be divided into two stages: the first stage is the penetration of water into the matrix of the composite material along the micro-cracks of the material. At this time, the moisture absorption law of the material is mainly based on Fick diffusion driven by the concentration gradient. The matrix absorbs moisture, and the expansion is not obvious, and the interface damage is weak; in the second stage, water enters the material through the capillary action at the interface. At this stage, the interface delamination damage between the fiber and the matrix will occur, and the composite grid structure is damaged. The two stages of moisture absorption of the material increase the mass change rate of the composite stiffened panels, but as the moisture absorption of the specimen gradually reaches saturation, the mass change rate of the specimen gradually grows slowly.

Figure 12: Compression damage of the specimen after aging for 90 days: (a and d) #10; (b and e) #11; and (c and f) #12.

Figure 13: Water absorption rate.
4.2 Analysis of the impact test

As shown in Table 4, the increase rate of the load decreases significantly when the time of damp-heat aging increases; the influence of damp-heat aging on the impact part with stiffeners is significantly lower than that of position 1 without stiffeners. As shown in Table 5, the internal damage areas of specimens under the impact are gradually reduced with the increase of damp-heat aging time, and the internal damage of the impact on the specimen with damp-heat aging for 90 days is almost the same. Damp-heat aging can reduce the damage resistance of the composite stiffened panels because the

**Table 4: Load growth rate**

| Time (days) | Position 2 by position 1 (%) | Position 3 by position 2 (%) |
|------------|------------------------------|----------------------------|
| 0          | 56.52                        | 4.53                       |
| 45         | 38.40                        | 4.22                       |
| 90         | 28.03                        | 2.97                       |

**Table 5: Internal damage area of the specimens under impact**

| Time (days) | Scan deep (mm) | Damage area (mm²) |
|------------|----------------|-------------------|
|            | Position 1    | Position 2 | Position 3 |
| 0          | 1.5            | 342        | 283.2     | 100.3   |
| 45         | 1.5            | 330.4     | 271.4     | 99.8    |
| 90         | 1.5            | 94.51     | 94.42     | 94.37   |

Figure 14: Specimen strain–load curves under 15 J impact: (a) #2; (b) #3; (c) #4; (d) #6; (e) #7; (f) #8; (g) #10; (h) #11; and (i) #12.
stiffeners can increase their resistance by absorbing the impact energy. The damp-heat aging can reduce the stiffness of the material by affecting the combination of the resin and fiber. The damp-heat environment can destroy the stiffness of the resin, so that the stiffeners are separated from the composite laminate, and the stiffness of the composite panels is reduced, in turn enhancing the toughness of the specimen.

4.3 Analysis of compression

As shown in Figure 14, when the stiffener is damaged, the strain value becomes larger. The maximum strain of specimens is $7,500 \times 10^{-6}$ for the impact located at position 1, which is much larger than the maximum strain of specimens with impact located at position 2 ($4,500 \times 10^{-6}$) and larger than the maximum strain of specimens with impact located at position 3 ($4,700 \times 10^{-6}$).

Impacts at different positions have different effects on the ultimate bearing capacity of the specimen. Stiffeners can enhance the ultimate bearing capacity and reduce the resistance to deformation of the specimen. When the stiffener is damaged, the ultimate bearing capacity and the resistance to deformation on the specimen will be significantly reduced.

5 Conclusion

The following conclusions can be drawn from the above experimental results: The impact strength of the grille will be reduced when it is designed in the damp-heat aging environment by affecting the adhesion of the resin and carbon fiber, and the impact resistance of the reinforced stiffener decreases with instant damp-heat aging. The debonding of stiffer ribs and delamination of laminates are more pronounced. Both damp-heat aging and impact damage can affect the compression resistance of the test piece. The more serious the debonding and delamination of the test piece, the lower the impact resistance and the mechanical properties of the test piece. Therefore, a new experimental idea for studying the mechanical properties of grid composites is provided for researchers and users.

Acknowledgements: The authors thank the National Natural Science Foundation of China (Grant No. 11972140) for this research.

Funding information: This research was funded by the National Natural Science Foundation of China, grant number 11972140.

Author contributions: Conceptualization, Hanhua Li and Shi Yan; methodology, Shi Yan; validation, Qiuhua Zhang; writing – original draft preparation, Changmei Du; writing – review and editing, Jiale Jia; supervision, Shi Yan; simulation and formal analysis, Xixi Chen. All authors have read and agreed to the published version of the manuscript.

Conflict of interest: The authors declare no conflicts of interest. The funders had no role in the design of the study, in the collection, analyses, or interpretation of data, in the writing of the manuscript, or in the decision to publish the results.

Data availability statement: The data in this article are all derived from the experiments of our research group, which are authentic, reliable, and trustworthy.

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