Impact Damage Characteristics of Quartz Fiber and NOMEX Paper Honeycomb Sandwich Panel composite materials

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Abstract—To provide a reference for practical engineering application of fiber composite materials, this work researches on the impact resistance of type-B quartz fiber/modified cyanate ester composite material laminates and NOMEX paper honeycomb sandwich panels. Firstly, low-speed impact tests are carried out on the quartz fiber laminates and the NOMEX paper honeycomb sandwich panels by setting different parameters to analyze the impact energy and punch mass on impact damage; secondly, based on the experimental results, impact responses are analyzed; and the damage morphology of the two composite materials is observed through visual inspection and with the aid of the CT scanning technology. The results show that according to time-load curves, the NOMEX paper honeycomb sandwich panels have two peak load moments, respectively corresponding to the moments when the upper and lower panels are penetrated; the quartz fiber laminates show three different types of failures, namely substrate cracking, fiber fracture and delamination. As for the NOMEX paper honeycomb sandwich panels, two types of damage are found: fiber fracture and honeycomb core extrusion fracture. When the punch mass is constant, the greater the impact energy is, the more serious the damage is; and when the impact energy is constant, the greater the punch mass is, the more serious the damage is.

1. Introduction
Different from the anisotropic characteristics of metal materials, fiber composite materials with such excellent properties as high modulus and high strength have been extensively applied to aircraft structures, such as aircraft radomes, antenna housing, and leading edges of wings [1,2]. As a structural/functional component, it plays an important role in the aircraft structures to ensure the proper functioning of antennas and microwave systems in harsh environments. However, because the composite materials are often prone to shock loads due to external impacts during manufacturing, service and even maintenance (for example, bird strikes, hail strikes and tool drops), especially damages caused under low-speed impact conditions, its structure will be changed due to external impact and its service life will be shortened accordingly [3,4]. The "Composite Materials Handbook" (CMH-17) points out that low-velocity impact on the composite material structure refers to "the fall of object weighing 10-20 pounds from a height of several feet" [5,6]. In addition to visible damage on the surface, there are invisible impact damages in the composite materials, which will be more serious to jeopardize the mechanical properties and structural integrity of the composite materials [7]. Hence, this paper researches on on the impact response and damage types of the composite materials under...
low-speed impact loads through evaluation and analysis to lay a basis for the practical application of the composite materials.

Many scholars at home and abroad have made theoretical and experimental studies on the impact damage performance of the composite materials. Shen Zhen [8] made analysis on the impact damage state of composite materials and divided them into low-energy without damage, small-energy with non-obvious damage, obvious indentation and penetrating damage. Hou [9] conducted an impact test on the T300 grade CFRP laminate with a pneumatic gun. The test shows that the damage mainly acts on the substrate extrusion and delamination failure. In thin ply laminates, fiber breakage becomes more relevant while matrix cracking is reduced and the consequent induced delamination is practically suppressed. It is thought that interlaminar stresses and fiber breakage induce delamination [10,11]. Choi's research [12,13,14] reported that low velocity impact events generated matrix cracks, which lead to delamination damage. This paper presents results of experimental studies on the effects of different punch mass and energies for the impacts performed.

2. Experimental

2.1. Test materials

Material 1: The Type-B quartz fiber/modified cyanate ester composite material laminate is prepared by AVIC Research Institute for Special Structures of Aeronautical Composites; structure [(+45/-45)/(0/90)]s, thickness of the single-layer board of 0.2mm, resin content 38%, and the size of the specimen 150×100×4.0mm.

Material 2: The NOMEX paper honeycomb sandwich panel is made of upper and lower composite material panels and the honeycomb core in the middle. The panel material is made of the B-type quartz fiber/modified cyanate ester composite material. There are 4 layers in the upper and the lower panels respectively, each of which is 0.2mm thick; the honeycomb core is of a regular hexagonal NOMEX paper honeycomb with nominal density of 80 kg/m³, hole size of 2mm, wall thickness of 0.05mm and height of 10mm; and the overall layering sequence of the sandwich panel is [0]s/honeycomb/[0]s, and the size of the specimen is 150×100mm.

2.2. Test scheme

The low-speed impact test is carried out according to ASTM D7136. The drop hammer impact test machine (equipment model ZCJ9302) is manufactured by MTS Industrial Systems (China) Co., Ltd. The test equipment includes the main frame, the transmission system, the secondary impact prevention device, the hammer, impact head, and supporting fixture, etc. The impact testing machine and specimen fixture are shown in Fig.1(a) and 1(b) respectively.

(a) Drop hammer impact testing machine     (b) Specimen fixture
Fig.1 Low-speed Impact Test Device
Two sets of experiments: 1. Set the punch mass unchanged, and change the impact energy by setting different punch speeds; 2. Change the combination of impact energy and different punch masses to perform the test with constant impact energy. The test schemes are shown in Table 1 and Table 2. The above two test schemes are applied to the impact tests on type-B quartz fiber composite material laminates and NOMEX paper honeycomb sandwich panels to analyze the impact on the impact properties of the two composite materials under the two schemes.

| specimen No. | Punch mass (kg) | Punch speed (m/s) | Height of drop hammer (m) | Impact energy (J) |
|-------------|-----------------|-------------------|---------------------------|-------------------|
| 1           | 5.5             | 4.2               | 0.976                     | 52                |
| 2           | 5.5             | 5.4               | 1.519                     | 82                |
| 3           | 5.5             | 6.2               | 1.971                     | 106               |

| specimen No. | Punch mass (kg) | Punch speed (m/s) | Height of drop hammer (m) | Impact energy (J) |
|-------------|-----------------|-------------------|---------------------------|-------------------|
| 1           | 5.5             | 5.2               | 1.409                     | 75                |
| 2           | 7.5             | 4.5               | 1.035                     | 75                |
| 3           | 10.5            | 3.8               | 0.738                     | 75                |

3. Analysis and Discussion on Test Results

3.1. Shock response analysis

3.1.1. Type-B quartz fiber/modified cyanate ester composite material laminate
According to test schemes 1 and 2, the time-load curves of laminates under six different test conditions are obtained, as shown in Fig.2 and Fig.3, respectively. It can be seen from the curve that according to test scheme 1, when with constant punch mass and the impact energy is 52J, 82J, and 106J, the maximum impact load is 12274N, 15517N, and 15796N, respectively; with the increase of the impact energy, the curve jitter amplitude is getting more and more severe, when the impact energy reaches 106 J, there is a sudden drop of load, indicating an initial delamination damage occurred at this moment, as shown in Fig.2. According to scheme 2: When the impact energy does not change to 75 J, and the punch masses are 5.5kg, 7.5kg and 10.5kg, the maximum impact loads are 14771N, 14918N and 15534N respectively, and the change of curve trend is roughly the same, as shown in Fig.3.
Fig.3 Time-load Curve of Type-B Quartz Fiber/Modified Cyanate Ester Laminate (Scheme 2)

3.1.2. NOMEX paper honeycomb sandwich panel

According to test schemes 1 and 2, the time-load curves of honeycomb sandwich panel under six different test conditions are obtained, as shown in Fig.4 and Fig.5, respectively. From Fig.4(a) and Fig.5(a), it can be seen that the time-load curve shows an upward trend and disappears near the maximum load with only one peak captured, and the corresponding limit peak loads of the upper panel and the honeycomb core are 4684N and 4817N respectively.

Under other test conditions, the time-load curve has two peak loads, as shown in Fig.4(b), 4(c), Fig.5(b), 5(c), the first peak load indicates the moment of penetration through the upper panel, and the appearance of the second peak load represents the moment of penetration of the lower panel. According to test scheme 1, the load values corresponding to the first peak of the time-load curve under impact energy 82 J and 106 J are 4612 N and 4986 N, respectively, and the second peak load is 4722N and 5431N; in scheme 2, when the punch masses are 7.5kg and 10.5kg, the corresponding first peak loads in the curve are 4638 N and 4907 N, respectively, and the second peak loads are 5036N and 5465N. It is found that the second peak load is always greater than the first peak load because the penetration of the upper panel absorbs the energy of the punch and slows down the speed of punching, resulting in a smaller impedance load on the upper panel than the lower panel.
Fig.4 Time-load Curve of NOMEX Paper Honeycomb Sandwich Panel (Scheme 1)

Fig.5 Time-load Curve of NOMEX Paper Honeycomb Sandwich Panel (Scheme 2)
3.2. Impact damage analysis

The damage degrees caused to the type-B quartz fiber/modified cyanate ester laminate as per test schemes 1 and 2 are shown in Fig. 6 and Fig. 7 respectively. It can be seen that the impact surface of the laminate (front side, the same below) has obvious pits, the impact front side damage is rhombic, and substrate cracking exists near the pits; while the reverse side of the laminate (reverse side, the same below) has obviously visible fiber breakage and substrate cracking; and as the impact energy increases, the damage becomes more serious.

![Fig. 6 Impact Damage of Type-B Quartz Fiber/Modified Cyanate Ester Laminate (Scheme 1)]

(a) 52J impact front side  
(b) 82J impact front side  
(c) 106J impact front side  
(d) 52J impact reverse side  
(e) 82J impact reverse side  
(f) 106J impact reverse side

![Fig. 7 Impact Damage of Type-B Quartz Fiber/Modified Cyanate Ester Laminate (Scheme 2)]

(a) 5.5kg impact front side  
(b) 7.5kg impact front side  
(c) 10.5kg impact front side  
(d) 5.5kg impact reverse side  
(e) 7.5kg impact reverse side  
(f) 10.5kg impact reverse side
The damage degrees of the NOMEX paper honeycomb sandwich panel as per test schemes 1 and 2 are shown in Fig.8 and Fig.9 respectively. It can be seen that the upper panel of the honeycomb sandwich panel is penetrated according to the two test schemes; the impact area on the front side of the specimen also has diamond-shaped damage, but the size of the crack near the pit is smaller than that of the quartz fiber. With the impact energy of 82J and 106J, the lower panels of the NOMEX paper honeycomb sandwich panel are also penetrated; and in the test scheme 2, the lower panels of the honeycomb sandwich panel under the impact of 7.5kg and 10.5kg punch masses are also penetrated.

![Fig.8 Impact Damage of NOMEX Paper Honeycomb Sandwich Panel (Scheme 1)](image1)

![Fig.9 Impact Damage of NOMEX Paper Honeycomb Sandwich Panel (Scheme 2)](image2)
To further examine the damage to the specimen near the impact damage area, computer tomography (CT) is used for specimen inspection. The MG452 CT inspection system manufactured by Germany YXLON is used for non-invasive analysis on the specimen. The equipment is characterized with density resolution $\leq 0.3\%$, spatial resolution $\geq 30$ Lp/cm, and defect detection accuracy of 0.1mm. Damaged specimen is placed on a horizontal platform to collect and process the three-dimensional scanned image of the damaged laminate at the center line of the impact area.

The test scheme 1 is analyzed to understand the impact on the damage of the type-B quartz fiber laminate with different impact energies; the CT inspection image is shown in Fig.10. It can be seen from the Figure that the damage degree of the laminate increases with the increase of impact energy, and penetration is also formed. It can be seen from Fig.10(a) that under the condition of impact energy of 52J, the specimen is not fully penetrated, but local delamination occurs in the impact area. Delamination is a primary type of damage, accompanied by a small range of fiber breakage. It can be seen from Fig.10(b) and 10(c) that when the impact energy is 82J and 106J, the specimen will have a large area of substrate cracking and fiber fracture with the range of damage expanding along with the increase of impact energy.

![Fig.10 CT inspection image of Type-B Quartz Fiber/Modified Cyanate Ester Laminate (Scheme 1)](image)

The test scheme 2 is analyzed to understand the punch mass impact on the damage of the composite material laminate under constant energy. The CT inspection image is shown in Fig.11. It can be seen from this Figure that when the impact energy is constant, the damage degree of the laminate increases with the increase of the punch mass. Regarding the impact test with a punch mass of 5.5kg, two failures of substrate cracking and fiber fracture occur; for impacts with heavier punch masses of 7.5kg and 10.5kg, as the punch mass increases, the damaged area of fiber in the impact zone is enlarged. As shown in Fig.11(c), the heaviest punch mass of 10.5kg, the greatest damage is caused with a larger range of fiber breakage produced in the impact area.

![Fig.11 CT inspection image of Type-B Quartz Fiber/Modified Cyanate Ester Laminate (Scheme 2)](image)
Observe the damage of the NOMEX paper honeycomb sandwich panel. The CT inspection image of Test scheme 1 is shown in Fig.12. It can be seen from Fig.12(a) that when the impact energy is 52J, the specimen is not completely penetrated, and the CT scan image shows that only the upper panel of the sandwich panel is penetrated; it can be seen from Fig.12(b) and 12(c) that when the impact energy is 82J and 106J, the specimen is penetrated completely. The damage covers panel fiber fracture and honeycomb core extrusion and fracture, and the damage area is enlarged from the impact center area to the surroundings.

![CT inspection image of NOMEX Paper Honeycomb Sandwich Panel (Scheme 1)](image)

The CT inspection image of Test scheme 2 is shown in Fig.13. The punch mass impact on the damage of honeycomb sandwich panel under constant energy impact is analyzed. It can be seen from Fig.13(a) that when the punch mass is 5.5kg, the upper panel of the specimen is penetrated; from Fig.13(b) and 13(c), it can be observed that for the punch masses of 5.5kg and 7.5kg, the damages are the panel fiber fracture and core extrusion fracture in the impact zone and outward expansion of honeycomb core inside the panel from the impact center area. It can be seen that at a constant impact energy level, with the punch mass increases, the damage to the sandwich panel gets aggravated.

![CT inspection image of NOMEX Paper Honeycomb Sandwich Panel (Scheme 2)](image)

4. Conclusion
(1) When the impact energy is 82J and 106J and the punch masses are 7.54kg and 10.5kg, two peak load moments will be generated when punching on NOMEX paper honeycomb sandwich panel, corresponding to the moments when both upper and lower panels are penetrated. The load on the
lower panel is greater than that of the upper panel because when the punch decelerates due to the resistance of the upper panel, the impact resistance of the lower panel will increase.

(2) For the type-B quartz fiber/modified cyanate ester laminate, with impact energy of 52J, delamination is the primary failure; with impact energies of 82J and 106J, the delamination further expands, resulting in substrate cracking and fiber fracture; for the NOMEX paper honeycomb sandwich panel, as the impact energy increases, the damage to the honeycomb core inside the sandwich panel will expand outwards along the impact center area.

(3) It is found that the type-B quartz fiber/modified cyanate ester laminate has three different types of failure: substrate cracking, fiber fracture and delamination. For NOMEX paper honeycomb sandwich panels, panel fiber fracture and honeycomb core extrusion are observed. When the punch mass is constant, the greater the impact energy is, the more serious the damage is, and when the impact energy is constant, the greater the punch mass is, the more serious the damage is.

(4) Research on impact damage of a quartz fiber composite and an NOMEX paper honeycomb sandwich panel composite material is a valued and challenging project, and research on impact damage and damage influence factors of the composite materials is beneficial to improving the efficiency of structural design, improving the applicability of composite material structures and fully exerting the advantages of the composite materials. This text has made a lot of research work, but still has a lot of incomplete contents needing to continue to be improved, and related deep research on the influences of punch materials, punch shapes, etc. on impact damage of the composite materials will be carried out in the follow-up process.

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