The effect of different structural designs on impact resistance to carbon fiber foam sandwich structures

Research Article

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The development of the composite materials in the past decades has made the composite materials more and more widely used in various engineering fields. The mechanical properties of the composite materials are gradually improved, especially the impact resistance. In this article, the damage of carbon fiber foam sandwich structure (material grade: W-3021FF/H60) under different sandwich thicknesses and impact energies was studied. Ultrasonic C-scan was used to measure the depth and area of impact damage area. Finally, the impact energy and foam core thickness on impact damage was analyzed by test results. The results show that the impact damage depth and area of foam sandwich structure were positively related to the impact energy, and with the increase in the impact energy, the growth rate of damage depth and damage area changes; the greater the thickness of the foam core was, the stronger the span-direction guiding energy for impact energy, the larger the damage area and the smaller the damage depth. Under the same energy, the more the layers of carbon fiber cloth with the foam sandwich structure, the larger the impact damage depth and the smaller the impact damage area. The proportion of ±45° ply in the foam sandwich structure can improve its impact resistance.

Keywords: composite, impact, ultrasonic C-scan, mechanical properties, sandwich structure

1 Introduction

With the continuous development of composite technology and its advantages of designability, high specific strength, high specific stiffness, fatigue resistance, corrosion resistance, etc., the demand for engineering application in various fields is getting higher and higher, especially in the aviation field (1–3). Compared with the ordinary composite laminates, the carbon fiber foam sandwich structure generally uses light material, so the stiffness and structural stability of the material can be greatly improved under the same quality (4,5). Therefore, carbon fiber foam sandwich composite materials are widely used in the production of general aircraft. In practical application, facing the complex working environment, in order to ensure the safety and reliability of the aircraft in flight, there are strict requirements on the mechanical properties of the carbon fiber composites, especially the damage caused by dynamic loads such as impact and vibration throughout the whole flight process from take-off, cruise to landing. Hence, many studies have been carried out on the impact damage of composite materials. Zhang et al. (6) studied the impact protection performance of different sandwich structures, and analyzed the influence of thickness, matrix content, impact energy, and other parameters. Dogan (7) has studied the investigation of the effects of different core types on the low velocity impact, three-point bending, and out-of-plane compression loading performance of sandwich composites. Three core materials were selected: Balsa wood, PVC foam, and Ayous wood. Anderson and Madenci (8) impacted the plates with different impact energy and summarized the relationship between plate damage and contact force rule. The impact test of different layers of skin, different thicknesses, and different densities of the foam sandwich plates was carried out. The test result showed that the damage degree of the foam core was only related to the pit depth of the upper skins, the increase in the density of the foam core and the
thickness of the skin could increase the damage energy of the sandwich plates. Crupi et al. (9–11) prepared various types of composite sandwich structures and carried out a series of low-speed impact tests on sandwich specimens by using a falling hammer tester, and used the thermal imager and three-dimensional computer tomography system to conduct in-depth research on the damage mechanism of the sandwich structures.

The factors affecting the bearing capacity of the sandwich structures have not been systematically studied in the above literature (12–18). In this article, the carbon fiber foam sandwich structures with different thicknesses and different laying sequences were prepared, and the impact tests were carried out with different impact energies.

| Sample | Foam thickness (mm) | Laying direction |
|--------|---------------------|-----------------|
| A01    | 2                   | [±45/(core)/±45]|
| B01    | 4                   | [±45/(core)/±45]|
| C01    | 6                   | [±45/(core)/±45]|
| B02    | 4                   | [±45/(0.90)/(core)/±45]|
| B03    | 4                   | [±45/(0.90)(core)/
|        |                     | (0.90)/±45]       |
| B04    | 4                   | [±45/±45/(core)/±45/±45] |

After the test, the impact damage areas were analyzed by ultrasonic C-scan. Finally, the influence of impact energy, thickness of foam, and laying sequence of the carbon fiber on the impact damage of foam sandwich structures was studied. The test and analysis results have certain reference significance for engineering designers to carry out relevant structural design.

2 Experimental methods

2.1 Preparation of specimens

The specimens in this test are carbon fiber sandwich structure composed of composite panels and sandwich materials. The brand of the carbon fiber woven cloth of the specimen is W-3021FF (manufacturer: Weihai Guangwei Composite Material Co., Ltd.), the foam brand is H60 (manufacturer: Kunshan Daibo New Material Co., Ltd.). The specimens were made by hand lay-up vacuum bag pressing process, the foam thickness and laying sequence of each specimen are shown in Table 1. The formed specimens were cut into 150 mm × 100 mm standard specimens (Figure 1) by water...
cutting machine (LTJ1613, Shanghai Shimai Technology Co., Ltd.) for subsequent mechanical tests and inspection.

2.2 Experimental procedure

ASTM D7136 Standard Test was used for the drop hammer impact test, and impact damage was introduced by drop hammer method. The support window size of the specimen was 125 mm × 75 mm, the impactor was a steel hemispherical punch with a diameter of 16 mm, the weight of the hammer was 5.5 kg, the impact energy was 6.67 J·mm⁻¹, and the test environment temperature/humidity was 25°C/40% RH. Before the test, the specimens were visually inspected to ensure that there was no initial damage on the surface of the specimens. The specimens were clamped by the chuck on the edge, and the impact energy could reach 10.58, 21.17, 31.75, and 42.34 J by manually adjusting the height of the hammer head. Each group of test adopts multiple specimens to ensure the accuracy of test results. Ultrasonic C-scan (SAM300 Basic, PVA TePla company, Germany) was used to characterize the damage characteristics after impact, as shown in Figure 2.

3 Results and discussion

3.1 Influence of impact energy on impact damage

Figure 3 shows the typical damage of specimen. Table 2 shows the test results of the depth of impact damage area of each specimen under the impact energy of 10.58, 21.17, 31.75, and 42.34 J. When the impact energy was 42.34 J, the impact damage depth of three groups of specimens reaches the maximum value, which was 2.53, 2.11, and 1.91 mm. Table 3 shows the test results of impact damage area of each specimen under the impact energy of 10.58, 21.17, 31.75, and 42.34 J, when the impact energy was 42.34 J, the area diameter of impact damage area of three groups of specimens reached the maximum value, which was 10,700, 13,800, and 15,804 μm. It can be seen from Tables 2 and 3 that the change rules of depth and area of impact damage area of each group under different impact energy were the same. With the increase in impact energy, the depth and area of impact damage area of specimens gradually increase.

Figure 4 shows the ultrasonic C-scan result of impact damage depth of A01 after impact. Figure 5 shows the ultrasonic C-scan result of impact damage area of A01 of each specimen under the impact energy of 10.58, 21.17, 31.75, and 42.34 J.
after impact. It can be seen from Figure 4 that the impact damage depth was 1.26, 1.50, 2.00, and 2.69 mm when the impact energy was 42.34 J, damage depth was the largest, and damage depth increases with the increase in the impact energy. It can be seen from Figure 5 that the area diameter of impact damage area was 4,900, 7,400, 8,501, and 10,700 μm when the impact energy was 42.34 J, damage area was the largest, and damage area increases with the increase in the impact energy.

3.2 Influence of foam thickness on impact damage

In this experiment, A01, B01, and C01 adopted the laying sequence of [±45/(core)/±45], and the foam thickness of A01, B01, and C01 was 2, 4, and 6 mm, respectively. Figure 6 shows the test results of impact damage depth of three kinds of specimens under different impact energies, the impact damage depth of A01 was the maximum for three kinds of specimens under four impact energies, and the impact damage area of three kinds of specimens shows an upward trend under each impact energy. It can be seen from Figure 6 that as the thickness of the foam increases, the pit depth of the specimen after impact decreases gradually, but the area diameter of damage area increases gradually, and there was no linear correspondence between the two sets of data. Under the same impact energy, the damage depth of A01 was the largest, followed by B01, and the damage depth of C01 was the smallest. When impacted by high energy, the damage depth of the former was 1.5 times that of the latter. The rule of damage area was different from that of damage depth. When the test piece have been at the low impact energy of 10.58 J, the damage area of C01 was the largest, followed by B01, and A01 had the smallest damage area. When the impact energy increases, the increase rate of damage area of C01 increases gradually. The reason was that when the thickness of the specimen was smaller, the impact energy extends along the thickness direction, and causes greater damage to the thickness direction; when the thickness of the specimen was larger, the impact energy gradually diffuses and was absorbed along the contact surface, resulting in larger damage area, but the penetration of impact energy into the thickness direction was weakened, and the damage depth decreases. When the specimen was impacted, the upper and lower panels bear the tensile and compressive stress in the thickness direction during the transmission.
of impact energy. Compared with the carbon fiber panel, the stronger energy absorption performance of the foam sandwich layer enables the energy to be transmitted in the spanwise direction. The foam sandwich layer mainly bears the shear stress in the spanwise direction to disperse the stress and improve the impact resistance of the whole structure.

3.3 Influence of laying sequence on impact damage

Figure 7 shows the influence of impact energy on the impact damage depth and area of specimens with different laying sequences. It can be seen from Figure 7a that under the same impact energy, the damage depth of B02 and B03 were larger, which was 3.04 and 3.72 mm at 21.17 J, and the damage depth of B01 and B04 were smaller, 1.51 and 1.57 mm at 21.17 J, respectively. The change rule of damage area was the same as damage depth. The impact damage area of B02 was the largest, which reached 10,800 μm at 10.58 J, the impact damage area of B04 and B05 were smaller, 5,500 and 4,000 μm at 10.58 J. With the increase in the impact energy, the increase rate of damage area of B01 increases gradually, which reached 138% higher than that at 10.58 J. Under the impact energy of 31.75 and 42.34 J, the damage area of B04 was the smallest, which was 11,300 and 6,700 μm, respectively. The damage area of B02 was the largest, which was 16,400 and 16,801 μm.

Under the same impact energy, the damage of B04 was smaller, and the damage behavior of two kinds of laying sequence of specimens would not be obvious when the impact energy did not exceed 21.71 J. When the impact energy reached 31.75 J, the load that B01 can bear decreases obviously, while B04 had greater bearing capacity and better impact resistance. The test results showed that increasing the proportion of ±45° ply can improve the impact resistance of foam sandwich
structure. Under the condition of different layers of carbon fiber woven cloth, the comparison between B01, B03, and B04 showed that under the same impact energy the impact damage depth of B01 was smaller, and it was still not penetrated at 42.34 J, but the impact damage area of B01 was the largest among them, which was 14,800 μm. The test results showed that under the same energy, more layers of carbon fiber cloth are arranged, the greater the impact damage depth and smaller the damage area. Because the warp and weft fibers in each layer were interwoven with each other, and there were interwoven points, so the anti-delamination ability increases with the increase in the fiber arrangement direction. When the impact energy increased to a certain extent, although the impact damage depth of B04 and B05 were larger, and the upper panel was almost penetrated, because the fibers were interwoven with each other, the crack propagation to a larger area was effectively inhibited. Therefore, the impact energy was mainly concentrated near the impact point, leading to serious damage in the local area, causing a large number of fiber fractures, partial delamination cracks, and compression failure of the sandwich. The scope of damage caused by the impact was smaller, so the damage area was much smaller than other groups. On the contrary, B01 lacks more fiber arrangement directions, so the damage form was mainly delamination, and the fiber fracture along the thickness direction was less (17,18).

Comparing B02 with B01, B03, and B04, the damage area of symmetrical ply was smaller and more regular, and the damage area was mainly concentrated near the impact point. Under higher impact energy, the damage areas of B01, B03, and B04 are smaller than that of B02, asymmetric laying sequence will greatly reduce the impact resistance. Because the anisotropy of thermal expansion coefficient of material caused the mismatch of shrinkage between the layers when the temperature of the asymmetric layer drops to room temperature after high temperature curing, thermal stress was generated.

Figure 6: Impact damage depth (a) and area (b) of the same laminate under different impact energies.

Figure 7: Impact damage depth (a) and area (b) of the same thickness under different impact energies.
and maintained between the layers. Under the action of thermal stress, the square sandwich panel was deformed into an arch shape, and the impact damage area of the specimen was larger.

4 Conclusion

(1) Under the impact of low energy, the crushing damage of foam sandwich structure was the main failure mode, and the impact damage depth and damage area increase with the increase in the impact energy.

(2) The thicker the foam sandwich was, the stronger the ability to guide the spanwise extension of impact energy, and the larger the impact damage area, the smaller the damage depth.

(3) Under the condition of the same layers of carbon fiber woven cloth, increasing the proportion of ±45° ply can improve the impact resistance of the foam sandwich structure.

(4) The asymmetric laying sequence of foam sandwich structure will greatly reduce the impact resistance.

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