Analysis of Surface Compressive Strength of Optical Fiber Composites Under Low Velocity Impact Damage Based on Big Data

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Abstract. The traditional method for analyzing the compressive strength of surface under low-speed impact damage of fiber-optic composites uses the aperture equivalent method to calculate the Compressive strength after impact (CAI) value with large error and insufficient accuracy. Aiming at the above problems, a method for calculating the CAI value of the fiber composite under low velocity impact damage by the damage accumulation method is proposed. Firstly, the materials and related equipment used in the experiment were selected, and then the initial damage state was determined by low-speed impact test. The failure state of the fiber composite under different compression loads was analyzed by compression test. Finally, the finite element model was established and the compressive strength was analyzed. The results show that compared with the open equivalent method, the calculation error of CAI value is reduced by 6.48%, the accuracy is improved, and the purpose of accurately analyzing the compressive strength is basically achieved.

Keywords: Optical fiber composites · Low speed impact · Impact damage · Compressive strength · Damage accumulation method · Finite element

1 Introduction

The history of human use of composite materials has been long, the adobe bricks that have been used since ancient times consist of straw or straw-reinforced clay. The reinforced concrete that has been used for more than 100 years is compounded by adding reinforcing steel to the concrete. In the middle of the 20th century, due to the needs of the aviation industry, glass fiber reinforced plastics have been developed, therefore, the name composite material appeared [1]. Composite materials are a large class of new materials. Its appearance has made the development of materials science rapid progress. Composite materials have high stiffness, high strength, light weight, and have anti-fatigue, high temperature, vibration reduction, many advantages such as designability, in recent decades, is widely used in aviation, aerospace, energy, construction, machinery, transportation, information, biological and other engineering fields and departments [2]. In contrast, fiber-optic composites refer to embedding optical fibers in composites. a new type of material that can be shared with them. With the addition of fiber, the strength of composites will not only decrease, instead, there is a certain degree of improvement. has been widely used in many fields, especially in

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aerospace and other military fields [3]. However, after the material is subjected to low speed impact, it is easy to generate a large number of matrix cracks and large-area delaminations inside. This hidden damage is very dangerous to the carrying structure [4]. It can seriously degrade the mechanical properties of laminated structures. Weaken the compressive strength of the structure, as a result, the carrying capacity is greatly reduced. potential threat to structural safety. Therefore, it is important to study the surface compressive strength (CAI) of optical fiber composites under low velocity impact damage using large data technology [5]. CAI is the maximum compressive stress that a surface is subjected to in a compression test until the surface of the specimen breaks (brittle material) or yields (non-brittle material). At present, there are mainly four methods for analyzing the compressive strength of optical fiber composites: softening inclusion method, sub-layer buckling method, opening equivalent method and damage accumulation method. The damage accumulation method is the most accurate method for calculating the CAI value. Based on the large data technology of this method, the surface compressive strength of fiber reinforced composite laminates after low velocity impact is calculated by establishing finite element model. This time through a specific experiment to analyze the compressive strength of optical fiber composites. First select the materials and related equipment used in the experiment, then, a low-speed impact was applied to the fiber composite laminate using an Instron 9250 HV drop hammer impact tester. then use the impact result (damage state) as the initial damage, finally, the compressive strength analysis of the optical fiber composite laminates with impact damage was performed by the damage accumulation method. To verify the accuracy of the CAI calculations by the damage accumulation method, a set of comparative experiments was performed together with the opening equivalent method. The results show: the damage accumulation method is used to calculate the surface compressive strength of the fiber composite material under low-speed impact damage. Compared with the opening equivalent method, the CAI calculation error is reduced by 6.48% increased accuracy. This proves that this method can analyze the compressive strength more effectively, helps improve the safety of fiber optic composites.

2 Evaluation Requirements and Research Status of Impact Resistance of Composite Materials Systems

With the structural design from static strength to structural integrity including static strength, stiffness, durability and damage tolerance, the concepts of material allowance and structural design allowance must be strictly distinguished. With the structural design from static strength to structural integrity including static strength, stiffness, durability and damage tolerance, the concepts of material allowance and structural design allowance must be strictly distinguished. Design allowables are: test results of specimens, components (including typical structural components), and the typical values of the materials allowed to represent the typical characteristics of the structure, according to the requirements of the specific project, and Design limit values determined based on design and use experience. It is pointed out that the allowable value of materials is a characterization of the mechanical properties of the material system, mainly used for material selection, acceptance and equivalence assessment. The design department shall, depending on the integrity requirements of the specific structure (usually including static strength, stiffness, durability, and damage tolerance), samples and components (including typical structural members) that have existing material allowable values and representative typical features of the structure. Based on the test results and design and experience, it is sometimes necessary to specify and verify the allowable values of the structural design based on the results of the assembly test to ensure that the structure designed according to the design allowable values meets its structural integrity requirements.

The impact resistance of the composite system was analyzed using the allowable values. Since the 1990s, a large number of studies have pointed out that the ability of composite systems to resist impact damage (damage impedance) and damage tolerance of composite systems are two different physical concepts, and damage resistance refers to the ability to resist impact events (Or the damage size caused by the impact force), and the damage tolerance is the effect of a certain damage state on the structural performance (or the intensity value corresponding to a given damage size). It is pointed out that a more complete understanding of the performance of the toughening system should be studied both the damage resistance and the damage tolerance. The above research results have been reflected in the latest US military manual, which clearly states that the damage characterization includes two elements, namely the impedance of the material to the damage caused by the impact (damage impedance), and the material or structure is safe after being damaged. Sexual ability (damage tolerance). But for a long time this concept has only stayed in the minds of a few researchers, and has not been accepted by the vast number of materials and engineering people. The author's experimental data also shows that the damage resistance of the composite depends not only on the toughness of the resin, but also on the elongation at break of the fiber and the interface between the resin and the fiber. The combination of the traditional brittle resin and different fibers may have different damage. Impedance composite system. The study of damage resistance in the United States began in the early 1990s. A large number of studies focused on the equivalence of low-speed drop hammer impact and quasi-static impact. The results show that the current low-speed drop hammer impact method can be simulated with quasi-static. The damage caused by the drop hammer impact and static indentation (QSI) methods with the same impact force is basically the same. At the same time, a large number of parameter impact studies were conducted. On this basis, ASTM released standard test methods for measuring damage resistance using quasi-static indentation (QSI) and drop impact test methods in 1998 and 2005, respectively.

3 Experimental Materials and Equipment

3.1 Experimental Materials

The optical fiber composite used for the test piece is CCF300/5228A, the fiber volume fraction in the material is approximately 60%. The laminate (test piece) made of fiber optic composite material has a thickness of 0.15 mm, a length of 825 mm and a width of 600 mm. The profile of the ribs is “H” type, the number of ribs is 4, the rib spacing is 150 mm. the ribs and the skin are formed by a co-curing process. Both ends of the test piece were glued to facilitate the compression test. The sequence of the test specimens is: [45/—45/0/—45/45/0/—45/45/90/45/—45/45/0] [6].

3.2 Experimental Equipment

The tests were conducted by the Instron 9250 HV drop hammer impact tester, the test process adopts the locking system. The secondary impact of the falling hammer is prevented from damaging the specimen. The impact energy is respectively 30 J and 50 J.

The impact test specimens were tested for post-impact compression strength on an INSTRON (3382) electronic drawing machine, continuous loading to specimen failure at a loading rate of 1.25 mm/min.

4 Low Speed Impact Test

According to the damage status of the material, impact is divided into high-speed impact and low-speed impact. When the impact causes penetrative damage to the material structure, that is high-speed impact; On the contrary, failure to cause penetration damage to the structure is a low velocity impact [7]. At low speeds, the experience time is very short, there will be no obvious damage to the laminate surface. therefore, it is not necessary to consider the correlation between creep effect and strain rate, however, matrix cracking and delamination damage occurred inside the laminate. However, matrix cracking and delamination damage occurred inside the laminate, the overall damage to the structure is potentially harmful [8].

Before the trial began, visually inspect all test pieces first, and sampling for non-destructive testing of ultrasound scans, make sure that there is no initial internal damage to the test piece. The test piece is placed on the support bracket during impact. In addition, it is also necessary to take another test piece for impact energy testing, determine the required impact energy. Due to the largest proportion of the skin between the ribs in the stiffened plate structure, according to the actual situation of the structure studied in the paper, a pit depth of about 1 mm will be generated at the impact position O as a criterion for selecting the impact energy, the impact is performed on the upper surface (skin surface). Through energy exploration tests, the final determination of impact energy is 50 J. then use 50 J energy to impact test the stiffened plate’s impact position O, the impact pit depth and damage area were measured immediately after impact completion [9].

5 Compression Test After Impact

When performing compression tests, the fiber-optic composite laminate used shall retain the damage and deformation after the impact test is completed, instead of modeling on the basis of the assumption of the impact of human injury damage simulation [10].

Refer to ASTM D7137/D7137M-12 standard, compression test of specimens with low speed impact damage, the effect of impact damage at different locations on the load-carrying capacity of laminate specimens was investigated. The upper and lower ends of the test piece are fixed by single row bolts on both sides of the fixture. Before the test, a strain gauge is attached to the symmetry between the ribs of the test piece and the ribs. After the trial began, the compressive load is applied step by step with a load gradient of 5kN/s, after each load is loaded, the strain value corresponding to each strain measurement point is recorded by a static strain gauge, after the test, the load-strain curve is used to determine the structural instability load [6]. Record the phenomena that occurred during the test and the ultimate damage load and damage patterns.

6 Compression Strength Analysis

6.1 Establishing a Finite Element Analysis Model

In the low-speed impact test of optical fiber composites, the damage area mainly exists in the impacted area, the damage pattern is mainly matrix cracking, basic fiber shear and fiber breakage. According to experimental phenomena, observe the damage pattern of the material under different compression energy and measure the area of the corresponding damage area. According to the damage mode, select the above corresponding degradation mode. The stiffness of the damaged area is degraded, damage-free areas are assigned, this establishes a finite element analysis model of fiber optic composites.

The experimental finite element analysis model for the damage area of fiber composites under 50 kN compressive loads was measured, as shown in Fig. 1.

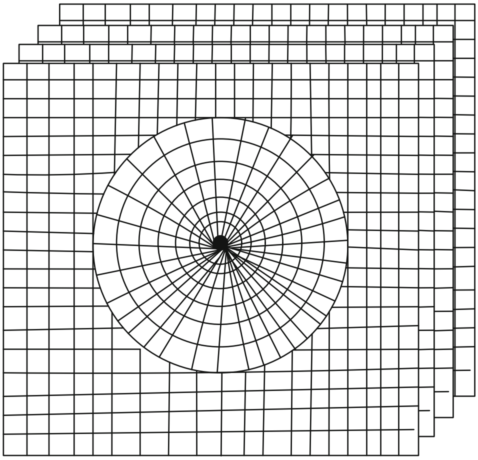

Fig. 1. Finite element analysis model of damage zone of optical fiber composite under 50 kN compressive load

When the compressive load is 50 kN, the test piece was subject to small cracks on the impact panel, there is a certain diverging phenomenon around the crack, however, the divergence area is not large. Basically confined to the affected area, the main type of damage is the cracking of the substrate, no fiber breakage occurred. A small amount of core material is accompanied by matrix cracking. there is no damage to the panel.

Finite element analysis model of damage zone of optical fiber composite under 100 kN compression load, as shown in Fig. 2.

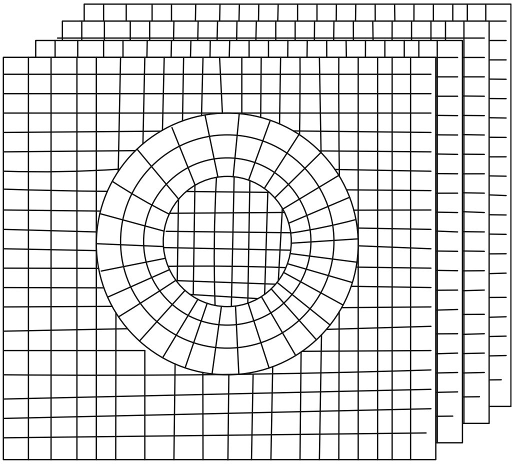

Fig. 2. Finite element analysis model of damage region of optical fiber composite under 100 kN compressive load

The damage caused by the impact of 100 kN compressive load and the 50 kN compressive load on the fiber optic composite material is different. Under the 0 kN compressive load, the surface of the fiber composite material is not broken, there is a slight depression in the damaged area. There is obvious damage on the lower surface. the main damage modes of the upper and lower surfaces are the matrix cracking mode. Under the 100 kN compression load, the surface of the optical fiber composite material is broken. The lesion area has a more regular circular shape. There is a significant damage extension in the surrounding area. The extended area is circular, the ring size is about 2 mm, mainly based on matrix cracking. The main body is cracking, there was no obvious damage on the lower surface.

Finite element analysis model of damage region of optical fiber composite under 150 kN compression load, as shown in Fig. 3.

For the effect of 150 kN compression load, the surface of the optical fiber composite is completely broken. the impact damage area is approximately circular, there are obvious damage extensions around. The extended area is circular, the ring size is about 2 mm, the extension range is not much different from the extension range of the

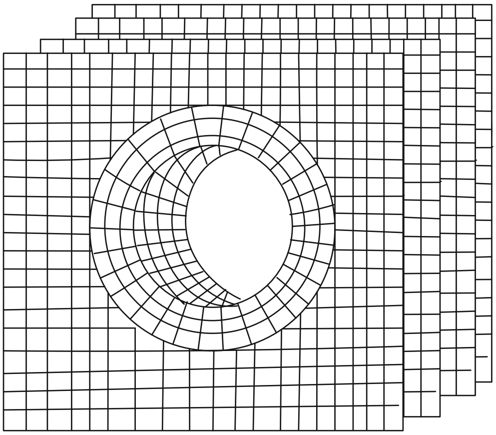

Fig. 3. Finite element analysis model of damage area of optical fiber composite under 150 kN compressive load

damage zone of the specimen under the 100 kN compression loa. The fibers in the impact zone are completely broken. The extended area is mostly matrix cracking damage, there is a small amount of fiber breakage.

6.2 Calculation of Compressive Elastic Modulus

Through the analysis of the compression performance of the finite element model, the stress caused by the displacement of the fiber-influenced area and the fiber-influenced area can be obtained separately, according to the number of implanted fibers. The calculation can obtain the average principal direction (X-axis direction) stress $\bar{\beta}_x$ generated when the entire intact specimen material is subjected to unit strain $\bar{\alpha}_x$. The material compressive elastic modulus T_c is:

$$T_c = \frac{\bar{\alpha}_x}{\bar{\beta}_x} \tag{1}$$

Substituting the calculation result of the finite element part, the elastic modulus of the test piece is shown in Table 1.

Table 1. Specimen elastic modulus.

Compression load (kN)	Compressible elastic simulation (GPa)	Relative change rate (%)
50	129.546	−0.064
100	150.458	−0.027
150	173.416	−0.154

According to the obtained elastic modulus of compression, calculate the compressive strength of fiber composites. Calculated as follows:

$$\wp = -\frac{P}{l \cdot h} \mathrm{T_c} \tag{2}$$

$\wp$ is the compressive strength of an optical fiber composite; P is the compressive load; The width and thickness of the l and h laminates.

6.3 Strength Calculation Results

The structure of optical fiber composites is more complicated, the degree of fiber bending is large, the compressive strength is more affected by the impact energy, therefore, only the compressive strength after impact was investigated. In order to verify the calculation accuracy of the damage accumulation method, optical fiber composites were subjected to relevant experimental studies, the compressive strength test after low-speed impact was performed. The actual and experimental values are shown in Table 2.

Table 2. Damage cumulative method strength calculation results.

Compression load (kN)	Actual value (MPa)	Experimental value (MPa)	Error (%)	Average error (%)
50	78.5	78.5	0	0.25
100	60.8	60.0	0.25	
150	53.2	53.2	0	

To further verify the effectiveness of the damage accumulation method, the opening equivalent method was used to calculate the strength of the fiber composite material in the above test, the calculation results are shown in Table 3.

Table 3. Open equivalent strength calculation results.

Compression load (kN)	Actual value (MPa)	Experimental value (MPa)	Error (%)	Average error (%)
50	78.5	75.0	3.2	6.73%
100	60.8	52.3	8.4	
150	53.2	45.2	8.6	

Comparison between Tables 2 and 3 shows that, the average intensity of the former calculation is 0.25%, the latter's strength calculation error is 6.73%. Compared with the two methods, the cumulative damage method is less than 6.48% and the accuracy has been greatly improved. This proves the effectiveness of the method.

7 Conclusion

With the application of optical fiber composite materials, the low-speed impact problem has attracted more and more attention. The impact of fiber optic composites refers to the manufacture of fiber optic composite structures, during the use and maintenance process, the low speed impact of unexpected objects is inevitable. Causes structural damage and declining bearing capacity. causes visually undetectable internal damage to the material structure, there is no or only slight indentation on the surface of the composite structure, in addition, a large number of matrix cracks and large-area delaminations have been generated within the laminates. This hidden damage is very dangerous to the carrying structure. It can seriously degrade the mechanical properties of laminated structures. Strength can be weakened by 35% to 40%, as a result, the carrying capacity is greatly reduced, there is a potential threat to the overall destruction and failure of the structure. Therefore, it is of great significance to calculate the surface compressive strength (CAI value) of fiber composites under low-speed impact damage. Damage accumulation is the most common and most accurate method of calculation, this method mainly analyzes and calculates the composite strength by establishing a finite element model. Compared with the aperture equivalent method, the accuracy of calculation has been greatly improved, this is of great significance in determining the damage tolerance of the fiber optic composite structure and improving the reliability and optimal design of the composite material.

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