

Development of Fiber Sensors integrated with Aerospace Composites for Structure Health Monitoring

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Abstract. The wide-spread use of composite material in aircraft across the world is expected to create a big need to improve structure health monitoring (SHM). Optical fiber sensors offer more advantages than conventional sensors, such as light weight, small size, immune to electromagnetic interference, easily embedded in composites. Extensive applications have been reported with a few embedded technology details by Boeing and Airbus, etc. In this paper, The methods of improved optical fiber surface-bonded composites by glass cloth and epoxy resin, as well as optical fiber embedded in composites were researched. The installation of fiber and composites, composites assembly pressure adaptability on FBG sensors, influences on structure properties of composite materials due to different fiber diameters and different numbers of optical fibers by the way of microscopic interface analysis and C-scan were studied. The adequate fiber embedded technology was found to obtain the most feasibility of SHM. Light intensity and wavelength of FBG sensor surface-bonded by glass cloth are affected by the structural assembly pressure. It can be seen that diameter of embedded optical fiber equal to the thickness of prepreg monolayer, the fiber embedded next to 0 degree layer, less than five fibers within a 25mm width composite unit have little impact on composite structure. Then, 12 FBG sensors were embedded in a typical aircraft structure, a carbon fiber enhanced stiffened composite plate with length 600 mm and width 600 mm, to detect position and energy of external impact load by a mathematical analysis method, cross correlation algorithm. Finally, suggestions on future study are listed from four aspects, co-forming technology of FBG sensor and composite skin, research on the extraction technology of optical fiber, new flexible wing testing technology and advanced fiber optical sensing technology.

Keywords: fiber sensor; structure health; structure health monitoring; embedded.

1. Introduction

With the wide-spread application of composite materials in the new generation of large aircraft structure, the structural health monitoring technology of composite materials has been brought unprecedented challenges[1-3]. Delamination and disbond easily occur in the interior of carbon fiber composites under impact load due to composite intrinsic anisotropy, while invisible on the surface, which brings great potential safety hazards. The traditional periodic damage inspection methods such as ultrasonic inspection, etc. are mainly manual and slowly, have not yet met the needs of real-time SHM of composite structures. In order to improve efficiency and ensure the safety of the composites, strain and damage should be identified online[4-6].

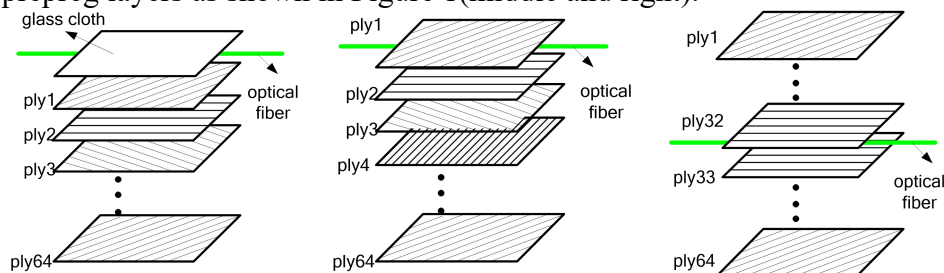
Strain and temperature can be obtained by FBG sensors with many advantages, such as smart structure, simple wiring, high efficiency, long durability, anti-electromagnetic interference. It has a broad application prospect in the development of weapons and equipment. Optical fiber as similar as "hair" can be easily embedded in composite forming an integrated smart structure. Hundreds of measuring points can be realized through one optical fiber, which makes it one of the best choices to realize online SHM of the composites[7-9].

FBG sensors can be surface bonded on or embedded in composite material. Traditional surface bonded method using high molecular adhesive, leaving poor aging performance and non-smooth surface, has a bad effect on assembly and stealth operation. In this paper, combining optical fiber characteristics with aviation composite material forming process, The surface-bonded method is to install optical fiber by fiberglass cloth and epoxy resin on the surface of composite material, which has little influence on structure performance. But composite assembling pressure on FBG sensor

performance should be considered. The embedding method is to install optical fiber during the prepreg stage before autoclave molding process. Influence of embedded fiber on positional accuracy, composite structural integrity and the micro-interface should be researched.

2. Installation of Optical Fiber and Composite Laminate

The surface of carbon fiber composites is usually covered with a 0.2 mm thickness layer of fiberglass cloth in order to reduce the surface splitting during subsequent processing and avoid potential corrosion between carbon fiber and metal. Combined the optical fiber installation with composites molding process, surface bonded method is installing optical fiber inside fiberglass cloth as shown in Figure 1(left), while the embedded method is directly installing optical fiber between two prepreg layers as shown in Figure 1(middle and right).



(left) surface bonding method (middle) embedded method (right) embedded method

Fig. 1 Schematic diagram of installation of optical fiber and composites

The fiberglass cloth with 0.15 mm thickness, orthogonal woven, and epoxy resin, optical fiber with 155 micron diameter, are used in surface bonded method with vacuum curing at room temperature for 24 hours. Embedding method refers to install the optical fiber between two layers of prepreg, be vacuumized, and experience the autoclave molding process at 180 °C. The composite laminates after fiber surface bonded and embedded are shown in the Figure 2.



Fig. 2 Composite laminates after fiber surface bonded and embedded

3. Composites Pressure Adaptability of FBG Sensor

The arrangement of screw holes in the composite panel of a certain type of wing is simulated, with 10mm screw diameter, 50mm longitudinal hole spacing, 26mm transverse hole spacing, and 40Nm as target torque. Two FBG sensors are embedded parallel to each other at the middle position of the screw hole in advance, while one is surface bonded as showed in Figure 3. The surface of the composite material with bonded optical fiber is connected with the aluminum plate through screws. Sensor signal is detected under torque increasing with sequence of screw 1#, screw 2#, screw 3# and screw 4# step by step of 2Nm.

The assembly pressure adaptability test system comprises a composite laminate installed with FBG sensors, demodulation instrument, signal display software and torque wrench with type SATA 21203, measure range of 10 Nm~50 Nm, resolution 0.5 Nm as shown in the Figure 3.

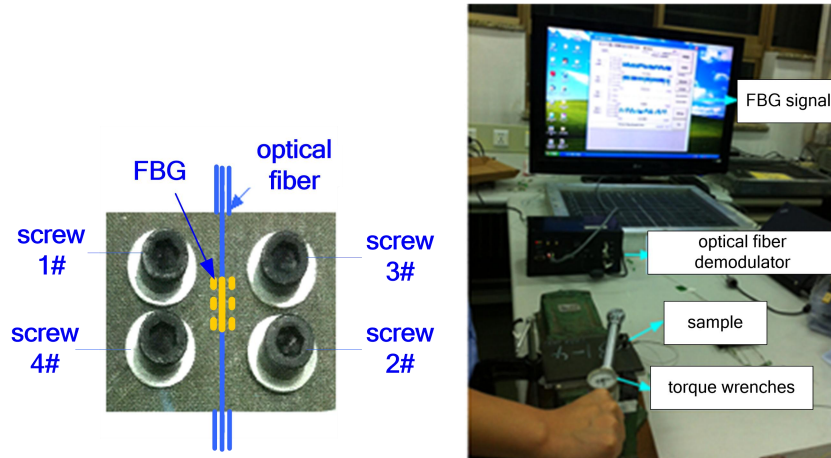


Fig. 3 Fiber installation position (left) and assembly pressure adaptability test system (right)

The peak value of the surface bonded sensor shows a multi-peak phenomenon when the torque reaches 18Nm as shown in Figure 4 (left), while the signals of both embedded sensors are normal. As shown in Figure 4 (right), the signal energy of surface bonded sensor decreases obviously with the increase of screw torque, while embedded sensor changes little, with demodulation instrument Gain in the range of 5-10, Noise Threshold 200. It can be seen that the assembly pressure of screws will have a great influence on surface bonded sensor.

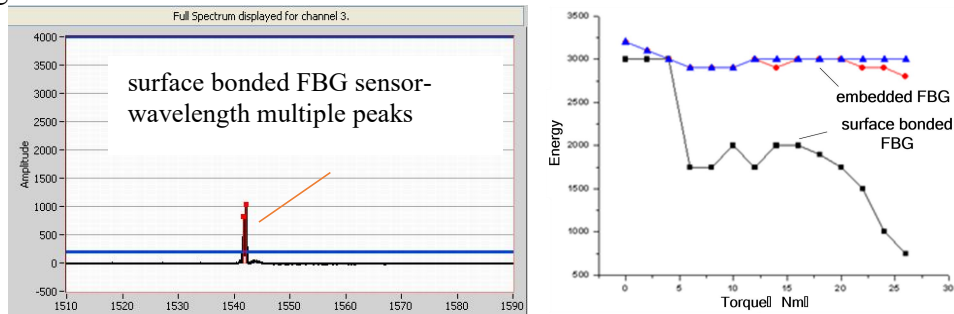


FIG. 4 Multi-peak phenomenon (left) and Change of wavelength with torque (right)

4. Reseach on Optical Fiber Embedded in Composites

4.1 Finite Element Analysis

Figure 5 shows the tensile strain field distribution of optical fiber embedded in the middle layer, with fiber diameter 155m, polyimide coated, single, 0 degree composites namely optical fiber parallel to the carbon fiber. It can be seen that the influence area likes a circular with diameter about 200m. When the fiber is vertical to the carbon fiber, the influence area likes a rhombus about 2.5 mm in length and 200 m in width.

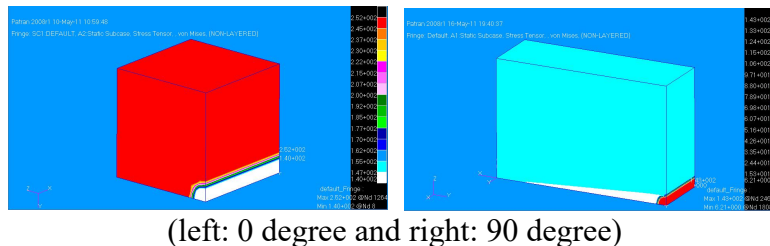


FIG. 5 Tensile strain field distribution of composites with single optical fiber

4.2 Microscopic Interface Analysis of Embedded Fiber and Composite

The composite material used is T700/5228 system, and the embedded condition of the optical fiber is shown in Table 1.

Table 1. Optical fiber embedded condition

serial number	Layers	optical fiber embedded layer	Numbers of optical fibers	fiber diameter (μm)	sample width (mm)	sample thickness (mm)
A	[0]4	P2-P3	1	155	15	1
B	[90]8	P2-P3	1	155	15	2
C	[45/0/-45/90/0/45/0/-45/0] _s	P2-P3	1	155	25	2.25
D	[45/0/-45/90/0/45/0/-45/0] _s	P4-P5	1	155	25	2.25
E	[45/0/-45/90/0/45/0/-45/0] _s	P7-P8	1	155	25	2.25
F	[45/0/-45/90/0/45/0/-45/0] _s	P9-P10	1	155	25	2.25

HIROX three-dimensional video microscopy was used to observe the interface morphology of the composite cross section with embedded fiber as shown in Figure 6. The area of fiber remains basically circular, without bending in 0 degree composites, while an obvious resin-rich region exists in 90 degree composites with length 2.5 mm, 16 times the diameter of the fiber. The optical fiber is pressed into the 0 degree layer as long as embedded between 0 degree layer and other degree layer with different angle, and is located in the middle of the two layers if both sides are 0 degree layers.

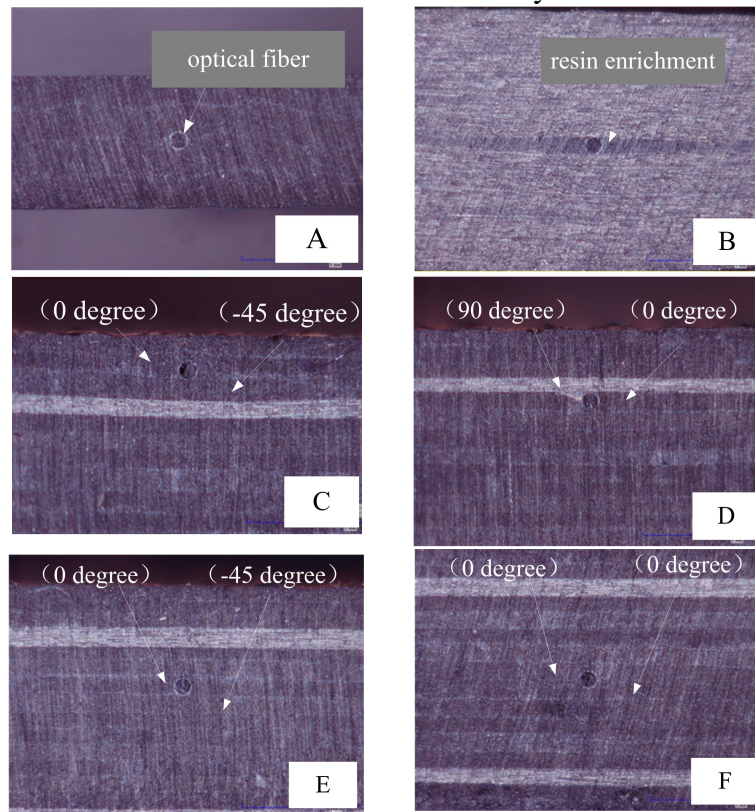


FIG. 6 Interface morphology of optical fiber embedded in different layers

4.3 Structural Compatibility of Optical Fiber and Composite Materials

The structural compatibility between fiber and composites with different diameters and different numbers of fibers was studied by means of C-scan. Two kinds of optical fibers with diameter 155 μm and 250 μm , T800 series of carbon fibers were used. The optical fibers were embedded in 0 degree and 90 degree composite specimens respectively. The width of the standard tensile specimen was 25mm as a unit. The design table is shown in the table 2.

Table 2. Design of fibers embedded composites

layers	90 degree				0 degree			
serial number	Sample 1#		Sample 2#		Sample 3#		Sample 4#	
fiber diameter	None	155μm	155μm	250μm	None	155μm	155μm	250μm
numbers of optical fibers in an unit	None	one	five	five	None	one	five	five

All the samples were tested by reflection plate method, with excitation voltage 400V, Gain 13dB. The test results were shown in the figure 7. Damage can be seen clearly in 90 degree composite laminates embedded in single fiber or five fibers. The 0 degree composite laminates embedded in single fiber or five fibers , with diameter 155 μ m , have little influence on the structure, conversely embedded in 250 μ m diameter fiber. Therefore, optical fiber with 155 μ m diameter can hardly damage the interior of the composite structure.

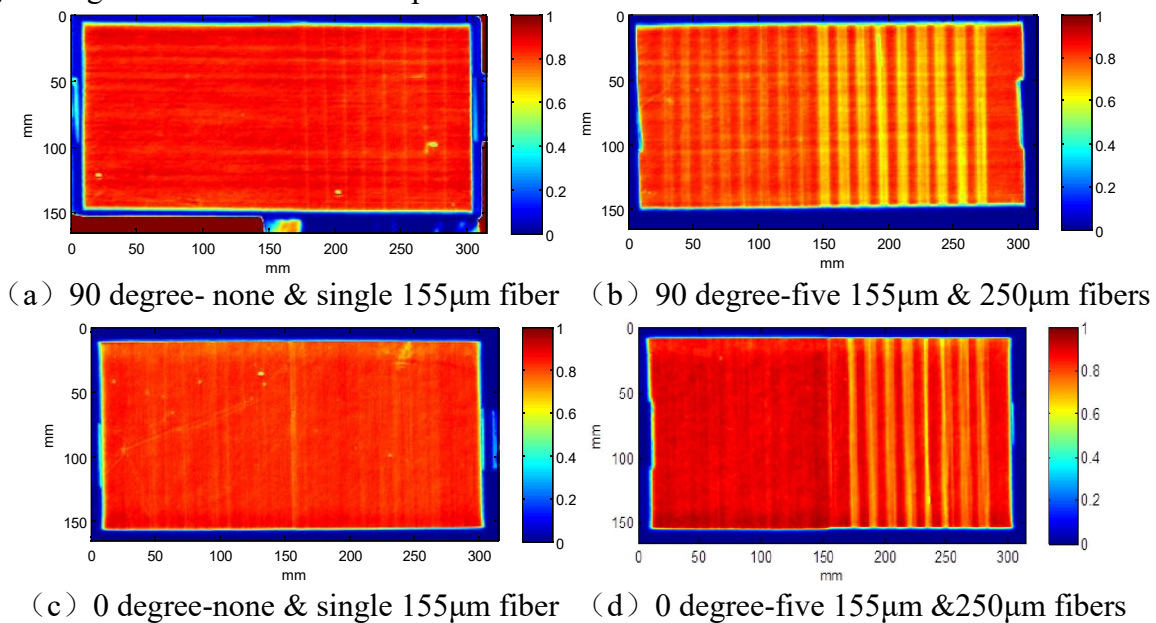


FIG. 7 Results of nondestructive testing by reflection plate meth

5. Application of Composite Materials Embedded with FBG Sensors

As composite I-shaped section stiffened panels are mostly used in aircraft central wing box, In this paper, the domestic carbon fiber reinforced composite material system of CCF300/5228A were manufactured to stiffened composite plate with dimensions of 600 mm*600 mm, skin thickness 3mm, skin and rib layers [45/0/-45/90/45/0/-45/90/45/0/-45/0/-45/0] s, and reinforced triangle area is filled with 0 degree prepreg.

One of the difficulties in the process of FBG embedding is the grating position accuracy and pre-stretched so as to withstand compression deformation. The pre-stress is applied by weight when fiber is mounted on the prepreg, and the wavelength offset is measured by demodulation instrument to ensure the fiber reaches -3000με. Then the fiber is fixed by fast-drying adhesive point and protected by Teflon casing on the outlet. Four optical fibers with three gratings respectively are uniformly embedded along the rib direction. The stiffened plate and impact load location identification interface are shown in Figure 8. The effective area of the composite stiffened plate is divided into 9 rows and 10 columns, 90 cells, with each length 5 cm and width 5 cm. A total of 12 FBG sensors are embedded in the composite. The impact load location identification is realized by cross correlation algorithm.

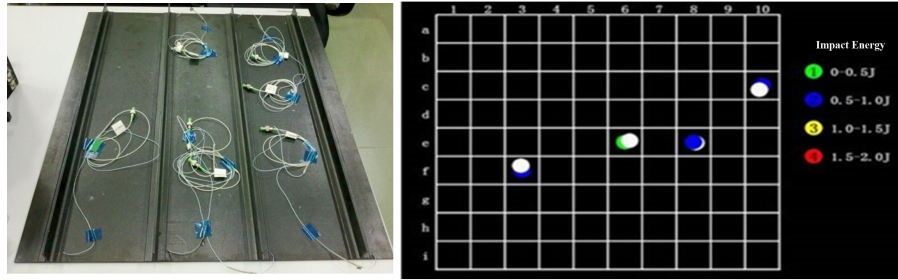


FIG. 8 The stiffened plate and impact load location identification interface

6. Summary

The method of composite material, with optical fiber surface-bonded by glass fiber, has little influence on the structural performance, but light intensity and wavelength of FBG sensor are affected by the structural assembly pressure. The method of composite material, with optical fiber embedded, which the angle of prepreg layer, the diameter and quantity of optical fiber affect. The diameter of optical fiber equal to the thickness of prepreg monolayer, the embedded layer next to 0 degree layer, less than five fibers within a 25mm width composite unit, reduce impact on composite materials. Embedded FBG sensors can be used to measure internal strain field of composites under external impact load, and identify impact position through cross-correlation algorithm.

Future study will be listed as below: 1)Co-forming technology of FBG sensor and composite skin.2) the extraction technology of optical fiber.3) New flexible wing testing technology.

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