Experimental study on three-point bending performance of CFRP shaft embedded FBG sensor

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Abstract. The bending deformation of Carbon Fiber Reinforced Polymer (CFRP) shaft is one of the important indicators reflecting its performance. Monitoring the deformation of CFRP shaft under different loads is of great significance for the optimal design of CFRP shaft. Fiber Bragg Grating (FBG) sensor is small in diameter, easy to be embedded inside the CFRP shaft, which has little influence on the structure itself. In addition, it can realize "one fiber multi-point" measurement, which is very suitable for the internal monitoring of anisotropy composites. This paper proposes a pre-embedded FBG sensor to monitor CFRP shaft strain. Prepared CFRP shaft test piece. Four FBG sensors are embedded inside the shaft, and four FBG sensors and four strain gauges are pasted on the surface of the shaft. The CFRP shaft was subjected to three-point bending loading on a universal testing machine. The strain data obtained by FBG sensor and strain gauge under various loads were compared and analyzed. The feasibility and accuracy of the embedded FBG sensor to monitor CFRP shaft strain were verified.

1. Introduction

Compared with traditional metal materials, carbon fiber composites have better specific strength, stiffness and fatigue resistance \cite{1,2,3,4}. Carbon fiber reinforced plastic (CFRP) shaft plays a very important role in power transmission system. Carbon fiber reinforced plastic (CFRP) shafts play an important role in power transmission systems and are widely used in heavy and high-end equipment, traditional metal shafts are heavy and inefficient. Carbon fiber shaft can solve the problem of heavy weight and low transmission efficiency while simplifying the shafting structure \cite{5}. In addition, the carbon fiber shaft lamination structure can be designed to monitor its internal health through sensors.

Bending performance is one of the important properties of CFRP shaft. The CFRP shaft is composed of several layers with different angles, and its internal mechanical properties are anisotropic. In addition, the initial damage and defects formed during the preparation of the CFRP shaft result in...
different strains in the layers inside the shaft, and the distribution is uneven. Therefore, obtaining the strain distribution inside the CFRP shaft under bending load is of great significance for the optimal design and health assessment of CFRP shaft. To achieve the strain measurement inside the CFRP shaft, the sensing technology needs to meet the following requirements: First, the sensor can be buried inside the shaft and has no effect on the structure to be tested; Second, it is easy to realize multi-point measurement, and the strain inside the shaft can be obtained distributed. However, the sensing strain measuring means, such as strain gauges, can only be attached to the surface of the shaft for measurement, and it is difficult to meet the above requirements.

In conclusion, FBG sensor has negligible damage effect on composite structure, and can be embedded into composite structure for real-time health monitoring [6, 7, 8]. In the existing research, FBG sensor is mainly used for curing monitoring and mechanical structure performance testing, and structural health monitoring during service.

This paper designs the layup and sensor pre-buried scheme of CFRP shaft. Prepare the CFRP shaft test piece and pre-embed the FBG sensor. The FBG sensor and the strain gauge were attached to the surface of the prepared CFRP shaft test piece. Three-point bending loading was performed by a CFRP shaft on a universal testing machine. The measured values of FBG sensors and strain gauges under various load conditions were collected and compared, and the feasibility and accuracy of measuring the strain of CFRP shaft by embedded FBG sensor and surface-bonded FBG sensor were verified.

2. experiment procedure

The layering of CFRP shaft and the embedded scheme of sensor are designed. Prepare the CFRP shaft and embed the FBG sensor. Paste the FBG sensor on the surface of the prepared CFRP shaft. Three-point bending loading was carried out on a universal test machine to collect wavelength data of FBG sensor under various loading conditions and convert them into strain.

2.1. Material, structure and layup design of CFRP shaft

Consider the working load, operating environment and life requirements of the CFRP shaft. Combine national and industry standards related to composite testing. The material, structure and layup design of the CFRP shaft were carried out, and the design of the CFRP shaft pre-embedded fiber grating was carried out. The FAR200RC38 unidirectional carbon fiber prepreg of Lianyungang Zhongfu Shenying Carbon Fiber Co., Ltd. is used for the CFRP shaft. The mechanical properties of the prepreg are shown in Table 1.

| parameter | Numerical value | parameter | Numerical value | parameter | Scheme |
|-----------|----------------|-----------|----------------|-----------|--------|
| $E_1$ (GPa) | 142 | $G_{13}$ (GPa) | 4.6 | $X_c$ (MPa) | 1100 |
| $E_2$ (GPa) | 9 | $G_{LT}$ (N/mm) | 50 | $Y_c$ (MPa) | 130 |
| $E_3$ (GPa) | 9 | 654 | 649 | $Z_c$ (MPa) | 130 |
| $v_{12}$ | 0.32 | $G_{TT}$ (N/mm) | 0.25 | $S_{12}$ (MPa) | 72 |
| $v_{23}$ | 0.46 | $\rho$ (kg/m$^3$) | 1620 | $S_{13}$ (MPa) | 72 |
| $v_{13}$ | 0.32 | $X_c$ (MPa) | 1900 | $S_{23}$ (MPa) | 70 |
| $G_{12}$ (GPa) | 4.6 | $Y_c$ (MPa) | 51 | $G_{1r}$ (N/mm) | 75 |
| $G_{23}$ (GPa) | 3.08 | $Z_c$ (MPa) | 51 | $G_{2r}$ (N/mm) | 0.75 |

Table 1. Mechanical properties of FAR200RC38 prepreg. $V_{12}$, $V_{23}$, $V_{13}$ indicate Poisson's ratio in the 12, 23, and 13 directions. $G_{12}$, $G_{23}$, $G_{13}$ indicate the shear modulus of the prepreg in each main direction. $X_c$, $Y_c$, $Z_c$ are longitudinal compressive strength and transverse compressive strength of Prepreg. $S_{12}$, $S_{13}$, $S_{23}$ indicate the shear strength of the prepreg in the planes 1-2, 1-3, 2-3. $GLT$, $GTT$ represent the tensile fracture toughness values of the prepreg in the longitudinal and
transverse directions. GLC, GTC indicate the compression fracture toughness values of the prepreg in the longitudinal and transverse directions. Represent the density of the prepreg.

The length of CFRP shaft is 400mm and inner diameter is 50mm and outer diameter is 58.8mm. There were all together 22 layers, 0.2 mm thick each, in an order of 0°/90°/45°/0°/0°/45°/-45°/0°/-45°/90°/0°/-45°/0°/90°/0°/-45°/0°/45°/0°/0°/45°/0°/90°/0°. In this thesis, PANI film was prepared by electrochemical method. The FBG sensor is embedded in the layer of the shaft during the coiling process. After the shaft is cured, FBG sensor is stuck on the surface of CFRP shaft. The location of the FBG sensor is shown in Figure 1.

2.2. sensor layout

FBG1, FBG2, FBG3, FBG4 were buried between the 18 and 19 layers, while FBG1s, FBG2s, FBG3s, FBG4s were pasted on the surface layers. The distance between the FBG sensor and the end face of the CFRP shaft is 100mm, and the FBG1, FBG2, FBG3, FBG4 are located for clockwise direction. FBG1 and FBG4 are located at the left end of the CFRP shaft, FBG2 and FBG3 are located at the right end of the CFRP shaft, with a circumcitial distance of 180 degrees.

![Figure 1. Embedded Location of FBG Sensor.](image)

The dimensions of the FBG sensor embedded shaft are shown in Figure 2.

![Figure (A) A and C point Figure (B) B1, B2, B3, D1, D2, D3 point](image)

Figure 2. No. 5 CFRP shaft FBG position.

2.3. Three point bending experiment of CFRP shaft

This experiment adopts DDL100 microprocessor-control electronic universal testing machine to three-point bending CFRP shaft. In order to guarantee the veracity of FBG sensor in measuring the internal and surface strain distribution of CFRP shaft. A, B1, B2, B3, C, D1, D2 and D3 were selected to load the bending load on the CFRP shaft at 8 points, as shown in figure 3.
Figure 3. No. 5 CFRP shaft loading type.
CFRP shaft three-point bending Schematic diagram of experimental system Figure 4. Universal testing machine loading head radius $R = 8$mm, bearing radius $R = 15$mm round corner. The shaft is loaded at A, B1, B2, B3, C, D1, D2 and D3. the load speed is set as 0.1mm/s, and load is continuously exerted up until 1.5mm. It took 10s to reach the maximum displacement. Gaussian photoelectric OPM800 demodulator is adopted to demodulate the wavelength of FBG sensors under the condition in loading process.

![Figure 4](loading_device_for_three_point_bending_test_of_CFRP_axial_pipe_fitting.jpg)

**Figure 4.** loading device for three-point bending test of CFRP axial pipe fitting.

### 2.4. Three point bending test and result of CFRP shaft

The strain value of the FBG sensor is converted from the wavelength offset data and the strain sensitivity coefficient of the FBG sensor. The strain values of each FBG sensor are shown in table 2 and table 3.

| Mount point | FBG1 strain (microstrain) | FBG2 strain (microstrain) | FBG3 strain (microstrain) | FBG4 strain (microstrain) |
|-------------|---------------------------|---------------------------|---------------------------|---------------------------|
| A           | -70                       | -65                       | 90                        | 104                       |
| B1          | 85                        | -28                       | -50                       | 125                       |
| B2          | -32                       | -90                       | -57                       | -17                       |
| B3          | -24                       | 83                        | 95                        | -18                       |
| C           | -62                       | -65                       | 90                        | 120                       |
| D1          | 30                        | -70                       | -78                       | -82                       |
| D2          | -61                       | -105                      | -104                      | -125                      |
| D3          | -43                       | -98                       | -60                       | -75                       |

According to table 2 strain FBG1, FBG2, and FBG3 and FBG4 were measured symmetrically at loading point A.A, and C are symmetric, and the result of loading point C basically conforms to A. When loading B1, the strain of CFRP shaft embedded at FBG3 and FBG4 is larger than that at FBG1 and FBG2 positions. The strain of CFRP shaft embedded in FBG2 and FBG3 is larger than that of FBG1 and FBG4 when loading B2. The size of FBG2 and FBG3 of CFRP shaft is very close when loading D1. The size of FBG2 and FBG3 of CFRP shaft is close to each other when loading D2.
Table 3. FBG sensor strain (microstrain) pasted on the surface of CFRP shaft.

| Mount point | FBG1s strain (microstrain) | FBG2s strain (microstrain) | FBG3s strain (microstrain) | FBG4s strain (microstrain) |
|-------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| A           | -49                         | -77                         | 68                          | 53                          |
| B1          | 86                          | 28                          | -26.5                       | 50                          |
| B2          | -18.7                       | -13.2                       | -63.7                       | -176.4                      |
| B3          | -16.4                       | 62                          | 23.6                        | -28.4                       |
| C           | 82.4                        | 57.4                        | -43.3                       | -25.4                       |
| D1          | -40.8                       | -27.8                       | -24.8                       | 31.9                        |
| D2          | -54.3                       | -42.3                       | -45.8                       | -50.9                       |
| D3          | -35.2                       | -28.7                       | 17.2                        | -42                         |

According to table 3, strain FBG2s and FBG3s were measured symmetrical at loading point A, and FBG1s and FBG4s were symmetrical. A and C are symmetric, and the result of loading point C basically conforms to A. When loading B1, the strain at FBG1s and FBG4s of CFRP shaft is larger than that at FBG2s and FBG3s. The strain of CFRP shaft at FBG3s and FBG4s is larger than that at FBG1s and FBG2s when loading B2. The size of FBG2s and FBG3s of CFRP shaft is very close when loading D1. The size of FBG2s and FBG3s of CFRP shaft is close to each other when loading D2.

3. The strain measurement experiment of CFRP shaft with surface bonded strain gauge

The surface strain information of the CFRP shaft is obtained by the strain gauge to observe the load deformation under the three-point bending load. Measurement results gained from strain gauge and FBG sensor under identical experimental conditions will be compared to obtain the measurement error. Experimental instruments:ddl100 microcomputer controlled electronic universal testing machine, Donghua strain gauge, notebook computer. The experimental setup is shown in Figure 5.

Figure 5. Diagram of CFRP three-point bending test device.
Strain gauge is a kind of element for strain measurement, which is composed of sensitive grid and so on. When used, it is firmly pasted on the designated measuring point of the carbon fiber composite pipe fitting. Deformation occurs at the measuring point after the CFRP shaft is stressed, the sensitive gauge will also deformed to change its resistance. Then, the resistance change was measured by Donghua strain measuring device and automatically converted to the strain value of the measuring point. The experimental system is shown in figure 6.

Figure 6. System diagram of CFRP three-point bending test device.

According to donghua strain gauge, strain information of CFRP shaft under each loading condition is measured, as shown in table 4.

Table 4. strain at each position of bonded strain gauge on the surface of CFRP shaft.

| Mount point | FBG1s strain (microstrain) | FBG2s strain (microstrain) | FBG3s strain (microstrain) | FBG4s strain (microstrain) | error  |
|------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|--------|
| A          | -49.4                       | -33.4                       | 68.7                        | 82.8                        | 0.8%   |
| B1         | 19.217                      | -15.566                     | -4.828                      | 69.367                      | 27%    |
| B2         | -87                         | -42                         | -75.8                       | -117.7                      | 15%    |
| B3         | -89.5                       | 83.5                        | 104.1                       | -45.7                       | 25%    |
| C          | 249.4                       | 88.6                        | -45.1                       | -18.8                       | 3%     |
| D1         | 58.5                        | -21.2                       | -17.9                       | -87.6                       | 31%    |
| D2         | -95.8                       | -94.7                       | -51.5                       | -135.7                      | 11%    |
| D3         | -57.8                       | -37.3                       | -55.9                       | -70                         | 23%    |

The strain detection of CFRP shaft on the surface is shown in table 3-1. The values of CFRP shaft at loading point A FBG1 and FBG2 were similar to those of FBG3 and FBG4. The strain value of FBG4 is the maximum at the loading point B2. At loading point B3, the strain of FBG3 is the maximum. The maximum value of CFRP shaft is at the loading point C FBG1. The maximum FBG2 of CFRP shaft is at the loading point C. The strain values of FBG1 and FBG4 of CFRP shaft at loading point D1 were similar to those of FBG2 and FBG3. The strain of CFRP shaft at load point D2 is similar to that of FBG1 and FBG2. The strain of CFRP shaft at load point D3 is similar to that of FBG1 and FBG3.

4. Conclusion
In this paper, With FBG sensor for key components, this paper builds the CFRP shaft axis strain monitoring system based on FBG sensor, the CFRP shaft axis strain monitoring experiment based on FBG sensor, and the surface of the CFRP strain gages axis shaft strain information data analysis, considering the fabrication technique of CFRP defect and error such as universal testing machine load sliding by a minimum error is 0.8% the feasibility of FBG sensor monitoring CFRP shaft axis strain.
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