Experimental Investigate on Pulling out of Anchor Based on Fiber Bragg Grating Monitoring

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Abstract: The stability of the anchor plays an important role in slope engineering, mining engineering and construction engineering. Based on the Fiber Bragg Grating (FBG) sensor detection technology, this paper carries out the pulling out the test of the anchor with different tensile strengths. The results show that the center wavelength of the FBG has a good mathematical relationship with its axial strain, and the wavelength change data can be processed into the strain result of the FBG sensor to characterize the strain deformation and stability of the anchor further. What’s more, the measured data from the FBG sensor agrees with the load of the test, and the accuracy of the FBG sensor monitoring data on the anchor is verified.

1. Introduction

Anchor problems are the most common engineering geological problems and are widely found in mining engineering, geotechnical engineering, transportation, water conservancy, and hydropower. These anchor-related projects often undergo deformation and instability during excavation or operation. During the whole life cycle, using appropriate monitoring methods to observe, intelligently evaluate the construction and operation of the anchor, and provide early warning signals for the engineering in the special environment and serious anomalies, provide basis and guidance, and ensure the people’s life and national property security.

Optical fiber sensing technology started in the 1970s. As a new technology, it uses light propagation as a carrier and optical fiber as a medium to sense and transmit signals. Inaudi et al. [1] applied this technology to engineering geological monitoring for the first time by monitoring a series of fiber-optic extensometers installed on another tunnel wall built next to a tunnel to monitor the adjacent tunnels during the new tunnel excavation. Deformation. Yang et al. [2] calculated the tilt angle of the beam by arranging two fiber grating sensors symmetrically on the beam and measuring the strain of the beam during pendulum motion. Dong et al. [3] placed three grating sensors on the beam in three directions (120 degrees from each other), and estimated the inclination of the strain beam by the strain changes in three directions, and then obtained the displacement value of the beam, which was measured by this method. The size and direction of the angle, but the measured displacement accuracy is low.

Liang et al. [4] used fiber Bragg gratings to detect the strain response characteristics of plates under different loads, and applied them to structural health monitoring and underwater structures. Li et al. [5] studied the application of fiber Bragg grating sensors in the grid structure, and achieved good results in both experiments and engineering. Casas et al. [6] studied the application of the FBG sensors in bridge monitoring. Li et al. [7] proved in the experiment that the fiber grating monitoring technology is an effective means to discover and observe the bonding state of the anchor interface. Yue et al. [8] showed that the fiber grating could monitor the initial cracking of the structure, and the fiber grating and strain...
gauge measurement data have a good consistency. Sun et al. [9] applied fiber gratings to ancient buildings as a temperature-sensing fire detector. Mohammed et al. [10] and Ahmad et al. [11] applied FBG with the temperature sensor. Based on the FBG, Li et al. [12] predict the damage position through time delay on the plate structure. Fiber optic sensors have many advantages that traditional sensors cannot match, and are gradually replacing the existing sensor systems and becoming the main force of the sensor family.

2. Experiment

2.1. Design of sample

The anchor used in the test was a circular 45# carbon structural steel with a diameter of 16 mm and a length of 160 cm, and the moment of inertia of the section was 3217 mm4. In the cross-section, three fiber grating strings are arranged on the surface of the anchor rod. On the longitudinal interface of the anchor rod, each fiber grating string is equidistantly distributed with five fiber grating monitoring sensors, and the distance between each adjacent two is 30 cm, and the outermost side. The sensor is 20 cm from the end of the anchor, as shown in Figure 1.

![Figure 1. Schematic cross-section of FBG bolt FBG.](image)

The three fiber grating strings are sealed with epoxy adhesive on the groove opened on the surface of the anchor rod, and the groove on the surface of the anchor rod is polished to a depth of about 1.5 mm and a width of about 2 mm to ensure the groove. It is clean and free of debris. Then, it is marked in the longitudinal FBG sensor position and fixed again, as shown in Figure 2.

![Figure 2. Sample anchor with FBG.](image)
2.2. The pulling out test of anchor

According to the pull-out experiment of the wire-drawing machine, the elastic modulus $E$ of the bolt is obtained, the axial force received by the bolt is reversed by the data acquired by the FBG sensor on the anchor, and the axial force applied by the drawing machine is made. Align, then apply the radial load to the anchor and simultaneously use the physical method of the dial gauge to record the radial deflection after the bolt is subjected to the radial load, and record the result with the data obtained by FBG. Comparison study. The two ends of the bolt are fixed by 10 cm with the clamp of the drawing machine. The drawing machine increases the pulling force at a rate of 10000 N/min, and then for every 200 N increase, the constant force is maintained for 0.5 min until the final load is 1000 N.

The elastic modulus of the bolt is 215 GPa by reading the data of the drawing machine. The data measured by the FBG during the drawing process is as follows. Since the pulling force of the wire-drawing machine is faster, the pulling force is maintained for a long time. Here, the average value of a piece of stable data is taken when the pulling force is 200N, 400N, 600N, 800N, and 1000N, respectively. The variation of each FBG wavelength in these five stages is shown in Table 1.

| Force /N | FBG | Position1 /nm | Position2 /nm | Position3 /nm | Position4 /nm | Position5 /nm |
|---------|-----|---------------|---------------|---------------|---------------|---------------|
| Original wavelength | 1 | 1544.95 | 1549.86 | 1555.14 | 1559.74 | 1564.91 |
| | 2 | 1544.75 | 1549.67 | 1554.81 | 1559.91 | 1564.97 |
| | 3 | 1544.95 | 1550.03 | 1555.50 | 1559.93 | 1564.99 |
| 200 | 1 | 5.38E-09 | 5.38E-09 | 5.38E-09 | 5.38E-09 | 5.38E-09 |
| | 2 | 5.37E-09 | 5.37E-09 | 5.39E-09 | 5.38E-09 | 5.37E-09 |
| | 3 | 5.39E-09 | 5.37E-09 | 5.40E-09 | 5.39E-09 | 5.38E-09 |
| 400 | 1 | 1.08E-08 | 1.08E-08 | 1.08E-08 | 1.08E-08 | 1.08E-08 |
| | 2 | 1.09E-08 | 1.09E-08 | 1.08E-08 | 1.08E-08 | 1.09E-08 |
| | 3 | 1.09E-08 | 1.08E-08 | 1.07E-08 | 1.08E-08 | 1.09E-08 |
| 600 | 1 | 1.62E-08 | 1.62E-08 | 1.62E-08 | 1.62E-08 | 1.62E-08 |
| | 2 | 1.61E-08 | 1.62E-08 | 1.62E-08 | 1.62E-08 | 1.62E-08 |
| | 3 | 1.62E-08 | 1.62E-08 | 1.63E-08 | 1.62E-08 | 1.63E-08 |
| 800 | 1 | 2.16E-08 | 2.15E-08 | 2.16E-08 | 2.15E-08 | 2.16E-08 |
| | 2 | 2.16E-08 | 2.16E-08 | 2.16E-08 | 2.16E-08 | 2.17E-08 |
| | 3 | 2.16E-08 | 2.16E-08 | 2.16E-08 | 2.16E-08 | 2.16E-08 |
| 1000 | 1 | 2.69E-08 | 2.69E-08 | 2.70E-08 | 2.70E-08 | 2.69E-08 |
| | 2 | 2.69E-08 | 2.70E-08 | 2.70E-08 | 2.70E-08 | 2.69E-08 |
| | 3 | 2.69E-08 | 2.69E-08 | 2.69E-08 | 2.69E-08 | 2.69E-08 |

According to the characteristic equation of FBG,

$$\frac{d\lambda_B}{\lambda_B} = \frac{dn_{eff}}{n_{eff}} + \frac{d\Lambda}{\Lambda}$$

where $\lambda_B$ is the wavelength, $n_{eff}$ is the effective refractive index of FBG, $\Lambda$ is the grating period.

It is in the linear range:
\[
\frac{d\lambda}{\lambda} = \varepsilon \quad (2)
\]

where \( \varepsilon \) is the axial strain of the FBG.

When considering only the axial deformation of the FBG, the change in refractive index is:

\[
\frac{d n_{\text{eff}}}{n_{\text{eff}}} = -\frac{n_{\text{eff}}^2}{2} [P_{12} - v(P_{11} + P_{12})] \varepsilon \quad (3)
\]

where \( P_{11}, P_{12} \) is the elastic constant, that is, longitudinal and transverse refractive index changes caused by longitudinal strain, and \( v \) is the poisson’s ratio of the FBG.

When \( P = \frac{n_{\text{eff}}^2}{2} [P_{12} - v(P_{11} + P_{12})] \varepsilon \),

\[
\frac{d\lambda_B}{\lambda_B} = (1 - P) \varepsilon \quad (4)
\]

The above equation is a mathematical expression of the wavelength variation under the axial strain of the fiber grating. It can be seen that once the material of the FBG is determined, it is a constant related to the FBG material and used to process the corresponding characteristic coefficient of the FBG strain sensor. This theoretically guarantees that the fiber grating is very useful as a strain sensor, and has a good linear relationship.

The \( a_\varepsilon = \lambda_B (1 - P) \) is the sensitivity coefficient of the FBG axial strain and central wavelength change,

\[
\Delta\lambda_B = a_\varepsilon \varepsilon \quad (5)
\]

Equation (5) is the mathematical relationship between the FBG center wavelength change and its axial strain, which can easily process the wavelength change data into the strain results of the FBG sensor. For fiber cases where the core is pure quartz, \( n_{\text{eff}} = 1.46 \), \( P_{11} = 0.121 \) and \( v = 0.17 \). Then, \( P \) is 0.22. For input light at a wavelength of 1550 nm, the wavelength shift caused by each microstrain is 1.209 pm, and strain sensitivity is 0.78/\( \mu \varepsilon \), that is, \( a_\varepsilon = 1.1625 \text{pm/} \mu \varepsilon \). It can be seen that the sensing sensitivities of different fiber gratings may be different due to different fibers, different grating writing processes and different annealing processes. Therefore, different fiber gratings must be calibrated before they can be used for on-site monitoring.

Table 2. Pulling the axial force of the anchor measured by each FBG sensor.

| Force /N | FBG | Position1 /nm | Position2 /nm | Position3 /nm | Position4 /nm | Position5 /nm |
|----------|-----|----------------|----------------|----------------|----------------|----------------|
| 200      | 1   | 2.00E+02       | 2.00E+02       | 2.00E+02       | 2.00E+02       | 2.00E+02       |
|          | 2   | 1.99E+02       | 1.99E+02       | 2.00E+02       | 1.99E+02       | 1.99E+02       |
|          | 3   | 2.00E+02       | 1.99E+02       | 2.00E+02       | 2.00E+02       | 2.00E+02       |
|          | 1   | 4.00E+02       | 3.99E+02       | 4.01E+02       | 3.99E+02       | 4.00E+02       |
| 400      | 2   | 4.03E+02       | 4.04E+02       | 4.01E+02       | 3.99E+02       | 4.03E+02       |
|          | 3   | 4.03E+02       | 4.01E+02       | 3.98E+02       | 3.99E+02       | 4.03E+02       |
|          | 1   | 6.01E+02       | 6.02E+02       | 6.02E+02       | 5.98E+02       | 6.02E+02       |
| 600      | 2   | 5.99E+02       | 5.99E+02       | 6.02E+02       | 6.01E+02       | 6.02E+02       |
|          | 3   | 6.01E+02       | 5.99E+02       | 6.05E+02       | 6.01E+02       | 6.05E+02       |
|          | 1   | 8.00E+02       | 7.97E+02       | 8.00E+02       | 7.98E+02       | 8.01E+02       |
| 800      | 2   | 8.00E+02       | 8.03E+02       | 8.00E+02       | 8.01E+02       | 8.04E+02       |
|          | 3   | 8.03E+02       | 8.00E+02       | 8.02E+02       | 8.01E+02       | 8.01E+02       |
As shown in the data in Table 2, the data measured by the FBG sensor is basically calculated to match the actual load, which proves that the strain measured by the FBG sensor on the anchor is accurate, and the elastic modulus of the bolt measured by the drawing machine is accurate.

3. Conclusions

In this paper, based on the engineering problem of anchor stability, the pull-out test based on fiber Bragg grating monitoring is carried out. The conclusions are as follows:

The center wavelength of FBG has a good mathematical relationship with its axial strain. The wavelength change data can be processed into the strain result of the FBG sensor to characterize the strain deformation and stability of the anchor further;

The data measured by the FBG sensor coincides with the load of the test, and the accuracy of the monitoring data of the FBG sensor on the anchor is verified.

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