Research Article

Long-Term Monitoring Reliability and Life Prediction of Fiber Bragg Grating-Based Self-Sensing Steel Strands

Heying Qin,1,2 Quanxi Shen,1 Jinping Ou,3 and Wanxu Zhu1,2

1Collaborative Innovation Center for Exploration of Hidden Nonferrous Metal Deposits and Development of New Materials in Guangxi, Guilin University of Technology, Guilin, Guangxi 541004, China
2Guangxi Key Laboratory of Geomechanics and Geotechnical Engineering, Guilin, Guangxi 541004, China
3School of Civil Engineering, Harbin Institute of Technology, Harbin 150090, China

Correspondence should be addressed to Wanxu Zhu; zhuwanxu@vip.163.com

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To analyze the long-term monitoring reliability and life expectancy of FBG-based steel strands, accelerated corrosion and tensile tests were carried out and a life-prediction model was constructed. The validation test results indicated that the monitoring strain sensitivity of FBG-based steel strands decreases with an increase in solution concentration and time in a corrosive acidic environment. When the sensitivity dropped to about 80% of its initial value, the FBG sensor suddenly failed. The life-prediction model indicates that the predicted monitoring life of an FBG sensor is about 56 years in an unstressed condition but about 27 years under the stressful conditions that FBG-based steel strands are subjected to in their working environment. So, to improve their monitoring reliability and monitoring life, it is suggested that FBG-based steel strands might be prepared by “pre-loading.”

1. Introduction

Steel strands are a core component of many engineering structures, including bridge cables, hanger rods, geotechnical anchor cables, and internal and external prestressed components. They operate in conditions where “a slight move in one part may affect the situation as a whole.” So, under the combined action of stress and environmental corrosion, the mechanical performance of steel strands slowly degenerates over time and they may even fail. In view of this, the real-time monitoring of stress in steel strands plays an important role in the safety management of engineering structures. Currently, the monitoring techniques for stress in steel strands include elastomagnetic sensors [1, 2], electrical strain gauges [3], piezoelectric transducer actuator [4], and so on. However, these types of electromechanical sensors are easily subjected to long-term risk as well as suffering from noise during long distance transmission and electromagnetic interference. On the other hand, fiber Bragg grating (FBG) sensors use light as their sensing medium [5]. They exhibit stable sensing characteristics and high accuracy and possess anti-electromagnetic interference capabilities [6]. This makes them well suited to the health monitoring of structural components [7–11]. FBG sensing technology was first adopted to monitor the cable tension of two 35 m long stay cables in Stork’s Bridge in Switzerland [12]. Researchers in Canada used 18 FBG sensors for the long-term monitoring of carbon fiber composite stiffeners in the Beddington Trail Bridge in Calgary [13]. Belgian researchers have tried installing FBG sensors in pre-stressed tendons in box girders to monitor the strain of concrete girder bridges during the stretching of pre-stressed steel strands [14]. A research team from Harbin Institute of Technology laid 15 FBG strain sensors in the box girders of the Hulan River Bridge in China during its construction. Here, it was possible for the FBG sensors to effectively monitor the strain placed upon steel strands during the stretching of the pre-stressed box girders. The impact of temperature changes and the strain when the bridge was placed under vehicle load were also assessed by the FBG sensors during the service life of the bridge [15].
FBG sensors generally need to be packaged prior to being used to monitor the stress in engineering structures. The changes in the performance of the grating being used as a sensing component need to be consistent with changes in the mechanical performance of the surrounding objects being monitored and to which the grating is coupled. However, the FBG material is brittle and only has a diameter of 125 μm, so it has poor shear resistance and can easily break. So, packaging is essential to ensure its survival in complex engineering environments. In order to improve the life expectancy of FBG and meet other performance requirements during monitoring, such as the provision of an adequate range of measurement and sensitivity, a lot of research has been devoted to the packaging of FBG sensors. Li et al. used a carbon fiber reinforced polymer-optical fiber Bragg grating (FRP-OFBG) rib, which was prepared through the pultrusion of an epoxy resin adhesive and a fiber reinforced resin, to replace the central wire of an ordinary steel strand. This enabled a new type of FRP-OFBG intelligent steel strand to be developed, which had good sensing linearity and repeatability and could monitor 75% of the limit strain of the steel strand [16]. The structure of retard-bonded pre-stressed steel strands was thoroughly examined by Lan et al. and a new kind of FBG retard-bonded intelligent steel strand that could provide the self-monitoring of pre-stressed strands was developed [17]. Kim et al. replaced the middle wire of the 7-wire pre-stressed steel strand with an instrumented steel tube in which the FBG sensor was embedded, and successfully applied it to the steel strand stress monitoring [18, 19]. A review of previous works related to the measurement of stress in steel strands using FBG sensors revealed that most research was conducted using methods involving mounting the sensor on the outer surface of the steel strand [20, 21] or combining the sensor with the strand using an advanced material with similar properties [16–19]. However, these methods are likely to provoke various problems such as field-applicability and constructability. Whether the replaced central wire and the helical wire can bear the force together, whether the durability of the steel strand can meet the requirements after replacement, etc., these issues have not been explained in the corresponding research. The authors of the current paper have designed a self-sensing steel strand where a groove is set in the central wire of a steel strand, into which the FBG sensors can be inserted while the central wire is being stretched. These kinds of FBG sensors can monitor steel strands in conditions close to their ultimate tensile force, thus improving their chances of survival when monitoring steel strands under stress and expanding upon the usual limitations placed upon their monitoring range [22].

Packaged FBG sensors are composed of a sensor matrix (directly packaged sensor matrixes were the objects subjected to testing for this paper), the fiber Bragg grating (FBG), and the packaging. The packaging currently usually consists of a polymer adhesive. In the complex environments in which engineering structures are both constructed and required to operate, FBGs may be corroded by acid rain and fog and subjected to all kinds of stress, resulting in their stability and monitoring reliability being diminished or lost. Out of the three parts of an FBG sensor, the durability of the sensor matrix load support is better than the packaging and the FBG itself offers a good service life [23]. The failure of FBG sensors is therefore often due to the failure or aging of the adhesive in the packaging, which leads to degradation of the interface between the FBG sensor and the sensor matrix [24–28]. As a core component in the sensor-based monitoring of structures, FBG sensors play a key role in monitoring danger and providing timely warning, so research regarding the monitoring reliability and durability of FBG sensors has far-reaching significance. The fatigue durability and corrosion durability of FBG sensors packaged in fiber composite ribs have been studied theoretically by researchers in Canada [29]. Similarly, the engineering durability of FRP-OFBG sensors has been studied in China [30]. The durability of optical fiber corrosion sensors was studied using both accelerated life [31] and freeze-thaw cycle tests. However, so far, there have been few studies on the environmental durability of FBG sensors packaged in epoxy polymer adhesives, so the long-term monitoring reliability and monitoring life of these sensors are in urgent need of investigation. In this paper, FBG self-sensing steel strands form the central research object. Their long-term monitoring reliability and the effectiveness of them under stress in various complex environments were studied by means of accelerated corrosion and tensile tests, leading to predictions of their likely monitoring life.

2. Accelerated Corrosion and Tensile Tests of FBG-Based Self-Sensing Steel Strands

2.1. General Description of the Tests. FBG-based self-sensing steel strand specimens were prepared as follows. We took an ordinary 2 m long 1 × 7 standard type of steel strand, with a nominal diameter of 15.2 mm, nominal cross-sectional area of 140 mm², tensile strength of 1860 MPa, yield load of 225 kN, and ultimate bearing capacity of 260 kN. The central wire was taken out through mechanical dispersion and a 1.0 mm deep and 1.0 mm wide groove was set into it. The bandwidth, reflectivity, and central wavelength of the FBG were 0.12 nm at 3 dB, 99.64%, and 1540 nm, respectively. The FBG demodulator was an Agilent 86142B spectrometer, the sampling frequency was 3 Hz, the wavelength range was 1525–1560 nm, the wavelength accuracy was 2 pm, and the resolution was 1 pm. The elastic modulus of the epoxy resin adhesive used for the FBG packaging was greater than 2.5 GPa. The central wire was then stretched to 11.8 kN and the FBG was packed into the groove with adhesive under a sustained state of loading. The packaging length needed to be ensured to guarantee uniform coverage by the adhesive of at least 20 mm around the grating. At the end of the central wire, the FBG was protected with a capillary hose. The central wire was unloaded and kept aside until the adhesive had achieved a sufficient bonding strength and the self-sensing central wire had been made.

According to the Chinese standards GB/T 21839-2008 and GB/T 25823-2010, other national standards, and the related literature [31–34], the main components of a corrosive acidic medium for accelerated corrosion life tests are
HCl, NaCl (5%), and Na₂SO₄. After a number of trial tests, HCl acidic solutions with concentrations of 0%, 0.3%, 0.6%, 0.8%, and 1% were prepared according to the ratios shown in Table 1 to simulate the environmental conditions of different acidic concentrations.

The accelerated corrosion life tests and tensile tests were carried out as follows. A 3-meter-long container was prepared, the inside of which was tightly covered with plastic film. The prepared acid medium was poured into the container and a glass rod was used to stir the solution and make it uniform. The pH value of the solution was measured to ensure the stability of the solution’s pH value during the test process. The specimens were put into the container containing different concentrations of the solution to carry out the corrosion tests. After 24 h, the specimens were removed and libero-cly cleaned with water; then absorbent paper was used to dry them. After that, the tensile tests were carried out. A center hole jack was used to load the specimens during the tensile tests and wavelength changes in the FBG were monitored by the demodulator. Any internal stress in the specimens was eliminated by pre-stretching before the actual stretching. This involved slowly loading the specimens from 0 kN to 10 kN and then slowly unloading them back to 0 kN again. The stretching range of the central wire was 0–10 kN and data was recorded every 2 kN. After stretching, the specimen was returned to the solution in the original container to continue to corrode and a tensile test was performed 24 h later. The test data continued to be recorded until the FBG sensor packaging material had peeled off, the FBG sensor monitoring data had lost its accuracy, or the FBG sensor had broken, and then the FBG sensor had been declared invalid.

Taking the sustained loading value of the central wire and HCl acidic solution as changing parameters, a total of 10 groups of specimens were designed with 3 specimens in each group for an overall total of 30 specimens. The specimen arrangement is shown in Table 2.

Images of the tests in progress are shown in Figures 1 and 2.

2.2. Experimental Data and Results Analysis

2.2.1. Experimental Phenomena. To describe the experimental phenomena, specimen II-03 will be taken as an example. Figure 3 shows the corrosion of specimen II-03, where the FBG-based self-sensing steel wire was immersed in a 0.6% acidic solution with a loading value of 0.3Ptrue = 11.8kN. It can be seen that the surface of the self-sensing central wire lost luster and that black spots started to appear. The adhesive bonding layer in the groove boundary began to gradually warp outwards in the early stages of corrosion. As the tests continued, the warping of the bonding layer gradually expanded from the boundary to the bottom of groove and the warped part became soft. The black spots on the surface of the central wire became deeper in color and larger in size, gradually transforming into speckles of rust. The warping outwards of the bonding layer boundary and the appearance of the black spots on the surface of the central wire sped up the failure of the FBG. When the adhesive peeled off and the FBG sensor had failed, there were numerous corroded pits visible in the groove at the boundary of the original bonding layer and the bottom of the groove was also seriously corroded. The velocity with which the changes appeared was related to the concentration of the acid medium. The higher the concentration of the acid medium, the faster the boundary of the bonding layer warped outwards and the black spots appeared.

2.2.2. Experimental Results and Analysis. The working principle of an FBG strain sensor is as follows. The matrix senses the change of external stress and strain. This is transmitted to the bare grating through deformation of the middle layer. A large number of experiments have shown that the strain transmitted by the FBG is different from the strain produced through the external changes sensed by the matrix. The ratio between the two is the sensor’s strain transfer capability, usually called the strain transfer rate. According to shear hysteresis theory [35–38], the strain transfer rate [39] β for FBG is as follows:

\[
\beta = \frac{\varepsilon_g}{\varepsilon_m} = 1 - \frac{\cosh (kL) - 1}{kL \sinh (kL)},
\]

where k can be expressed as

\[
k^2 = \frac{2G_p}{r_g^2E_g \ln (r_m/r_g)}.
\]

\(\varepsilon_g\) and \(\varepsilon_m\) represent the strain in the FBG sensor and the matrix, respectively; L represents half the adhesive length of the optical fiber sensor; \(G_p\) and \(E_g\) represent the shear modulus of the bonding layer and Young’s modulus of the fiber, respectively; and \(r_m\) and \(r_g\) represent the outer diameter of the bonding layer and the outer diameter of the optical fiber, respectively.

According to the above formula, the main factors affecting the strain transfer rate are the thickness of the bonding layer, the bonding length, and the shear elastic modulus of the bonding layer. When the performance of the adhesive changes under the action of the external environment, the bonding length is shortened and the shear elastic modulus becomes smaller. This makes the strain transfer rate smaller and the strain transfer capacity of the FBG decrease, or even fail. In that case, the strain transfer rate is an important index for evaluating the monitoring reliability of an FBG strain sensor.

FBG strain is reflected by changes in its central wavelength. When the grating is only affected by axial stress, the relationship between the change in the grating’s central wavelength and the strain is [40–42]

\[
\Delta \lambda = \left(1 - \frac{\eta_2^m}{2} \frac{P_{12} - \mu (P_{11} + P_{12})}{P_{11}} \right) \cdot \lambda_s \cdot \varepsilon_g = \lambda_s (1 - P) \cdot \varepsilon_g = K_s \cdot \varepsilon_g,
\]

where \(\Delta \lambda\) is the change value of wavelength; \(\mu\) is the Poisson ratio; \(P_{11}\) and \(P_{12}\) are photo-elastic effect coefficients; \(P\) is a...
photo-elastic coefficient; \( \varepsilon_g \) is the FBG sensed strain; and \( K \varepsilon \) is the strain sensitivity of the FBG sensed. This can be obtained by substituting \( \varepsilon_g = \beta \cdot \varepsilon_m \) into equation (3), giving

\[
\Delta \lambda = K_\varepsilon \beta \cdot \varepsilon_m = K'_\varepsilon \cdot \varepsilon_m,
\]

where \( K'_\varepsilon = \beta \cdot K_\varepsilon \) is called the monitoring strain sensitivity of the FBG and its value is the product of the strain sensitivity of the FBG and the strain transfer ratio; \( K'_\varepsilon \) directly establishes the relationship between the change value of wavelength \( \Delta \lambda \) and the matrix strain \( \varepsilon_m \). This is the most important index reflecting the monitoring reliability of FBG. \( \Delta \lambda \) can be obtained from the difference between the central wavelength measured by the FBG demodulator and the initial wavelength, \( \varepsilon_m \). The strain in the matrix is given by \( \varepsilon_m = F/EA \). In this test, the matrix is the central wire of the steel strand being tested, \( F \) is the tensile force of the central wire in the stretching test, \( E \) is the elastic modulus of the steel strand with a value of \( 1.95 \times 10^5 \text{MPa} \), and \( A \) is the cross-sectional area of the central wire’s matrix, with a value of \( 21.2 \text{mm}^2 \).

The reliability and accuracy of the FBG monitoring reflect its monitoring strain sensitivity for each time period. Changes in the monitoring strain sensitivity for Groups I and II are shown in Figures 4 and 5.

It can be seen in Figures 4 and 5 that the change law for the monitoring strain sensitivity of the Group I and Group II specimens was basically the same. Over the course of the

### Table 1: Components of the acid medium.

| Concentration gradient for acidic corrosion (%) | Concentrated HCL (37%) (ml) | NaCl | NaSO₄ | Distilled water (L) | pH value |
|-----------------------------------------------|-----------------------------|------|-------|---------------------|----------|
| 0.0                                           | 0                           | 315.789 g | 44.375 g | 6                   | 7        |
| 0.3                                           | 49.05                       | 315.789 g | 44.375 g | 6                   | 1.08     |
| 0.6                                           | 98.9                        | 315.789 g | 44.375 g | 6                   | 0.71     |
| 0.8                                           | 132.6                       | 315.789 g | 44.375 g | 6                   | 0.58     |
| 1                                             | 166.7                       | 315.789 g | 44.375 g | 6                   | 0.56     |

### Table 2: Specimen arrangement.

| Specimen number | I-01 | I-02 | I-03 | I-04 | I-05 | II-01 | II-02 | II-03 | II-04 | II-05 |
|-----------------|------|------|------|------|------|-------|-------|-------|-------|-------|
| Sustained loading value of central wire        | 0    | 0    | 0    | 0    | 0    | 0.3P₀ | 0.3P₀ | 0.3P₀ | 0.3P₀ | 0.3P₀ |
| Corrosion solution concentration (%)           | 0.0  | 0.3  | 0.6  | 0.8  | 1.0  | 0.0   | 0.3   | 0.6   | 0.8   | 1.0   |

Note: \( P₀ \) is the ultimate bearing capacity of the central wire. \( P₀ = 39.5 \text{kN} \) according to the strength of the test material.
experiment, the monitoring strain sensitivity of the self-sensing strands fluctuated after being corroded in the solution, with the sensitivity decreasing rapidly at first, then rising rapidly, and then decreasing slowly. The fluctuations were at their maximum after 72h of corrosion. The most typical feature of the two groups of samples was that the monitoring strain sensitivity did not decrease slowly to zero, but to about 80% of the initial value, at which point the sensor suddenly failed, and the failure mode was that the packaging material was peeled off. The failure time was related to the concentration of the corrosive solution: the higher the concentration, the shorter the time until failure. The failure time for the Group I specimens was 912 h, 528 h, 480 h, and 408 h, respectively. The failure time of the Group II specimens was 816 h, 504 h, 456 h, and 384 h, respectively. However, the time until failure did not decrease in proportion to the concentration of the corrosive solution. The interval until the failure time reduced with an increase in the concentration, meaning that the failure time tended to be the same as the increase of the solution’s concentration.

A comparison of the sensor monitoring strain sensitivity between the two groups of specimens in corrosive solutions of the same concentration is shown in Figures 6–9. Figures 6–9 show the monitoring strain sensitivity of the FBG sensors under two different stress conditions in identically corrosive environments. As time passed, the monitoring strain sensitivity of the self-sensing central wire in Group II decreased more than it did in Group I. This is because the self-sensing central wire in Group II was simultaneously being corroded by the acidic environment and

![Figure 3: The corrosion process for specimen II-03. (a) Before corrosion. (b) Corrosion after 72 h. (c) Corrosion after 144 h. (d) Corrosion after 264 h. (e) Corrosion after 360 h. (f) Corrosion after 456 h.](image)
subjected to stress corrosion, which accelerated its failure time.

3. FBG Corrosion Durability and Life Expectancy

3.1. Methods for Predicting Life Expectancy. Predicting life expectancy refers to the calculation of the service life of a product under natural conditions using mathematical models that are based on a series of accelerated experimental results realized by enhancing the conditions of environmental stress. Mathematical models are usually used that can combine the action of multiple kinds of environmental stress. The relationship between environmental stress and life expectancy is established by linear regression. The Arrhenius model and inverse power law model are two of the most commonly used acceleration models [43–46]. Their linearization equations can be uniformly expressed in the following form:

\[
\ln \psi = a + bv,
\]

where \( \psi \) is the life expectancy; \( a \) is a constant; \( b \) is a constant associated with the activation energy; and \( v \) is the degradation impact factor. In that case, the acid durability life expectancy equation for an FBG sensor will be

![Figure 4: Comparison of the sensor sensitivity for the Group I specimens.](image-url)

![Figure 5: Comparison of the sensor sensitivity for the Group II specimens.](image-url)
Here, $\psi$ is the life expectancy of an FBG sensor; $v$ is the pH value of simulated acidic solution; $A = e^a$; and $a$ and $b$ are parameters still to be determined.

The undetermined parameters can be obtained by linear fitting through the least square method. The pH value can be calculated using the ratio of the simulated acidic solution. The life expectancy, $\psi$, of an FBG sensor can thus be determined according to the acid durability test results. These are shown in Table 3.

The data in Table 3 can be substituted into equation (5), and linear fitting of the data can be conducted. This delivers the results shown in Figures 10 and 11.

The fitted results of the durability test for FBG sensors in an unstressed state were $a = 5.269$, $b = 1.425$, with the degree of fit, $R^2$, having a high value of 0.9916. The fitted results of the durability test for FBG sensors under conditions of pre-loading with 30% of the ultimate bearing capacity were $a = 5.313$, $b = 1.284$, with a degree of fit, $R^2$, of 0.9913. The degree of fit was once again very high, so the correlation can be considered good.

3.2. Life Expectancy. The equation for predicting the acidic corrosion durability of an FBG sensor can be obtained by substituting the fitted results of the test data into equation (6). This produces the following equation for predicting the acid durability and life expectancy of an unstressed FBG sensor:

$$\psi = 194.222e^{1.425v}.$$  \hfill (7)
Figure 8: Comparison of the sensor sensitivity for specimens I-04 and II-04.

Figure 9: Comparison of the sensor sensitivity for specimens I-05 and II-05.

### Table 3: Durability test results.

| Specimen number | I-01 | I-02 | I-03 | I-04 | I-05 | II-01 | II-02 | II-03 | II-04 | II-05 |
|-----------------|------|------|------|------|------|-------|-------|-------|-------|-------|
| pH value        | 7    | 1.08 | 0.71 | 0.58 | 0.56 | 7     | 1.08  | 0.71  | 0.58  | 0.56  |
| Failure time (h)| —    | 912  | 528  | 480  | 408  | —     | 816   | 504   | 456   | 396   |
The equation for predicting the acid durability and life expectancy of an FBG sensor subjected to 30% strain is as follows:

$$\psi = 202.974 e^{1.2849}.$$  \hspace{1cm} (8)

According to the above equations, predicted life curves for FBG sensors can be drawn, as shown in Figure 12. Because the $\psi$ value and increment of ordinate are very large, when pH = 4, the data seems to be close to 0. In order to express more clearly and avoid visual errors, the ordinate in Figure 12 uses logarithmic coordinates.

The pH value of the working environment of a steel strand is about 5-6, so 5.5 was selected as the pH value for predicting the sensor’s life. The predicted life until failure of an FBG sensor in a loaded state or under conditions of a pre-loaded strain of 30%, subjected to acidic corrosion, is 237203h, which is about 27 years. The predicted life in an unloaded state or in unstressed conditions is 493195h, which is about 56 years. In summary, the FBG sensor has the longer corrosion resistance life in an unstressed condition. In practical engineering applications, steel strands are always subjected to tension, and the technique of “pre-pressing” can be used to improve FBG sensor’s monitoring reliability and monitoring life. In other words, the FBG can be bonded under the loading conditions of the central wire and the central wire can be relaxed until the adhesive is fully playing its role. This gives the FBG sensor in self-sensing steel strands a “compressive stress” before service, such that the “tensile stress” produced during service can be completely or partially offset by this “compressive stress.” That can make
FBG sensor close to zero stress state or reduce stress level, so as to improve its monitoring reliability and monitoring life.

4. Conclusion

In the study reported here, simulated acidic environment corrosion tests, in combination with tensile tests, were carried out on FBG-based self-sensing steel strands. The monitoring reliability and predicted service life of them in an acidic environment were studied. The conclusions of the study are as follows:

1. The main reason for the failure of FBG-based self-sensing steel strands in acidic environments is the corrosion of the bonding interface between the adhesive and the steel strand matrix. Corrosion developed from edge to groove bottom. Finally, when the FBG sensor is not broken, the adhesive peeled off completely and the FBG sensor monitoring failed.

2. In the corrosive acidic environment, the monitoring strain sensitivity decreases with time. However, the value did not drop straight to 0, but rather to about 80% of the initial value, at which point the sensor suddenly failed.

3. The failure time for FBG sensors is related to the concentration of the corrosive solution. The higher the concentration, the earlier the failure time. However, the failure time did not reduce in proportion to the concentration of the corrosive solution.

4. The corrosion resistance life of FBG-based self-sensing steel strands is related to the FBG sensor’s stress state. The sensor that has the longest corrosion resistance life is in an unstressed condition. The technique of “pre-pressing” can make FBG sensor close to zero stress state or reduce stress level, so as to improve its monitoring reliability and monitoring life.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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