The experimental evaluation of FBG sensor for strain measurement of prestressed steel strand

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Abstract
Multi-wire steel strands have been widely used in various prestressed concrete structures. In this study, experimental evaluation of fiber Bragg grating (FBG) sensors for strain measurements in a seven-wire prestressed steel strand has been carried out. An installation technique of FBG sensors has been developed to fulfill the special requirements of the prestressed steel strand. The experiment results show that fiber Bragg gratings can represent the overall stress of the prestressed steel strand without being affected by the specific structure of the strand when it is only fixed on one wire. It is also demonstrated that the maximum strain that the FBG sensor can measure is $6260 \, \mu\varepsilon$, while the prestressed steel strand usually endures the strain greater than $10000 \, \mu\varepsilon$. This means that an offset of about $4000 \, \mu\varepsilon$ is necessary to measure the maximum strain that the strand could experience in its applications.

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The Experimental evaluation of FBG sensor for strain measurement of prestressed steel strand

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ABSTRACT

Multi-wire steel strands have been widely used in various prestressed concrete structures. In this study, experimental evaluation of fiber Bragg grating (FBG) sensors for strain measurements in a seven-wire prestressed steel strand has been carried out. An installation technique of FBG sensors has been developed to fulfill the special requirements of the prestressed steel strand. The experiment results show that fiber Bragg gratings can represent the overall stress of the prestressed steel strand without being affected by the specific structure of the strand when it is only fixed on one wire. It is also demonstrated that the maximum strain that the FBG sensor can measure is 6260 \( \mu \varepsilon \), while the prestressed steel strand usually endures the strain greater than 10000 \( \mu \varepsilon \). This means that an offset of about 4000 \( \mu \varepsilon \) is necessary to measure the maximum strain that the strand could experience in its applications.

Keywords: fiber Bragg grating, fiber sensing, prestressed steel strand, strain

1. INTRODUCTION

Prestressed concrete structures have been widely used in bridges, buildings, tunnels and dams because of their obvious advantages such as reducing the cross-section and weight of the structures, saving materials, and reducing the deflection, etc. Among the different types of materials already used in the prestressed concrete structures to generate the tension, multi-core steel strands have the features such as flexible and easy to transport, therefore have been popularly adopted. The steel strand embedded in a concrete structure can experience non-uniformly distributed forces along its length because of the friction loss and lateral stress. In large-span structures, the force occurred at different locations of a strand could vary quite significantly. As the strand is embedded inside the structure, it is almost impossible to examine the condition of the strand from the surface of the structure. This means that any signs of possible failure of the strand would not be easily detected. Therefore, it is important to monitor the stress distribution along the length of a strand in a concrete structure during its construction period and the whole lifetime of its service. This is extremely important for large-span structures such as bridges and public buildings to avoid catastrophic damages. Furthermore, monitoring the internal strains and strain variations in the prestressed concrete structures can also provide valuable information for maintenance purpose.

Electrical sensors such as strain gauges have been widely used to measure the strains of concrete structures. However, limited by the lifetime of the electrical sensors, it is difficult to build a measurement system for the long-time monitoring purpose. On the other hand, electrical sensors are sensitive to electrical interferences from naturally happened incidents such as lightening and storms, and man-made electrical sources.
In recent years, optical fiber based sensing systems have been developed and used extensively in concrete and steel structures to monitor strain and temperature\textsuperscript{1-3}. In contrast to the conventional strain gauges, fiber sensors have a number of advantages, such as small physical size, inherent immunity to electro-magnetic interference, and wavelength multiplexing capability. Particularly, with the invention and the rapid development of fiber Bragg grating (FBG), a new class of fiber sensing systems has been explored and applied in various areas including the structural health monitoring\textsuperscript{4,6}. As FBGs can be easily embedded into the structure to be measured, they have become important parts of the so-called smart structures, and have attracted much research attention in recent years. FBG sensors have been used to measure strain and temperature of the concrete structures. In this study, we investigate the feasibility of applying FBG sensors in monitoring the strain of multi-wire steel strand for prestressed structures. In the following sections, after a brief introduction the FBG sensing, we describe the fabrication and calibration of the FBG sensors used in our experiments. In Section 4, we give a detailed description of the sensor installation and the sample preparation. Section 5 presents the experiments and results. We conclude in Section 6.

2. FBG SENSING SYSTEM

A fiber Bragg grating (FBG) is formed by periodically modulating the refractive index of the core of an optical fiber. This all-fiber component can selectively reflect the light of a wavelength defined by the grating period and the refractive index of the fiber core. The potential applications of FBG devices in both optical fiber communications and fiber sensing areas had been realized immediately after its discovery in 1978 and, since then intensive research has been devoted to the development of FBG sensing systems and their applications\textsuperscript{7,8}. FBG sensing provides unique advantages over conventional electrical sensors and can be used in applications where electrical sensors are limited. These advantages include:
1. High bandwidth and multiplexing capabilities;
2. Immunity to electromagnetic and RF interference;
3. Immunity to chemicals, radioactivity, corrosion and lightning;
4. Intrinsic sensing of multiple measurands without referencing;
5. Stability, repeatability and durability against harsh environments; and
6. High sensitivity and resolution, and fast response.

In recent years, FBG sensing is gaining considerable attention in both scientific research areas and engineering applications. This is evidenced by the exponentially increased numbers of published research works in this area. FBG sensing has been widely used to measure strain, temperature, and pressure in various fields ranging from the smart structures, structural health monitoring to aerospace industries. FBG sensing and its applications in various situations have been well described in a number of recently published reviews\textsuperscript{9,10}.

FBG sensing is based on the detection of the shifted Bragg wavelength of the light reflected by a fiber grating which is sensitive to strain and temperature. A Bragg grating with an effective refractive index of \( n_{\text{eff}} \) and a period of \( \Lambda \) will reflect the light at the so-called Bragg wavelength, \( \lambda_B \). The relation is given by

\[
\lambda_B = 2n_{\text{eff}} \Lambda .
\]  

(1)

The Bragg wavelength will vary with the grating period \( \Lambda \) and the effective refractive index \( n_{\text{eff}} \). The change of the Bragg wavelength, \( \Delta \lambda_B \), can be expressed as

\[
\Delta \lambda_B = 2n_{\text{eff}} \Delta \Lambda + 2\Lambda \Delta n_{\text{eff}} .
\]  

(2)

Both \( \Delta \Lambda \) and \( \Delta n_{\text{eff}} \) depend on the strain that is applied to the grating and the temperature that the grating experience because the physical elongation, thermal expansion, and photoelastic effects. The wavelength shift caused by strain and temperature variations can be expressed as

\[
\Delta \lambda_B = 2n_{\text{eff}} \Lambda \left( \left\{ 1 - \left( \frac{n_{\text{eff}}^2}{2} \right) \left[ p_{11} - \nu (p_{12} + p_{11}) \right] \right\} \Delta \varepsilon + \left[ \alpha + \left( \frac{dn_{\text{eff}}}{dT} \right) / n_{\text{eff}} \right] \Delta T \right) ,
\]  

(3)
where, $\Delta \varepsilon$ is the change of the applied strain; $p_{11}$ and $p_{12}$ are the Pockels’s coefficients of the fiber material; $\nu$ is Poisson’s ratio; and $\alpha$ is the coefficient of thermal expansion of the fiber material.

Using Eq.(3) and the parameters of an FBG, the sensitivities of an FBG sensor to strain and temperature can be calculated. Typical values for an FBG with a central wavelength of 1550 nm are $1.2 \, \text{pm/}\mu\varepsilon$ and $11.3 \, \text{pm/}^\circ\text{C}$. Normally these factors need to be experimentally calibrated before the sensor is installed to the structure.

In order to detect the wavelength shifts, a wavelength demodulation system has to be used. Optical spectrum analyzers (OSAs) are frequently used to measure the wavelength shifts in FBG sensing systems. An OSA is most suitable for laboratory tests, but not an ideal solution for field applications in terms of the cost and convenience. Different wavelength demodulation methods have been developed for FBG sensing purpose, including scanning Fabry-Perot filter-based interrogation, tunable acousto-optic filter interrogation, and prism/CCD-array technique. Another method is employing a bulk linear edge filter to convert the wavelength shifts to intensity variations.

\[ \text{Fig.1 Measured transmission spectrum of an FBG sensor} \]

### 3. FBG SENSOR FIBRICATION AND CHARACTERIZATION

FBGs were fabricated and characterized for measuring the strains of a seven-wire steel strand. Standard communications fiber was first hydrogenated to make it photosensitive to UV light. A frequency-doubled Argon laser operating at 244 nm wavelength was used for writing grating structures into the fiber through a phase mask. The length of the grating part was 10 mm. After writing, the gratings were thermally annealed to stabilize the change of the refractive index. The fabricated gratings were measured by using an OSA. A measured spectrum is shown in Fig.1.

\[ \text{Fig.2 Schematic diagram of the experimental set-up for measuring the strain sensitivity of an FBG} \]
In order to measure the strain sensitivity of the gratings, we generated the strain by fixing one end of the grating on a PZT stage (from PI). The PZT stage, which is equipped with a capacitive feedback sensor, can provide sub-nanometer resolution and stability in displacement. By changing the voltage applied to the PZT actuator and taking the readings of the displacement sensor, we could accurately generate and control the strain applied to the grating under test. A schematic diagram of the experimental set-up is shown in Fig. 2. An ASE source was used as the broadband light source in the test. Through a three-port circulator, the reflected light by the grating was coupled to a...
wavelength meter (Burleigh WA-1100) to measure the wavelength of the reflected light. The wavelength meter has a resolution of 1 pm nm and uncertainty of ±3 pm. An OSA was also used to monitor the spectra reflected by the grating under test. The measurements were carried out in an air-conditioned laboratory. The room temperature was 25°C during the tests. Shown in Fig. 3 is the measured wavelength shifts under different strains, from which the strain sensitivity of the grating was calculated as 1.04 \( \frac{\text{pm}}{\mu \text{e}} \).

4. FBG SENSOR INSTALLATION

The steel strand used in this study consists of seven wires, with a total cross-section of 140 mm\(^2\). The strand is made of high tensile strength steel (class 1860). A cross-section of the strand is shown in Fig. 4a. The central wire has a diameter slightly larger than those surrounding it. From Fig. 4a, it can be seen that FBG sensor (with a diameter of 125 \( \mu \text{m} \)) and the fiber cable (diameter 0.9 mm) can be easily installed in the space between two adjacent steel wires. This will make it possible that after the installation of the FBG sensor, the strand can still be used as normal without extra treatment. A 3D drawing of the test piece of the strand with an FBG sensor attached is shown in Fig. 4b. The length of the test piece was 660 mm. A section of the surface of one of the seven wires was polished and cleaned thoroughly. Then the FBG sensor was attached to the wire along its spiral shape. In order to install the sensor in the designated position, two ends of the sensor were first fixed with sticky tapes, and after fine adjustment, epoxy resin was applied to the grating part (10 mm long) and the lead fibers. The lead fibers were protected by using plastic tubes with an outer diameter of 0.9 mm. The ends of the plastic tubes were also glued with the epoxy resin. The epoxy resin had been cured in room temperature for 24 hours before it was used in the tests. Fig. 5 depicts the details of the steel wire with an FBG sensor attached.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig5.png}
\caption{FBG sensor installed on one of the seven steel wires of a strand}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig6.png}
\caption{Schematic diagram of the test equipment}
\end{figure}
5. TESTS AND RESULTS

Tests were carried out on a testing machine (LEX-600). Fig. 6 shows the experimental set-up. The strand with an FBG sensor attached was vertically clamped to the testing machine. An elongation gauge was also attached to the strand to measure the elongation under different tensions applied to the strand. One of the fiber leads was connected to an ASE broadband light source, and another was coupled to an OSA (Agilent 86142) to measure the Bragg wavelength shifts in the transmission spectra of the FBG sensor. Through the front panel of the testing machine, one could control the tension applied to the strand and record the force generated. In the tests, the force applied to the strand was first increased to a certain level, and then decreased with an increment of about 10 kN. The Bragg wavelength was monitored and measured by the OSA during the cycles of loading and unloading. From the measured wavelength shifts, the strains under different tensions were calculated (using the calibrated strain sensitivity). During the experiments, the environment temperature was kept constant (23°C), hence the wavelength shifts were believed to be caused only by the strain variations.

The measured strains under different tensions at the first and the third cycles are shown in Fig. 7. It can be seen that a reasonably linear relation between the strain and the applied force exists and there is no hysteresis between the loading and the unloading processes.

When the force reached 152 kN in the third loading, we noticed that the shape of the transmission spectrum of the FBG sensor changed dramatically and the central wavelength did not increase any more. Further increasing the tension caused the wavelength decreasing. This indicated that the FBG sensor was damaged at the tension of 152 kN, at which the strain was measured as 6260 με.

![Fig. 7 Measured strains under different tensions](image)

6. CONCLUSIONS

The rapid development of FBG sensors creates the possibility to monitor the strain distribution along multi-wire steel strands which have been widely used in the prestressed concrete structures. We have experimentally investigated the feasibility of using FBG sensors for measuring the strain of a seven-wire steel strand. Preliminary test results show that by properly installing the FBG sensor on one of the steel wires, the overall strain of the strand can be measured. With the sample prepared, the force could reach 152 kN before the failure happened to the sensor. The strain was measured as 6260 με at this tension. As the maximum force that the strand can endure is 250kN, in order to...
measure the behavior that the strand could have at the maximum tension, it is therefore necessary to modify the sensor installation. One possible method is to install the sensor at a certain amount of pre-tension, so that the measurement range of the FBG sensor will be shifted towards a higher region. Alternatively, polymer fiber gratings with a much larger strain measurement range should be used for this purpose.

REFERENCES