Strain Measurement and Defect Detection with Fiber-Optic Sensors Embedded into the Cement Sample

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Abstract. The application of embedded into material fiber-optic sensors based on Bragg gratings for strain measurement on the example of a cement sample during the manufacturing stage, under operational loads and upon the appearance and development of a defect is studied in the paper. The integrity and performance of fiber-optic sensors at all stages of the study, as well as the efficiency of strain measurement, have been demonstrated. An approach is implemented to register the appearance and development of defects based on information received from embedded fiber-optic sensors. The approach considered in the study is based on the location of sensors in the vicinity of the expected damage. The results obtained indicate the possibility of using embedded fiber-optic sensors to assess the mechanical state of civil structures.

1. Introduction
Structural health monitoring systems allow for a timely assessment of the structural integrity, and therefore increase the operational safety, optimize the economic costs associated with repairs and extend the service life of various structures [1,2]. In this regard, research related to the introduction of more advanced and effective monitoring systems, ranging from simple and sometimes insufficiently effective, to the ones that utilizes sensors that can be embedded into the material at the manufacturing stage of structure, is of great importance. Fiber-optic sensors (FOSs) based on fiber Bragg gratings (FBGs) have a number of distinctive advantages [3] over standard sensing elements and allow to obtain accurate and reliable information about the observed structures. Their ability to work in a wide temperature range, immunity to electromagnetic interference, as well as their small size, which allows them to be embedded in various materials, open up prospects for monitoring the mechanical state and integrity of structures throughout the entire life cycle, starting from manufacturing [4–6].

The reliability of measuring the controlled value (strain, temperature, force, etc.) by fiber-optic sensors based on Bragg gratings is influenced by many factors, including the features and methods of mounting sensors on the surface of the structure and options for arranging protection of the sensors when they are embedded in the material structure [7,8]. Despite the fact that the presence of additional protective encapsulation for FOSs embedded into concrete structures is of great practical importance [9] from the point of view of ensuring the integrity of the fiber, they inevitably lead to measurement errors and the need to use additional calibration experiments. In this study, an attempt was made to embed an optical fiber that does not contain additional protective packages in the FBG location area, except for the standard polyimide coating. Thus, it was possible to avoid the additional recalculation of the strain values obtained with the FOSs, which is necessary to restore the real strain distribution picture in the controlled material [10,11].

The research objective was to study the possibility of using fiber-optic sensors embedded into the structure for registration the mechanical behavior and state of the structure at different stages of its life cycle, including the manufacturing stage. Cement mixture was used as a structural material, which is an important component of concretes, since it is largely determines the future properties of the structure.
The work identifies three main stages at which the data are recorded by the embedded fiber-optic sensors: registration of process-induced strains at the manufacturing stage; registration of mechanical behavior under operational loads, as well as the possibility of registering the formation and development of defects. The experimental results were compared with the results of numerical simulation.

2. Manufacturing and formation of the studied sample

A prismatic shape sample with dimensions of 400x70x70 mm made from cement mixture was selected as an object of study. During the preparation of the sample an optical fiber with three 5 mm length FBGs (s1, s2, s3) located at a distance of 25 mm from each other was embedded at a distance of 20 mm from the bottom surface of the sample according to the scheme in figure 1a. After placing the fiber-optic line, with the tension necessary to maintain the straight-line arrangement of the fiber, the mold made of moisture-resistant plywood was filled with cement mixture. To create a cement sample, Portland cement 400 and river sand were used in a ratio of 1:5. The view of the manufactured sample with embedded optical fiber (FOS) is presented in figure 1b.

![Figure 1. Scheme (a) and photograph (b) of a cement sample with embedded fiber-optic sensors.](image)

The data from fiber-optic sensors was continuously collected with sampling frequency of 1 Hz during 500 hours after pouring of the sample. In figure 2a the resonance wavelength shift $\Delta\lambda$ of the reflected from the gratings optical signal is shown for the designated period of time. At the initial stage of sample formation, chemical reactions occur associated with the release of heat. Since the temperature compensation procedure was not carried out during the experiment the readings recorded with the help of fiber-optic sensors are the reaction of the sensing element, both to temperature changes and mechanical strain. According to the results obtained in the earlier study [13] during the formation process after the initial stage of heating of the sample, it cools down to room temperature. The data obtained from the embedded FOSs shows that after the initial heating of the cement mixture, there is a constant decrease in the resonance wavelength with time, which indicates the formation of process-induced strains.

In order to be able to assess the mechanical state of an object during its operation, the FOS must maintain its integrity and operability after being embedded as well as at the end of the formation process of the sample. The integrity of the sensor is ensured by the recorded reflected optical signal, while the quality of the measurements can be affected by the shape of the reflected spectrum. It is known that after embedding an FBG sensor into various materials, situations are possible when the reflected optical spectrum becomes significantly distorted, as a result of which measurements can become less stable and predictable [14,15]. As a demonstration of embedded into cement mixture fiber-optic sensor’s condition, the spectra of the s2 sensor are shown at the initial moment of time before pouring the sample (1 in figures 2a and 2b), at the moment of maximum heating of the cement mixture, when the shift of the resonant wavelength to the right reaches its maximum (2 in figures 2a and 2b), and 500 hours after pouring the sample (3 in figures 2a and 2b). The spectrum of the reflected signal retains its shape, and only shifts in one direction or another with a change in temperature or strain.
Figure 2. Changes in the wavelength shift of the FOSs in time (a) and the spectra of the FOS s2 presented at certain points in time (b).

The microscopic picture of the cross section of previously manufactured cement sample [13] in the area of the embedded optical fiber without additional protective packages, apart from standard coating is shown in figure 3.

Figure 3. Internal structure of the sample in the area of the embedded optical fiber [13].

3. Strain measurement by embedded FOSs during three-point bending test of a cement sample

The next stage of the study is related to the strain measurement in manufactured cement sample under external loading according to the three-point bending scheme shown in figure 4a with the help of embedded FOSs based on Bragg gratings. To transfer the load, a prismatic steel element with an octagonal section was used. A photograph of the sample under loading is shown in figure 4b.

Figure 4. A three-point bending loading scheme of a cement sample (a) and photo of the experiment (b).

In the course of the experiment, a stepwise increase in the load was carried out with holding the constant load level at each stage for 2 minutes and unloading before each stage of loading (figure 5). The obtained
experimental results were compared with the results of numerical simulation by the finite element method. In numerical modeling, a linear elastic model of material behavior was used. The mechanical characteristics of the cement (\(E = 9.2\, \text{GPa}, \ \nu = 0.18\)) were selected according to the results of the experiment at one of the loading stages. The given values of the numerical simulation are the average result over the length of the corresponding Bragg grating.

In figure 6, the solid line shows the strain distribution at different load levels along the line of the optical fiber embedded in the material, obtained using the finite element method. The points, the coordinate along the length of the sample of which corresponds to the center of each of the Bragg gratings, show the experimental values obtained by the embedded FOSs.

![Figure 5. Applied loading levels.](image1)

![Figure 6. Strain distribution along optical fiber and embedded sensors measurements at various loading levels.](image2)

Figure 7 shows the strain-force dependences obtained using embedded FOSs and using the finite element method. Table 1 shows the experimental (FBG) and numerical results (FEM) obtained for each of the sensors and the difference (\(\delta\)) between them.

![Figure 7. Strain dependence on load during bending of a cement sample obtained using the embedded fiber-optic sensor and numerical simulation.](image3)

The high sensitivity of the FOSs should be noted, which makes it possible to measure even small levels of strain. The experimental results showed a close to linear behavior of the material at these load levels and good agreement with the results of numerical simulation within 2.5% for sensor s1, 6% for sensor s2 and 10% for sensor s3.
### Table 1. The strain values obtained from the embedded FBGs, using the numerical simulation method and the relative error between them.

| Force, N | FBG s1 (με) | FEM s1 (με) | δs1 (%) | FBG s2 (με) | FEM s2 (με) | δs2 (%) | FBG s3 (με) | FEM s3 (με) | δs3 (%) |
|---------|-------------|-------------|---------|-------------|-------------|---------|-------------|-------------|---------|
| 107.87  | 3.45        | 3.46        | 0.43    | 3.54        | 3.65        | 2.94    | 3.18        | 3.46        | 8.11    |
| 157.14  | 5.16        | 5.21        | 0.82    | 5.15        | 5.48        | 5.99    | 4.69        | 5.21        | 9.83    |
| 205.71  | 6.97        | 6.92        | 0.76    | 7.25        | 7.29        | 0.52    | 6.88        | 6.92        | 0.62    |
| 306.51  | 10.68       | 10.48       | 1.91    | 11.28       | 11.04       | 2.19    | 10.77       | 10.48       | 2.73    |
| 355.08  | 12.50       | 12.20       | 2.47    | 12.83       | 12.84       | 0.12    | 12.27       | 12.20       | 0.58    |
| 403.22  | 13.86       | 13.90       | 0.30    | 14.77       | 14.63       | 0.93    | 14.60       | 13.90       | 5.05    |

4. Defect detection using embedded fiber-optic sensors

Structural health monitoring systems should not only be able to measure strain at different locations of the structure under operational loads with high reliability but also have the ability to detect the appearance and development of defects with the help of applied sensors. In this paper, the defect detection approach is based on the registration changes in the strain field introduced due to the defect appearance using embedded sensors [16]. The ratio \( k \) of the current strain level \( \varepsilon^* \) in the area of the sensor location to the strain in the initial undamaged state \( \varepsilon_0 \) at the same load level is used as an indicator of damage:

\[
k = \frac{\varepsilon^*}{\varepsilon_0}.
\]

Thus, if there are no changes in the strain field as a result of damage occurring in the sensor’s sensitivity zone, this ratio will be equal to 1, a change in the ratio signals the appearance and growth of damage.

To assess the approach efficiency, a series of experiments was carried out with the imitation of the crack appearance in the sample by introducing the cut out. During experiment, the length of the cut was increased from 5 mm to 15 mm in several stages and the sample was loaded with a force of 403 N according to the scheme described in section 3. The location of the crack was shifted from the center along the length of the sample in order to assess the different response of the side located sensors to the introduced defect (figure 8).

Initially, the implementation of this approach was carried out using numerical simulation and showed the greatest response to the introduced defect of the centrally located s2 sensor. Since the introduced defect is located between the s1 and s2 sensors, the s1 sensor also effectively register the appearance and growth of the defect, while the readings of the s3 sensor are weakly dependent on the defect appearance and growth in the size.

![Figure 8. Scheme (a) and photograph (b) of a cement sample with a defect.](image)

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\( \varepsilon^* \) is the current strain level and \( \varepsilon_0 \) is the strain in the initial undamaged state.
Figure 9 shows the experimental and numerical dependences of the analyzed ratio $k$ on the defect length. There is a qualitative agreement between the numerical and experimental results. According to the strain distributions along the optical fiber at different defect lengths, obtained with the help of finite element method shown in figure 10, it is possible to estimate in which zones of the strain gradient the embedded FOS are located.

![Figure 9. Dependence of the ratio $k$ on the defect length.](image1)

![Figure 10. Strain distribution along the optical fiber at different defect lengths.](image2)

It is important to note that the considered approach is limited to cases when the force acting on the controlled object is known, as well as the reference readings of the sensors at a given load in the initial defect-free state. Nevertheless, the considered method allows a rough assessment of the presence of a defect in the structure and can be used as a source of additional information for conducting non-destructive testing of the structure under study.

5. Conclusions
The possibilities of using embedded fiber-optic sensors for registration the mechanical behavior and state of a cement sample at different stages of the structure's life cycle are presented. It is shown that the embedded optical fiber without additional protective encapsulations retains its integrity and operability after pouring and hardening of the cement mixture and makes it possible to record the process-induced strains arising during the material formation. A three-point bending experiment was carried out in order to test the ability of the Bragg gratings embedded into the cement sample to measure strain under operational loads. A good agreement of the experimental data obtained with the embedded FOSs based on Bragg gratings with the results of numerical simulation is shown. The possibility of using embedded FOSs for registration of a defect appearance and development has been demonstrated. Despite a number of limitations associated with ensuring the integrity of the optical fiber, the considered approach can be used for various laboratory studies.

Acknowledgments
The research was supported by Russian Science Foundation (project No. 19-77-30008).

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