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IMPLEMENTATION OF FIBER-OPTIC SENSING SYSTEMS IN STRUCTURAL HEALTH MONITORING OF CONCRETE

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Abstract. *The study explores various fiber-optic sensing approaches, focusing on their application, implementation, and performance assessment for monitoring the structural health of concrete frameworks. It emphasizes the use of single-mode optical fibers due to their effectiveness in detecting microcracks, deformations, and temperature shifts in reinforced concrete. The investigation involved analyzing changes in optical characteristics through tests utilizing fiber Bragg grating (FBG) sensors embedded within concrete specimens exposed to mechanical loads and temperature fluctuations. Both graphical and quantitative analyses demonstrate that fiber-optic sensors enable real-time monitoring of stress and strain in concrete with high microstrain-level accuracy. Simulation work conducted using MATLAB confirmed the sensors' responsiveness and long-term stability, particularly in detecting structural changes resulting from thermal effects and mechanical stress. Additionally, the thermal behavior of the sensors was examined using laser-based measurement systems in conjunction with Peltier modules. The research contributes to the advancement of intelligent SHM systems, aiming to enhance the durability and safety of civil infrastructure, especially in seismically active regions.*

Keywords: fiber-optic sensors, structural health monitoring, concrete deformation, Bragg grating, temperature sensing

ZASTOSOWANIE SYSTEMÓW CZUJNIKÓW ŚWIATŁOWODOWYCH W MONITOROWANIU STANU TECHNICZNEGO KONSTRUKCJI BETONOWYCH

Streszczenie. *Badanie analizuje różne podejścia do czujników światłowodowych, koncentrując się na ich zastosowaniu, implementacji oraz ocenie wydajności w monitorowaniu stanu technicznego konstrukcji betonowych. Szczególną uwagę poświęcono jednomodowym światłowodom, ze względu na ich skuteczność w wykrywaniu mikropęknięć, odkształceń oraz zmian temperatury w żelbetowych strukturach. Przeprowadzono analizę zmian parametrów optycznych za pomocą testów z wykorzystaniem siatek Bragga (FBG), osadzonych w próbnych elementach betonowych, poddanych obciążeniom mechanicznym i zmianom temperatury. Analizy graficzne i ilościowe wykazały, że czujniki światłowodowe umożliwiają ciągłe monitorowanie naprężeń i odkształceń w betonie z wysoką dokładnością w zakresie mikroodkształceń. Symulacje przeprowadzone w środowisku MATLAB potwierdziły wysoką czułość i trwałość czujników, szczególnie w wykrywaniu zmian strukturalnych wynikających z rozszerzalności cieplnej oraz działania sił mechanicznych. Zachowanie termiczne czujników zostało dodatkowo zbadane przy użyciu systemów pomiarowych opartych na laserach oraz modułach Peltiera. Przeprowadzone badania przyczyniają się do rozwoju inteligentnych systemów SHM, których celem jest zwiększenie trwałości i bezpieczeństwa infrastruktury cywilnej, zwłaszcza na obszarach zagrożonych trzęsieniami ziemi.*

Słowa kluczowe: czujniki światłowodowe, monitorowanie stanu technicznego, deformacja betonu, siatki Bragga, pomiar temperatury

Introduction

As global construction activity and infrastructure development accelerate, construction projects are increasingly facing complex challenges. To ensure both the safety during construction and the long-term reliability of structures, it is essential to design and implement appropriate engineering solutions. In this context, structural health monitoring (SHM) has become a vital strategy for evaluating structural performance and forecasting potential issues during the maintenance phase.

A key element in effective SHM systems is the careful selection and strategic placement of sensing devices. A broad spectrum of technologies is employed in this field, ranging from electro-optical and electromechanical sensors to acoustic emission techniques, fiber-optic systems, remote sensing, imaging tools, and vibration analysis methods.

Concrete remains a widely adopted construction material due to its strength and widespread availability. Nonetheless, it is susceptible to cracking, deformation, and other forms of deterioration that may compromise its structural capacity. To monitor these changes, both traditional and modern diagnostic methods are used. While conventional techniques rely on physical strain gauges, newer approaches utilize fiber-optic technology for enhanced sensitivity and coverage.

Fiber-Optic Gauge (FOG) systems, based on Fiber-Optic Sensors (FOS), use slender optical fibers that contain embedded light-guiding components. When the fiber undergoes deformation, the optical path length changes, which alters the frequency of light traveling through it. This frequency shift is detected using optical spectrometers, providing precise measurements of strain.

Compared to other modern strain detection techniques, FOS offer several benefits. They function without the need for direct contact with structural surfaces, making them suitable for use in restricted or hard-to-access areas. Additionally, they deliver high sensitivity in stress detection and are capable of long-term operation due to their robust design.

In 2004, Nan Li conducted a comprehensive survey on the deployment of fiber-optic sensors (FOS) in a range of structural applications, including high-rise buildings, tunnels, pipelines, shafts, dams, and bridges. This early work laid the foundation for understanding the role of FOS in structural health monitoring. Subsequently, research led by Chan and collaborators expanded on these findings by offering deeper insights and presenting new use cases for fiber-optic technologies in civil engineering [7].

A structural monitoring project utilized an integrated optical fiber sensor (OFS) system to track deformation both during and after construction phases. The system was specifically employed to record structural changes occurring before, during, and following the removal of formwork. Optical sensors were selected for their discrete installation capabilities, lightweight characteristics, and strong resistance to environmental degradation. The monitoring campaign spanned ten months and was focused on a 5-meter section of a suspended slab, allowing for detailed observation of structural responses over time [15].

The present article delivers a focused analysis and comparative evaluation of several fiber-optic techniques used for microcrack detection in construction materials. It emphasizes critical areas where current detection strategies may require refinement. Furthermore, the research assesses how well the latest fiber-optic sensors perform in identifying damage within concrete structures, considering both reliability and integration potential. The article concludes with an in-depth overview of the technological landscape and discusses potential pathways for advancing optical sensing solutions in structural damage assessment [2].

A novel approach utilizing femtosecond laser processing has been developed for the measurement of relative humidity in advanced concrete composites. This method involves the integration of a Bragg grating within a low-mode CYTOP polymer optical fiber, which operates based on three dominant transmission modes. The sensor was evaluated for its sensitivity to temperature, mechanical strain, and moisture levels, demonstrating superior performance metrics when compared with similar fiber-optic configurations. The ability to precisely monitor humidity is particularly significant for high-strength concrete, where moisture levels directly affect structural durability and integrity [19].

Current literature surveys highlight recent progress in structural reinforcement methods within the construction sector, offering valuable insights for both civil and mechanical engineering disciplines. However, much of the existing research on sensor integration in reinforced concrete predominantly focuses on piezoelectric sensor technologies [10, 14].

Following the 2024 seismic event in Almaty and in accordance with updated safety regulations mandating the deployment of structural monitoring systems on construction sites, the implementation of building condition assessment technologies has become increasingly pressing [4]. Reports from Kazakhstan's National Data Center indicate that seismic tremors in the region reached a magnitude of 6.5 on the Richter scale (Fig. 1) [17].

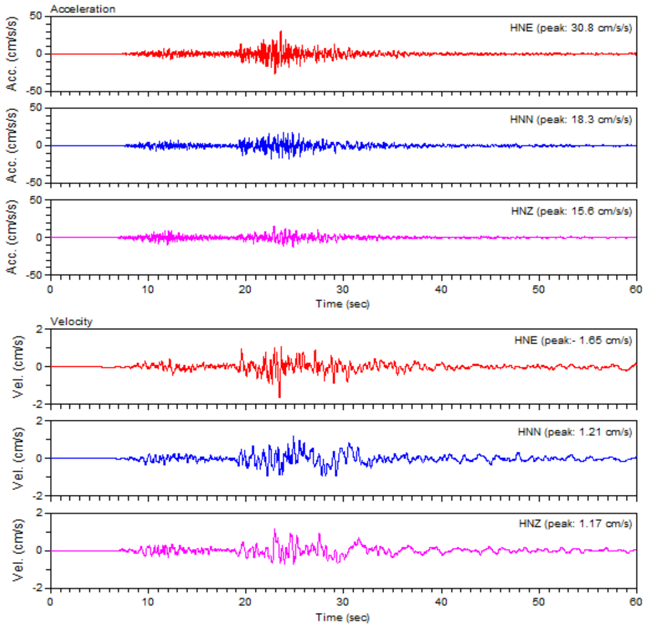

Fig. 1. Results of processing accelerometer data from the KNDC station

High-occupancy facilities such as schools, hospitals, and hotels require advanced structural monitoring systems to enhance occupant safety in regions prone to seismic activity. Integrating sensor technologies directly into buildings is essential for capturing diverse structural parameters, issuing real-time public alerts, and supporting predictive analysis of potential structural issues such as cracks, compressive damage, bending, and axial displacement [3]. This study proposes a fiber-optic sensor (FOS) setup as a promising solution to meet these needs.

Recent research has presented findings from seismic monitoring trials, highlighting the enhanced performance of geophones reinforced with graphene-coated membranes. The application of graphene contributes to improved durability without compromising the sensor's sensitivity to seismic waves. A key feature of the geophone system is its reliance on fully optical mechanisms for signal detection. Experimental comparisons indicate that the use of optical interferometry leads to a notable increase in sensitivity, outperforming traditional electrically-based detection approaches [5].

1. Materials and methods

Concrete structures are subject to various forms of movement not only during the initial placement of the material but also after full curing, continuing throughout their lifespan [9]. Monitoring these structural shifts in real time is made possible through the use of fiber-optic sensors, which are capable of detecting and quantifying deformation with a high degree of precision [20].

For the experiment, a concrete specimen with dimensions of 22×15×3 was prepared. We constructed a concrete beam that encompasses several layers of embedded single-mode SM-3.0-2.0m optical fibers. Additionally, we did not apply temporary or permanent protection to the optical fibers (Fig. 2) [1].

Fig. 2. Optical fiber integrated into concrete

The optical sensing system incorporates a dual-loop configuration utilizing a single-mode fiber segment without external protective cladding, as illustrated in Fig. 2. This design enables the fiber to maintain direct contact with the surrounding concrete, thereby enhancing its responsiveness to localized strain and the formation of microcracks. By embedding the fiber in this manner, the system achieves highly accurate detection of structural deformation from early-age behavior through to the completion of the curing process.

During experimental testing, controlled mechanical loads were applied to evaluate stress distribution throughout the concrete specimen. The evolution of internal stress was continuously tracked over time using the procedure outlined in Fig. 3.

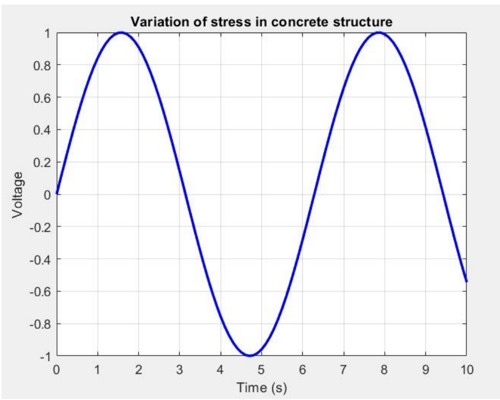

Fig. 3. Variation of stress over time in a concrete structure

According to Fig. 3, the graph displays representative signal outputs from six optical fibers positioned within the concrete element. These readings were captured both prior to and following the application of lateral and combined mechanical loads. The observed signal patterns reflect the condition of the structural beam before and after load application. Minor fluctuations in signal amplitude can be observed as the applied force (Fv) increases from 0 to 500 kg, which aligns with the elastic response range of the concrete section under examination [11].

2. Experiment and results

The monitoring system for detecting defects in concrete pavement utilizes a single-mode optical fiber, which serves as both the sensing medium and the detection component. Mechanical stress applied to the fiber alters its core signal characteristics, including phase, light frequency, and transmission intensity. These signal changes are compiled into a unified output dataset for further analysis [6, 13]. The structural response of the optical fiber under applied stress is illustrated in Fig. 4, highlighting the deformation behavior within the fiber core. Prior to experimentation, all safety protocols were rigorously followed, including verification of the physical setup, inspection of laser and fiber-optic components, and ensuring proper cable integrity.

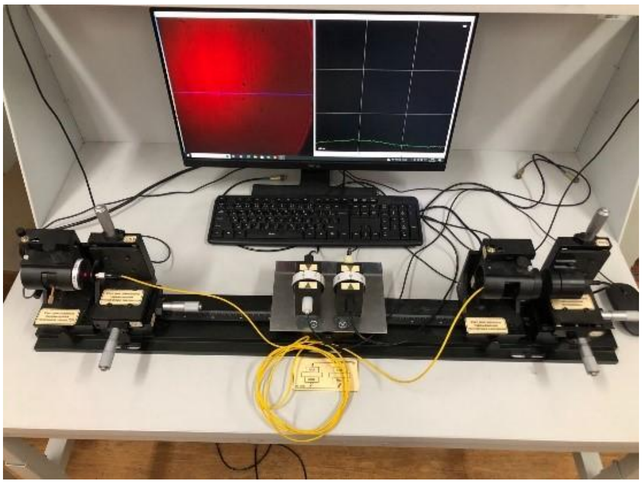

Fig. 4. Studying the structure of a single-mode optical fiber

System performance was evaluated using signal measurements summarized in Table 1, which reports power levels corresponding to various modulation frequencies at both the input and output terminals. Testing was conducted under standardized conditions, including a 1310 nm laser input, to assess system stability in response to mechanical deformation. The recorded data demonstrates consistent signal behavior, confirming the reliability of the sensing setup under dynamic stress conditions.

Table 1. Input and output values of a single-mode optical fiber in the structure of a concrete construction

Input: 1310 nm	Output: 1310 nm
0.27 kHz – 6.50dBm	69.59 dBm
100 kHz – 6.50dBm	69.69 dBm
200 kHz – 6.50dBm	70.00 dBm

Cracking in concrete structures can significantly compromise both their load-bearing capacity and projected service life. As a result, Structural Health Monitoring (SHM) systems have become a critical complement to traditional visual inspection methods in the maintenance and evaluation of these structures. Timely monitoring of a structure's condition is vital, as it facilitates early detection of anomalies and supports the implementation of effective repair strategies [16, 18].

Recent advancements in SHM technologies have produced a variety of techniques tailored for use in concrete infrastructure. These include systems based on fiber-optic sensors, piezoelectric elements, and even radiographic approaches utilizing X-rays and gamma rays. Such methods offer high-resolution, real-time data that aid engineers and maintenance professionals in identifying structural concerns at an early phase and applying suitable preservation measures. In particular, continuous monitoring using fiber-optic sensors enables the detection of subtle material changes, helping to mitigate more severe deterioration and extend the operational lifespan of concrete assets [8, 12].

The evaluation of deformation using fiber-optic sensors is based on the following formula:

$$\varepsilon[\mu\varepsilon] = \frac{10^6}{k} \cdot \frac{\Delta\lambda}{\lambda_0}$$

where: λ_0 – the initial wavelength of the sensor before deformation; $\Delta\lambda$ – is the change in the sensor′s wavelength relative to the reference value during deformation; k – is the sensor deformation factor.

Thus, deformation ε is measured in microstrain με and is calculated by dividing the change in wavelength $\Delta\lambda$ by the initial wavelength λ, multiplied by the reciprocal value of the deformation sensitivity coefficient (k) (Fig. 5).

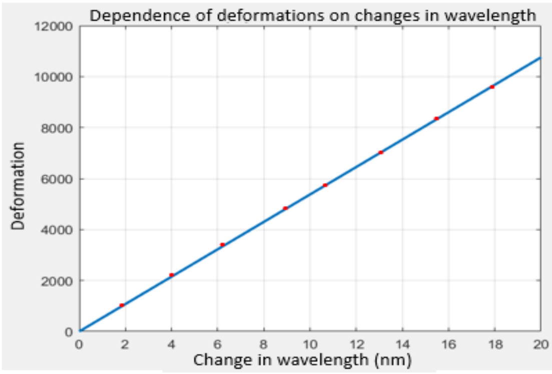

Fig. 5. Variation of deformation in relation to the change in wavelength

As illustrated in Fig. 5, a direct linear relationship is observed between the change in sensor wavelength and the increase in structural deformation. This behavior confirms the sensor's reliable and proportional response to strain, in accordance with the established deformation equation.

The study of fiber-optic deformation sensors is based on a MATLAB model that relies on the deformation equation, which is crucially dependent on the initial wavelength λ_0 and the deformation factor k. Using the linspace function, we can see a vector of wavelength change $\Delta\lambda$ from 0 to 20 nm with 100 points. Furthermore, for each value of the change in wavelength, the deformation ε is calculated using the following expression $\varepsilon = (10^6/k)\cdot(\Delta\lambda/\lambda_0)$ The resulting plot demonstrates the predicted linear dependency, and the use of labeled axes, titles, and legends improves the clarity and interpretability of the visual data.

To determine the deformation value, the change in wavelength is normalized by dividing it by the initial wavelength, and the result is then scaled using the sensor's sensitivity coefficient. A higher sensitivity constant k enhances the precision of the system, allowing it to detect finer structural changes with increased responsiveness.

In the simulation setup, an initial wavelength of 1310 nm was selected, which is a standard reference in fiber-optic sensing. A wavelength shift of 100 picometers, resulting from structural deformation, was applied to reflect realistic measurement conditions used in high-precision monitoring environments:

$$\varepsilon[\mu\varepsilon] = \frac{100\text{pm} \cdot 10^6}{1310\text{nm}} = 0.076$$

This indicates that the sensor is capable of measuring deformations up to 0.076 micrometers per meter.

3. Conclusions

This study confirmed that single-mode fiber-optic sensors are effective tools for detecting structural stress and changes within concrete components. By embedding the fibers directly into the concrete matrix and conducting a series of mechanical tests, the system successfully captured stress variations corresponding to the material's elastic behavior. The sensor output aligned closely with theoretical expectations, and subsequent validation through analytical testing confirmed the reliability of the fiber-optic measurements.

A simulation model developed in MATLAB revealed a strong linear correlation between wavelength shift and predicted strain, supporting the theoretical foundation of the sensing mechanism. These findings suggest that real-time implementation of structural health monitoring (SHM) using fiber-optic systems is both feasible and practical for concrete infrastructure. This approach offers early identification of microcracking and deformation, enabling predictive maintenance while improving overall structural safety.

The outcomes of this research contribute to the advancement of autonomous infrastructure monitoring solutions based on fiber-optic technology. Future work should focus on adapting and validating these methods under actual field conditions to support widespread adoption in infrastructure health assessment.

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