Study of the Influence of Mechanıcal Loads on the Characteristıcs of Dıstrıbuted Fıber-Optıc Sensors Usıng Numerıcal Modelıng

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***Abstract*—**This work develops a comprehensive physical-mathematical model describing the changes in light wave parameters traveling through the core of a single-mode optical fiber embedded within a reinforced concrete beam. The fiber serves as both a sensor and a signal transmission channel. Using finite element method-based software (ANSYS and COMSOL), 3D visualizations of stress-strain states were obtained under applied loads. The paper studies opto-mechanical interactions via photoelastic effects, analyzes factors influencing optical wave intensity and phase shifts due to microbends, and evaluates fiber strength and lifespan under mechanical loads, advocating protective coatings for durability. Algorithms based on artificial intelligence are proposed for real-time structural health monitoring of civil engineering objects using the optical fiber sensor system.

***Keywords*—**fiber‑optic sensors; physical-mathematical modeling; laser diode; optical attenuation; safety, structural health monitoring.

I. Introduction

The main objective is to create a physical-mathematical model (PMM) that reflects changes in emission parameters passing through a single-mode optical fiber (standard G652) housed inside a reinforced concrete beam. The fiber's role extends to monitoring technical condition and transmitting signals. Modeling software ANSYS and COMSOL were applied to simulate the nonlinear stress and deformation states (SDS) of the beam and fiber under load. Experimental data gained during extensive laboratory testing were used to validate the models [1]. The primary application is a quasi-distributed and distributed fiber optic sensor (FOS) system for continuous monitoring of structural deformation and stress, functioning in real-time for timely alerting of changes potentially signaling cracks or failures.

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Fiber optic sensors (FOS) have emerged as a promising technology for structural health monitoring of concrete infrastructures due to their high sensitivity, durability, and ability to provide continuous, real-time information about structural states. These sensors can be embedded within concrete during construction or attached to existing structures, allowing for accurate monitoring of deformation, strain, crack formation, corrosion, and other degradation processes.

Unlike traditional electrical sensors, fiber optic sensors operate without electrical currents, making them safe for use in harsh environments and eliminating risks of electromagnetic interference. Among fiber optic sensors, fiber Bragg gratings and distributed fiber optic sensors have gained prominence for applications in civil engineering.

The most widely used optical fibers for sensing applications are single-mode fibers, such as the G652 standard, due to their low attenuation (approximately 0.22 dB/km at 1550 nm wavelength) and the ability to transmit signals over long distances. Multimode fibers, such as G651, are less suitable for long-distance monitoring because of significantly higher attenuation and limited effective range.

FOS enable detailed monitoring of mechanical stress and strain in concrete structures through changes in optical properties, such as wavelength shifts caused by strain-induced variations in the refractive index or microbending-induced attenuation. This facilitates early detection of structural damage, enabling timely repairs and extending the life of civil infrastructure.

This article presents a study combining experimental and numerical methods to analyze the mechanical effects on fiber optic sensors embedded in reinforced concrete beams. The work aims to develop a comprehensive understanding of the sensor behavior under various loading conditions and to propose improved protective measures and modeling techniques for reliable long-term monitoring.

II. Materials and Methods

A. Modeling Environment and Methods.

It is necessary to develop the physico-mathematical foundations for creating fiber optic sensors (FOS) capable of monitoring the stress-strain state of a structure, its loading parameters, and, importantly, determining the distance to the location of crack formation. The crack location can be identified using quasi-distributed and distributed methods. The

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classical method using point electrical strain gauges is not used in this case due to its imperfection and unsuitability for monitoring the technical condition of reinforced concrete structures, which may be quite extensive.

A second important point is the rejection of electrical signals and copper conductors in favor of optical conductors and the transmission of light waves over significant distances with minimal attenuation. The proposed FOS is based on the well-known photoelastic effect, where changes in the properties of the light wave occur due to the microbending of the standard G652 optical fiber. This single-mode optical fiber was chosen based on its low signal attenuation parameters within 0.22 dB/km at a wavelength of 1550 nm, which is a sufficiently high indicator providing minimal energy consumption.

It should also be noted that this fiber is the most widely produced and has a lower cost compared to other types of optical fibers, unlike the multimode optical fiber standard G651, which is also used for FOS manufacturing but has an effective distance limited to about 500 meters. This multimode fiber is not recommended for longer distances since its losses increase by hundreds of times compared to the single-mode G652 fiber.

Considering that the foundation may have a large perimeter, the multimode optical fiber standard G651 is excluded from further consideration, as are higher standards such as G653 and above, which are specifically designed for backbone cables in telecommunication systems. Higher standard numbers, especially 700 and 900, are resistant to bending and unsuitable for making FOS aimed at the dissertation’s objectives.

For a better understanding of the processes occurring in the optical fiber and establishing the main parameters, one can refer to sources [3], which contain known information also available from open sources. These scientific and technical works will be further used to justify own reasoning and explain some aspects of fiber optic technology and optics theory. Although these sources span different time periods, the theoretical information presented therein correlates well and remains relevant.

3D finite element modeling was conducted using ANSYS and COMSOL for stress-strain analysis of the reinforced concrete beam with embedded optical fiber. Mathematical modeling and experimental data processing utilized Wolfram Alpha and ANETR software. The optical fiber's behavior was described considering geometrical and wave optics, including variations in intensity, frequency, and phase of the electromagnetic wave under mechanical stress and temperature changes.

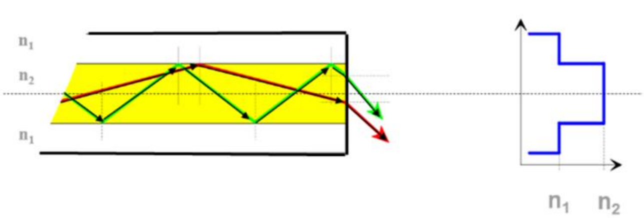


Fig. 1-Stepped profile of G651 multimode fiber

Physical Mathematical Model and Optical Effects. The study focused on the photoelastic effect caused by microbending in the fiber when subjected to mechanical loads. The G652 single-mode fiber was selected for its minimal attenuation (~0.22 dB/km at 1550 nm) and cost-effectiveness for long-distance sensing applications. The model mathematically relates mechanical loads to changes in refractive indices, optical losses, and modulation of the intensity and phase of light transmitted through the fiber [2].

One of the tasks is to develop a mathematical framework to describe the processes of changes in the properties of the light wave propagating through the optical fiber under mechanical load, which causes the transformation of visual images of the light spot into a pattern of intensity variation. The condition is that the formed light spot follows the Gaussian distribution law and the Poisson model.

To understand the process, we first consider the well-known theory of the Mach-Zehnder optical two-beam interferometer, which is one variation of the earlier proposed Jamin optical two-beam interferometer. Scientific works of domestic and foreign researchers [3] were studied; these sources provide detailed information on the principles and construction of the Mach-Zehnder optical two-beam interferometer and other types of interferometers. These sources span different time ranges and have their own approaches to description. Information about optical interferometers can also be found in open sources. Further, known expressions for mathematical modeling will be used to reveal the theoretical foundations of the Mach-Zehnder optical two-beam interferometer’s operation. The drawbacks of using the Mach-Zehnder interferometer are presented in article, where the authors propose their version of a fiber optic sensor for monitoring displacement of rocks in a quarry.

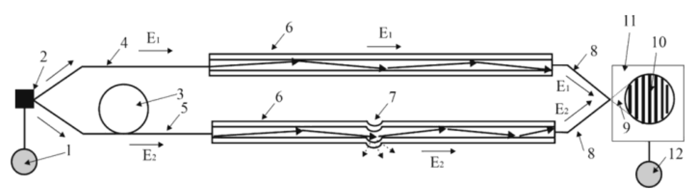


Fig. 2-Schematic diagram of a fiber-optic double-beam Mach-Zehnder interferometer

Figure 2 shows a simplified diagram of a Mach-Zehnder fiber-optic two-beam interferometer, which clarifies some aspects of the design and operating principle of this device; analogues of this diagram can be found in references [1-2]. Since the diagram is schematic, the fiber-optic sensor is depicted on an enlarged scale to illustrate the phase propagation of the light wave along the core of the optical fiber. This Mach-Zehnder fiber-optic two-beam interferometer uses a G652 standard optical fiber. The directions of light wave propagation are indicated by arrows[4]. The radiation source may be a laser or an LED diode, all belonging to the semiconductor group. It is mandatory that the radiation source be coherent, as any fluctuations and frequency deviations will disrupt the operation of any optical interferometer and significantly increase noise levels, making operation impossible in some cases. Because the Mach-Zehnder two-beam optical interferometer is quite sensitive to temperature changes, temperature fluctuations within one degree can cause changes in the phase of the propagating light signal, leading to false readings from the measuring device [5]. There are methods to combat this phenomenon, but they are not discussed here; they can be found in [6]. This optical interferometer is sufficiently sensitive and greatly exceeds electrical strain gauges in resolution.

When mechanical stress is applied to the optical fiber, a site of microbending forms at position 7. The refractive index changes, and the known photoelastic effect occurs, causing changes in the intensity and phase of the light wave propagation. When microbending occurs, part of the light wave escapes from the optical fiber outside the cladding; this phenomenon is called induced additional losses and is the basis of first-type fiber-optic sensors. The escaping light wave is shown by dashed lines with arrows. This phenomenon will later be used in the development of the monitoring system. The theoretical basis of the Mach-Zehnder two-beam optical interferometer is well studied; it is the sum of two electromagnetic field intensity vectors of the light waves E1 and E2. Changes in the parameters of E1 and E2 cause changes in the light wave intensity parameter I. All changes in the intensity Iare detected by the photodetector at position 11. The intensity parameter Ican be expressed through the electromagnetic field intensity vector E2.

Interferometer Design and Limitations. An optical Mach–Zehnder two-beam interferometer was analyzed for detecting phase shifts due to deformation. Despite its high resolution compared to electrical strain gauges, the interferometer shows sensitivity to temperature fluctuations causing measurement errors, limiting its applicability in harsh environments without sophisticated temperature compensation.

Fiber Strength and Lifetime Estimation. Experimental tensile tests of G652 fibers (1 m samples stretched at 20 mm/min) showed failure at 7% elongation under 54–58 N loads, with factory specs reaching 26% elongation under 180 N. The presence of Griffith microcracks reduces fiber strength and lifespan, emphasizing the necessity of protective coatings (e.g., acrylic, vinyl, or titanium-doped layers) for durability and moisture resistance. Modeling suggests relative elongation of the fiber should not exceed 0.8% over 20 years of operation to prevent premature failure [6].

III. Results and Discussion

Computer Modeling Outcomes. The simulations revealed patterns of mechanical stresses and deformations in the beam and the optical fiber. Microbending of the fiber induces additional optical losses and refractive index changes, affecting signal intensity and phase, which form the basis for sensing deformation. FEM visualizations demonstrated stress concentration zones and deformation patterns aligning with expected physical behavior are shown in Figure 3 [7].

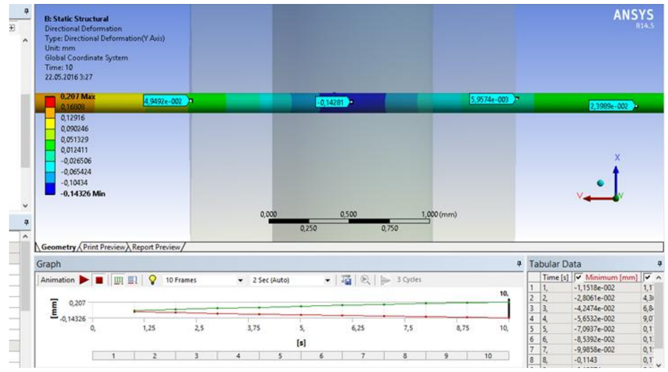
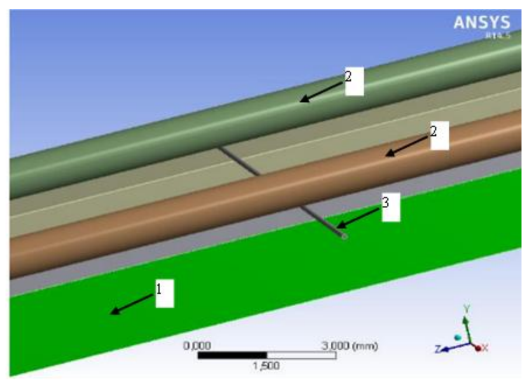


Fig. 3-Computer model of G652 type

This model simulates the mechanical impact on the fiber-optic sensor and visualizes the stress-strain state of the optical fiber. ANSYS is used for numerical analysis and modeling of the impact on the optical fiber and its stress-strain state. The ANSYS STATIC STRUCTURAL finite element method is applied. The software allows simulation of microbending of the optical fiber when different magnitudes of load are applied to it.



1 - Foundation; 2 - Metal rods; 3 - Optical fiber

Fig. 4 – Computer model of the fiber optic sensor system

Figure 4 shows the computer model of the fiber optic sensor system (FOS) created using the ANSYS software. The optical fiber (OF) is embedded within the beam, subjected to mechanical impact by two reinforcing metal rods acting on the OF, which lies on a rigid foundation.

This model simulates the mechanical impact on the FOS and visualizes the strain-stress state of the OF. ANSYS is used for numerical analysis and simulation of the effect on the OF and its strain-stress state. The finite element method ANSYS STATIC STRUCTURAL is applied. The program allows simulating microbending of the OF under varying load magnitudes.

The simulation addressed tasks directly related to experiment planning, parameter determination for future models, selection of approximation methods and quality assessment of the model, as well as solution search during discrimination and deviation evaluation.

Boundary conditions set the number of load increase steps to 10, each step corresponds to an increment of 1 MPa. Thus, the load varied from 1 to 10 MPa, which is the designated load range. The duration of each step was one second. The fiber experienced tension and microbending.

After obtaining the numerical simulation results, the data were processed using computer software. The accuracy of the results was evaluated by the root mean square deviation criterion expressed as a percentage. The established criterion requires that the RMS deviation should not exceed 20%. Regression analysis and the Fisher criterion were used for accuracy assessment. The ANETR software was used for data processing. For high reliability with a confidence level of 0.99, the Fisher value F should be ≥ F001, and at confidence 0.95, F ≥ F005.

The selected software supports experimental design matrix operation, with m representing the number of independent input variables. Parameter n sets the level for each variable; each matrix has a varying number of independent variables. The condition for achieving the required precision of results is that m ≥ n + 1. The obtained experimental design matrix combines data from several experiments, their number chosen per the Student's t-test criterion. The regression dependence and variance of all obtained data were assessed. The number of repetitions per experiment should be at least 10.

Processes of the strain-stress state (SSS) variations in the investigated reinforced concrete beam containing the single-mode optical fiber were studied. A stepwise increase of pressure on the metal rods causing microbending of the OF was performed. ANSYS provided numerical calculation of stress and strain parameters of the OF during the 10-step load application, with load gradually increasing from minimum to maximum.

This allowed calculation of displacements, strains, stresses, and internal forces arising in the sensor body under static load. All load parameters, materials, and finite element sizes are set in the ANSYS Mechanical application. Contact interaction between the OF, metal rods, and foundation was considered in the simulation. Numerical results of the SSS variation depending on the load change were obtained.

During modeling, the following tasks were solved, which are directly related to experiment planning, determination of parameters for future models, selection of approximation methods and assessment of model quality, and searching for solutions during discrimination and deviation evaluation.

The ANSYS program provided numerical calculation of the stress and strain parameters of the optical fiber when a load was applied in 10 increments, with the load gradually increasing from minimum to maximum. This allowed the calculation of displacements, strains, stresses, and internal forces arising in the body under static load. All load parameters, materials, and finite element sizes are set in the Mechanical application of the ANSYS program. The numerical computer experiment took into account the contact interaction between the optical fiber, metal rods, and the base. Numerical results were obtained showing changes in the stress-strain state depending on the variation of the load. Visualization of the mechanical impact of the steel rod on the optical fiber and its stress-strain state is shown in Figure 5.

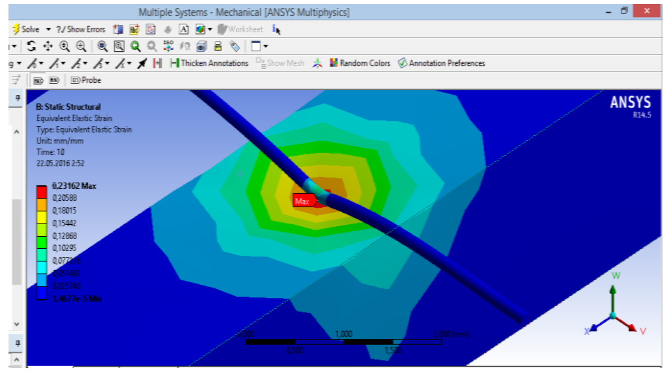


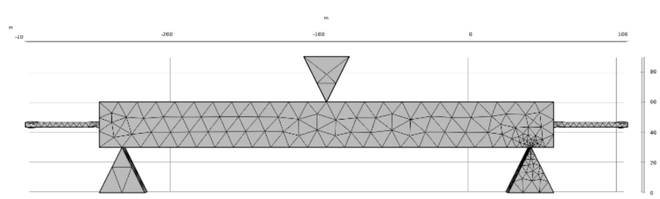
Fig. 5 – Visualization of the mechanical impact of a steel rod on the optical fiber

Methods of visualization for three-dimensional modeling of mechanical stresses were used in the COMCOL software. This program offers a well-developed set of tools and is recognized by engineers and scientists worldwide as one of the most effective means for modeling various structures, devices, and processes in nearly all fields of science and engineering.

COMCOL enables the analysis of individual and interconnected physical processes and the solution of contact problems. The finite element method is employed within the software. The program supports all stages of modeling, from the creation of a 3D geometric model and assignment of material properties to conducting numerical calculations and analyzing simulation results.

For example, it can visualize the distribution of mechanical stresses and deformation in a reinforced concrete beam with an embedded optical fiber. The computer model of the reinforced concrete beam containing the optical fiber, created in COMCOL, is presented in Figure 5.

Protective Coatings Recommendations. Three protection types for optical fiber in concrete were proposed, each covering the original fiber (9 μm core, 125 μm cladding) with buffer gels, silicone/plastic jackets (0.9–3 mm diameter), and reinforcement fibers. Modeling confirmed the composite protects optical and mechanical integrity, enabling reliable long-term embedding in concrete [8].



1 – Beam; 2 – Optical fiber;
3 – Pressure element on the beam; 4 – Fixed supports.
Fig. 6 – Computer model of reinforced concrete beam with embedded optical fiber created in COMCOL software.

Figure 6 shows the visualization of mechanical stress distribution under load applied to the center of the beam. Zones

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of mechanical stresses are shown in different colors. It is visible that the maximum stresses concentrate in the center of the beam where the load is applied. The optical fiber embedded in the beam is equally subjected to loading, developing stresses and strains that lead to changes in the refractive index and properties of the transmitted light wave. This confirms the previously proposed hypothesis that the optical fiber will sense the load while embedded in the beam.

With deformation, the optical fiber experiences microbending, which causes the photoelastic effect, in turn altering the intensity of the light wave and its optical power loss.

IV. Conclusion

Developed a comprehensive PMM integrating optics and mechanics for an optical fiber embedded in concrete under mechanical loading. Verified that mechanical loads induce microbending in the fiber, triggering photoelastic changes detectable via light intensity and phase modulation. Demonstrated computer simulation capability using ANSYS and COMSOL to visualize mechanical stress and deformation.

Highlighted the critical role of protective coatings to enhance fiber durability, extending operational life to 20+ years with elongation limits. Confirmed the challenges of temperature effects on interferometric sensing necessitate advanced signal processing using AI algorithms. Proposed the embedded fiber optic sensor system as a viable real-time monitoring tool for structural health in civil engineering.

A physical-mathematical model of opto-mechanical processes of mechanical impact on a fiber-optic sensor has been developed, which will make it possible to create fiber-optic sensor systems capable of monitoring the stress-strain state of reinforced concrete structures.

The basis of the proposed fiber-optic sensor system is the well-known photoelastic effect, which occurs as changes in the properties of the light wave when microbending of the G652 standard optical fiber arises.

Using mathematical methods, the relationship between temperature, additional losses, and changes in refractive indices depending on the applied load on the side surface of the optical fiber has been established. A physical-mathematical model has been obtained describing the change in the intensity parameters of optical radiation propagating through the core of the optical fiber as a function of the distance from its center. It has been established that the deformation of a beam can be controlled by the level of change in losses, intensity, and volumetric density of optical radiation passing through the core of the optical fiber.

A scheme of a Mach-Zehnder fiber-optic two-beam interferometer has been developed for monitoring an extended object. It has been established that this interferometer is not suitable for creating a system for monitoring the technical condition of building structures based on fiber-optic sensors, and is more suitable for conducting physical experiments and demonstrations.

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