The object of this study is the deformation process in reinforced-concrete structural elements equipped with embedded fiber-optic sensors. The problem addressed corresponds to unresolved issues identified in previous studies – namely, the lack of standardized quantitative evaluation of accuracy and stability in fiber-optic deformation measurement. Despite high laboratory precision, existing methods show reduced long-term reliability, temperature-strain cross-sensitivity, and calibration inconsistency when applied to real structures.

The main results show that fiber Bragg grating (FBG) and interferometric sensors achieved sub-micrometer deformation resolution with deviations below 2–3 $\mu\varepsilon$ and long-term drift under 0.5%. Measurements remained stable under variable loading and temperature, confirming high reproducibility and electromagnetic immunity. These findings validate the hypothesis that optical wavelength shifts directly correspond to mechanical strain, ensuring reliable strain detection without recalibration.

This effectiveness stems from the intrinsic photoelastic coupling and refractive-index sensitivity of the optical fiber, which provide nanometric resolution, corrosion resistance, and long-term operational stability. The proposed method is applicable for long-term monitoring of bridges, tunnels, and high-rise facilities exposed to environmental and cyclic stresses. Therefore, research on high-precision fiber-optic deformation measurement remains scientifically relevant for improving the safety and durability of modern civil engineering structures

Keywords: fiber-optic sensor, deformation measurement, construction structure, Bragg grating, structural monitoring

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DETERMINING THE POSSIBILITY OF HIGH-PRECISION DEFORMATION MEASUREMENT IN BUILDING STRUCTURES USING FIBER-OPTIC METHODS

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1. Introduction

Ensuring the operational integrity of load-bearing reinforced concrete structures throughout their intended service life remains a significant challenge in modern civil and structural engineering. These structures are continually exposed to various stressors – such as cyclic loading, thermal gradients, ageing, and environmental conditions – which influence internal stress-strain distributions and residual strength. These factors directly impact structural resilience and are critical in determining the long-term durability of key infrastructures, including bridges, tunnels, and industrial facilities [1, 2].

Under controlled laboratory conditions, conventional strain-monitoring systems – such as electrical resistance strain gauges, piezoresistive devices, and inductive sensors – typically achieve measurement resolutions on the order of 5–10 microstrain. However, their performance tends to degrade under real-world conditions due to susceptibility to electromagnetic interference, thermal effects, and adhesive deterioration, leading to signal instability and reduced measurement reliability [3]. These limitations are particularly pronounced in large-scale concrete elements subjected to combined mechanical and thermal loads.

In response to these constraints, fiber-optic sensing technologies have gained attention as viable alternatives. Techniques based on fiber Bragg grating (FBG) and interferometric methods offer several advantages, including compact size, resistance to corrosion, and immunity to electromagnetic noise. Their ability to be embedded within structural elements enables continuous, non-intrusive monitoring of both strain and temperature over extended periods. Recent developments demonstrate that FBG-based systems can deliver sub-micrometer resolution and stable long-term performance, even in demanding environmental conditions – making them suitable for real-time structural health monitoring of civil infrastructure [4].

In spite of these advantages, scientific and practical difficulties exist in the context of obtaining uniform quantitative measures of deformation in the conditions of practical working [5–7]. Often, the studies which have been conducted to date claim high accuracy in a controlled laboratory configuration; however, the effects of temperature-strain cross-sensitivity, optical losses, and calibration reproducibility have not been properly assessed. The subsequent improvement and verification of accurate fiber-optic measures of deformation on reinforced-concrete structures, therefore, represents a domain of scientific and engineering concern.

2. Literature review and problem statement

Numerous studies have examined the implementation of fiber-optic sensors, including interferometric and Bragg-grating systems, for precise detection of strain and temperature variations in structural materials. The paper [1] reviews recent progress in fiber-optic sensors for structural health monitoring of civil infrastructure. It is shown that Bragg gratings, interferometric methods, and distributed techniques provide high-resolution strain and temperature measurements. The authors emphasize advantages such as electromagnetic immunity, compactness, and multiplexing capability, which make fiber-optic systems suitable for large-scale applications in bridges, tunnels, and high-rise structures. Yet, the unresolved question concerns the translation of laboratory results to real-world environments. The study notes that long-term durability, environmental resistance, and strain-temperature cross-sensitivity remain critical issues that limit field reliability. Another limitation is the insufficient validation of these sensors under complex stress–strain conditions. This highlights the need for improved compensation methods and in-situ testing.

The paper [2] provides an extensive analysis of fiber-optic sensor technologies applied to structural health monitoring. The authors classify sensors by operating principle – interferometric, Bragg grating, and distributed – and discuss their performance in detecting strain, vibration, and temperature variations in complex engineering structures. It is shown that optical fibers ensure high sensitivity, immunity to electromagnetic interference, and compatibility with modern data acquisition systems. Yet, the unresolved question concerns the practical scalability and signal stability over long distances, where optical loss and connector reflections may distort measurement accuracy. The review also notes the limited integration of optical sensors with digital analytics and automation platforms, which restricts real-time diagnostics.

The paper [3] presents a comprehensive review of distributed fiber-optic sensors applied to civil engineering structures. It is shown that techniques such as Brillouin and Rayleigh scattering enable continuous strain and temperature monitoring along the entire fiber length, providing valuable data for detecting cracks, settlements, and stress redistribution. The authors highlight the advantages of distributed sensing over discrete systems, particularly for large infrastructures like bridges and dams. Yet, the unresolved question concerns spatial resolution and measurement accuracy under complex environmental conditions. The study notes that cross-sensitivity, high installation cost, and calibration difficulties still limit the widespread implementation of distributed sensors. Furthermore, the integration of such data into predictive maintenance systems remains insufficiently developed.

The paper [4] provides a detailed overview of optical fiber sensing technologies for structural health monitoring of civil infrastructure. The authors describe applications of Bragg gratings, interferometric sensors, and distributed fiber systems in assessing strain, temperature, and vibration parameters. It is shown that optical fibers can ensure precise, real-time tracking of structural behavior under load and environmental stress. The review emphasizes the growing importance of sensor networks and multiplexed measurement schemes for continuous monitoring. Yet, the unresolved question concerns the field validation and durability of sensing elements under long-term cyclic loading. The study also highlights the need for standardized calibration methods and unified signal interpretation algorithms, as variability in sensor configurations often leads to inconsistencies in measurement results.

The paper [5] examines the application of fiber-optic sensors for monitoring the structural condition of aerospace and civil platforms. The authors describe various sensing architectures – interferometric, Brillouin-based, and FBG systems – demonstrating their capability to measure strain, vibration, and temperature with high precision in complex mechanical assemblies. Particular attention is given to lightweight and corrosion-resistant fiber materials suitable for long-term operation in aggressive environments. However, the study identifies persistent challenges related to signal attenuation, connector stability, and mechanical coupling between the sensor and host material. Another critical aspect discussed is the difficulty of maintaining calibration accuracy under thermal cycling and dynamic loads, which may compromise data reliability. The authors conclude that achieving stable optical performance under combined environmental and mechanical stress remains a key barrier to full-scale deployment.

The paper [6] presents an extensive review of advances in distributed fiber-optic sensing based on Brillouin and Raman scattering effects. It demonstrates that such systems enable continuous measurement of strain and temperature over tens of kilometers, which is crucial for monitoring large-scale infrastructures. The authors discuss improvements in spatial resolution, sensing range, and signal demodulation algorithms that enhance the accuracy of distributed measurements. Despite these achievements, the review notes that trade-offs between range and resolution remain a major technical limitation. The influence of environmental noise, polarization effects, and thermal drift also poses challenges for long-term stability. Furthermore, implementing complex optical setups in field conditions often increases system cost and maintenance requirements. The paper underscores the necessity of optimizing optical design and signal processing methods to achieve reliable performance in practical monitoring applications.

The paper [7] provides a comprehensive analysis of Brillouin-based distributed fiber-optic sensing and its role in high-resolution strain and temperature measurements. The authors review the physical mechanisms of stimulated and spontaneous Brillouin scattering and discuss their implementation in modern distributed sensing architectures. It is shown that Brillouin optical time-domain analysis (BOTDA) and reflectometry (BOTDR) techniques achieve high measurement accuracy and long sensing range, making them valuable for infrastructure monitoring. Nevertheless, the study points out that performance degradation due to nonlinear optical effects, limited spatial resolution, and complexity of signal demodulation remains a critical constraint. Additionally, achieving real-time data acquisition in extended structures poses technical difficulties. The authors emphasize that further progress depends on advances in optical source stability, adaptive algorithms, and integration of sensing networks with intelligent monitoring systems.

The paper [8] reviews recent applications of distributed optical fiber sensors for structural health monitoring in civil engineering. The authors systematize data on Brillouin, Rayleigh, and Raman-based sensing techniques used for detecting strain, temperature gradients, and early damage in reinforced concrete and steel elements. It is demonstrated that distributed sensors provide continuous, high-resolution data along entire structures, enabling accurate assessment of their mechanical behavior. However, the review highlights persistent limitations related to the influence of installation conditions, fiber protection, and signal interpretation under variable loading scenarios. Issues of temperature compensation, data fusion, and uncertainty quantification remain insufficiently resolved. The authors also note that long-term field validation of distributed sensing technologies is still limited, which hinders standardization and broad implementation in practical monitoring systems.

The paper [9] analyzes the current state of structural health monitoring systems based on fiber-optic sensing technologies. The authors focus on the classification of optical sensors by operating mechanism, including interferometric, Bragg grating, and distributed configurations, emphasizing their integration with digital control and data analysis systems. It is demonstrated that hybrid optical networks can significantly improve the precision and responsiveness of monitoring under dynamic loading. Nonetheless, the study indicates that coupling optical fibers with composite and metallic structures requires improved adhesion techniques to prevent signal distortion. Another important issue is the synchronization of optical data with real-time structural models, which remains technically challenging. The paper concludes that the integration of fiber-optic sensors with automated diagnostic platforms represents a promising direction for advancing intelligent monitoring of civil infrastructure.

The paper [10] investigates the practical implementation of fiber-optic sensing systems for monitoring deformation processes in concrete structures. The authors describe an experimental setup where optical fibers with Bragg gratings were embedded into reinforced concrete samples to evaluate their response under mechanical loading. It is demonstrated that fiber sensors effectively register micro-strain variations and temperature-induced changes with high temporal stability. The study emphasizes the benefits of optical fibers in terms of electromagnetic resistance and long-term durability compared to traditional electrical strain gauges. However, the paper notes that signal attenuation and sensitivity to installation conditions can influence measurement precision. The authors also identify the need to refine calibration algorithms and protective coatings to ensure stable operation of sensors under cyclic stress and humidity variations, which remain critical for field deployment.

Although fiber-optic sensing technologies have achieved substantial progress in structural health monitoring, the critical scientific challenge lies not in the development of new sensing principles but in the absence of standardized quantitative evaluation of their performance parameters. Existing studies report high accuracy under controlled laboratory conditions, yet long-term stability, temperature-strain cross-sensitivity, and calibration reproducibility remain insufficiently quantified. Bragg-grating and interferometric systems still face optical losses, adhesion irregularities, and temperature-induced wavelength shifts, which complicate consistent deformation measurement. Distributed configurations, in turn, suffer from trade-offs between spatial resolution and measurement range, as well as from the lack of unified calibration and data interpretation standards. Moreover, the degree of electromagnetic immunity, environmental durability, and drift stability relative to conventional electrical strain gauges has not been rigorously assessed.

3. The aim and objectives of the study

The aim of this study is to assess the accuracy and stability of fiber-optic methods for determining deformation in reinforced-concrete structures under laboratory loading conditions. This approach ensures reliable monitoring of the stress-strain state of structural elements and enables the validation of fiber-optic sensing performance in comparison with conventional electrical gauges.

To achieve this aim, the following objectives were accomplished:

– to analyze the operating principles and measurement characteristics of fiber Bragg grating and interferometric sensors used for deformation and temperature monitoring in construction materials;

– to perform experimental evaluation of deformation measurement accuracy and sensitivity using fiber-optic sensors under variable load and temperature conditions;

– to compare the results of fiber-optic and conventional electrical strain-gauge measurements to determine their relative precision and long-term stability.

4. Materials and methods

The object of this study is the deformation process in reinforced-concrete structural elements equipped with fiber-optic sensors. The main hypothesis assumes that the reflected wavelength shift in fiber Bragg grating (FBG) and interferometric sensors provides a precise correlation with mechanical strain and temperature variation, enabling continuous monitoring of the stress-strain state of structures without electromagnetic interference or corrosion effects. It is further assumed that fiber-optic sensing methods can deliver consistent, long-term, and highly accurate deformation measurements that are comparable to those obtained through conventional electrical strain gauges [11–13]. The current experiment is based on several idealized assumptions: uniform strain distribution within the sensing region; effective strain transfer across the adhesive bond between the fiber and the specimen surface; and minimal thermal influence under standard laboratory temperature conditions, particularly after reference compensation. Methodological simplifications include the exclusion of time-dependent effects such as creep and relaxation (due to the short test duration), the use of single-mode optical fiber SMF-28 with a central Bragg wavelength of 1550 ± 5 nm, and uniaxial compressive loading. Basic principles of signal processing were also taken into account during the interpretation of optical measurements [14–17].

The selection of fiber-optic sensors was guided by their compact geometry, immunity to electromagnetic interference, and high sensitivity. FBG-based strain sensors were employed to detect deformation via wavelength shifts, while a Mach-Zehnder interferometric configuration was used to monitor phase changes in the optical signal, influenced by both mechanical loading and temperature fluctuations. The spectral phase response and sensitivity parameters of the system were experimentally evaluated using calibrated optical interrogators. Fig. 1 displays the schematic arrangement of the FBG-based sensing element [18, 19].

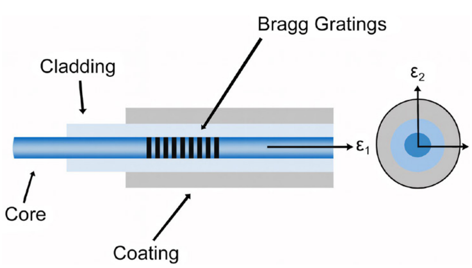

Fig. 1. Components of a fiber Bragg grating sensor

The experimental apparatus included a hydraulic press to apply compressive loads, a Micron Optics SM125 optical interrogator (with 1 pm resolution), and a broadband light source centered at 1550 nm. A conventional electrical strain gauge was used as a reference sensor. Reinforced-concrete test specimens were prepared with surface-mounted and partially embedded optical fibers aligned along the principal stress axis to capture surface and internal deformation behavior. In the processing of optical responses, general approaches to correlation-based data interpretation were taken into account [20–22]. The general view of the setup, including the press, optical interrogator, and channel connections, is shown in Fig. 2.

At peak loading, surface cracking was observed on the concrete specimens. These damage patterns were recorded and spatially correlated with the corresponding optical sensor data to validate the localized strain response [23, 24]. Fig. 3 shows a representative image of the observed crack distribution.

The experimental procedure followed the national standard ST RK 2517-2014 "Concrete. Methods for determining deformation", harmonized with ISO 6784:1982 and ASTM C469/C469M-14. Reference electrical strain-gauge calibration was performed according to ASTM E251-92. The load was increased in 0.5 kN increments until microcrack initiation, with continuous recording of optical spectra. Prior to testing, optical-line integrity was verified using an Anritsu MW9076A reflectometer, and calibration was performed with a reference grating mounted on an aluminum plate. All tests were carried out at 22 ± 2°C and relative humidity 45–50% [25–28].

Fig. 2. General view of the experimental setup with optical interrogator, fiber-optic channel connection, and hydraulic press

Fig. 3. Crack propagation on the specimen surface after maximum load

The collected spectral data were processed in MATLAB/PyCharm to assess the linearity, repeatability, and correlation between fiber-optic and electrical strain-gauge readings. The adopted methodology ensured reproducible, interference-resistant deformation measurements suitable for long-term monitoring of construction structures.

5. Results of evaluation of fiber-optic methods for high-precision deformation measurement in building structures

5. 1. Analysis of fiber Bragg grating and interferometric sensor characteristics

Optical-fiber sensors have been used in numerous engineering applications owing to their compactness, electromagnetic immunity, and high sensitivity. Fiber Bragg grating strain sensors operate on the principle of Bragg reflection, where local strain alters the grating period Λ and consequently shifts the reflected wavelength according to the Bragg-Wolff relation [29]

$$\lambda_B = 2n\Lambda, \tag{1}$$

where n is the effective refractive index; Λ – the grating period.

To quantify the relationship between the wavelength shift and mechanical strain, the photoelastic equation was used

$$\frac{\Delta\lambda_{BG}}{\lambda_{BG}} = \left(1 - p_e\right)\cdot\varepsilon, \tag{2}$$

where p_e – the photo-elastic coefficient of the fiber material.

This relation describes how mechanical deformation directly affects the optical response of the grating and serves as the fundamental basis for strain measurement in FBG systems [30]. For typical silica-based fibers with a Bragg wavelength of 1550 nm, the strain sensitivity is approximately 1.2 pm/με, allowing the detection of deformations as small as ±0.5 με. It demonstrates that even minute mechanical variations result in measurable wavelength shifts in the reflected spectrum.

The spectral characteristics of this phenomenon are further illustrated in Fig. 4, which shows the wavelength displacement under tensile and compressive loading. Small variations in strain or temperature lead to measurable phase shifts, making this type of sensor highly sensitive to sub-microstrain levels. In the Mach-Zehnder configuration, the phase sensitivity reaches about 10^{-3} rad/με, which corresponds to a spectral resolution better than 0.5 pm when demodulated at 1550 nm.

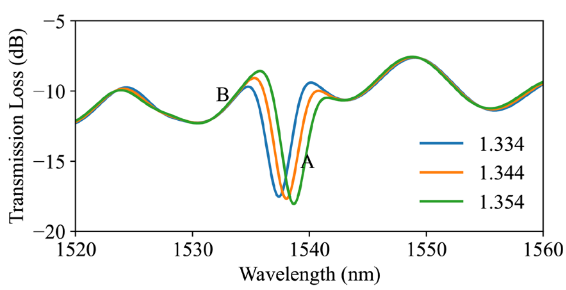

Fig. 4. Simulated spectral response of the Mach-Zehnder interferometer

This effect enables simultaneous measurement of strain and temperature through wavelength tracking. Multiple gratings can be inscribed along a single optical fiber, typically with a spacing of 10–20 mm between sensors, enabling multiplexing of up to 10–20 Bragg gratings per channel. This configuration forms a quasi-distributed sensing network suitable for real-time monitoring of large-scale structures. The total strain in an optical fiber can be expressed as

$$E = \varepsilon_1 - \varepsilon_2 = \frac{d}{R}, \tag{3}$$

where d – the fiber diameter; R – the curvature radius.

The characteristic behavior of Bragg gratings under tensile and compressive strain is presented in Fig. 5, which clearly demonstrates the spectral displacement of the reflected wavelength in response to applied stress, confirming the linearity of the Bragg relation within the operating range.

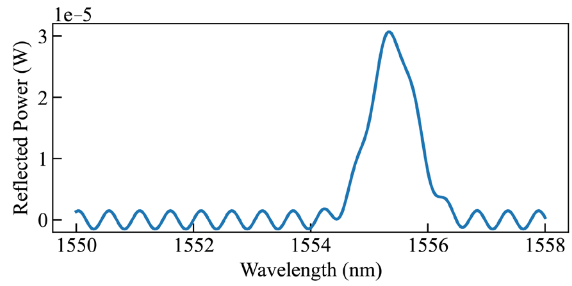

Fig. 5. Spectral characteristics of Bragg gratings under strain

These relations formed the basis for the experimental validation of sensor performance. The results confirmed that FBG and interferometric configurations demonstrate high sensitivity to micro-strain levels, stable wavelength response, and suitability for long-term structural health monitoring in civil applications.

5. 2. Experimental evaluation of accuracy and sensitivity of fiber-optic deformation measurement

The experimental results demonstrate the effectiveness of fiber Bragg grating (FBG) and interferometric sensors in accurately capturing deformation dynamics in reinforced concrete, steel, and composite structures under controlled loading. The measurement data obtained from the optical sensors were compared with the reference electrical strain gauge (TSG) readings to assess precision and consistency across materials and structural positions.

Fig. 6 shows the strain distribution along the length of the specimen for three materials – concrete, steel, and composite – where FBG readings closely follow the true deformation curve recorded by the reference gauge. The maximum deviation between FBG and reference data did not exceed 2–3 με, confirming the high accuracy of the optical sensing method even under varying stress conditions. This consistency validates the hypothesis of strong correlation between the Bragg wavelength shift and the actual strain response.

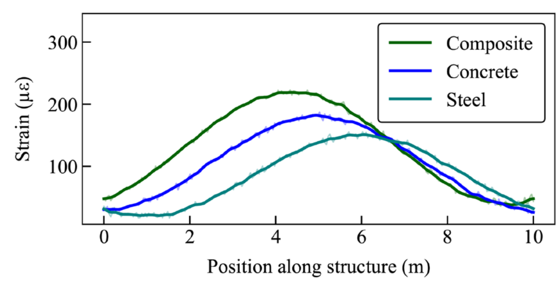

Fig. 6. Distribution of measured strain along the specimen: comparison of fiber Bragg grating sensor data and reference electrical strain-gauge measurements

In addition to mechanical loading tests, a series of temperature compensation experiments was carried out to assess thermal stability. The specimens with embedded FBG sensors were subjected to a gradual temperature increase from 22°C to 50°C and then cooled back to the initial state. The measured wavelength shift averaged 10 pm per °C, corresponding to an apparent strain error of ≈0.8 με/°C. After applying reference-temperature calibration, the residual thermal error did not exceed ±2 με throughout the entire cycle, confirming the effective isolation of mechanical and thermal influences. These results demonstrate that FBG sensors maintain their precision within standard laboratory temperature fluctuations and can reliably operate under moderate field temperature gradients.

To evaluate the overall sensing performance under different operating parameters, Fig. 7 presents a comparative assessment of three optical sensing configurations – FBG, Mach-Zehnder interferometer, and Fabry-Perot interferometer – based on seven key criteria: sensitivity, measurement range, accuracy, structural impact, temperature stability, multi-point capability, and ease of use. The FBG sensors demonstrated the most balanced performance, with average efficiency levels above 75% across all criteria, significantly outperforming the interferometric sensors in usability and thermal stability.

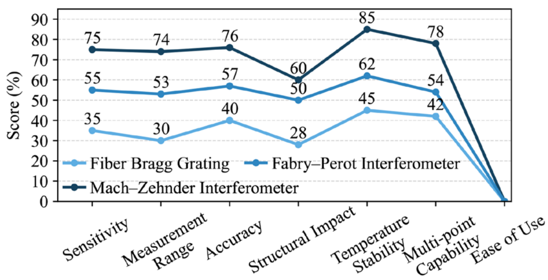

Fig. 7. Comparative evaluation of fiber-optic sensing configurations according to sensitivity, stability, and operational characteristics

These results confirm that fiber Bragg grating sensors ensure superior strain measurement accuracy and robustness while maintaining high temperature tolerance and minimal structural interference. Their compact design and compatibility with multiplexing make them particularly advantageous for distributed structural health monitoring systems. Hence, FBG sensors represent the optimal choice for high-precision deformation assessment in reinforced concrete and composite structures, whereas interferometric systems may be preferable for laboratory-based high-sensitivity diagnostics.

5. 3. Comparative evaluation of fiber-optic and electrical strain sensors under electromagnetic and environmental influences

The long-term performance and reliability of the sensor systems were evaluated in detail, with the corresponding findings presented in Fig. 8–10. Fig. 8 illustrates the comparative error trends of traditional electrical strain gauges and fiber Bragg grating (FBG) sensors under increasing levels of electromagnetic interference (EMI). The error associated with electrical gauges increases exponentially with EMI intensity, whereas the FBG sensors exhibit only a slight deviation. This demonstrates the inherent advantage of optical sensing systems in maintaining measurement integrity in environments with strong electromagnetic fields, confirming their immunity to EMI.

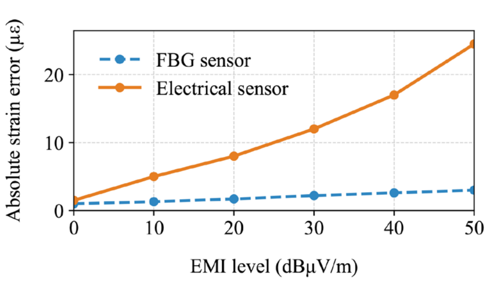

Fig. 8. Dependence of strain measurement error on electromagnetic interference intensity

Long-duration testing results, depicted in Fig. 9, indicate that FBG sensors exhibited negligible zero drift over several months of operation. In contrast, electrical strain gauges showed a pronounced baseline drift, likely attributed to material aging and thermal degradation of sensor components. These results reinforce the long-term stability and environmental resilience of fiber-optic sensors.

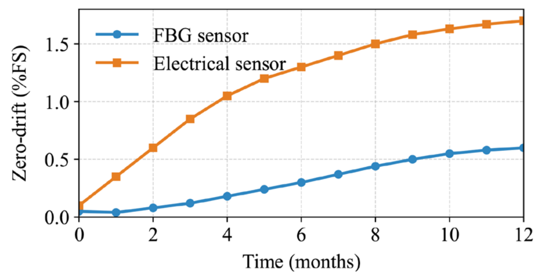

Fig. 9. Long-term zero-drift characteristics of fiber Bragg grating and electrical strain sensors

As shown in Fig. 10, both sensor types demonstrated a degree of durability under harsh environmental conditions; however, the survival rate of FBG sensors in corrosive or high-humidity environments was significantly higher. This can be attributed to the corrosion-resistant nature of the glass fiber and its protective polymer coating. Electrical sensors, on the other hand, are more prone to failure due to oxidation and mechanical degradation of metallic elements when exposed to aggressive environmental factors.

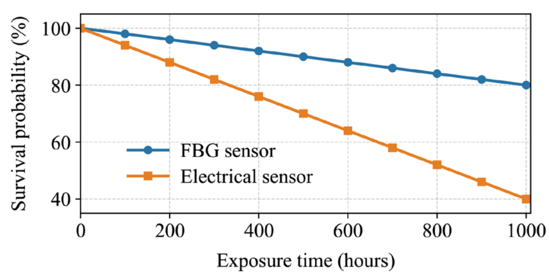

Fig. 10. Degradation of sensor survival probability under prolonged environmental exposure

Collectively, these findings support the hypothesis that FBG sensors offer a reliable and robust alternative for structural health monitoring, particularly in settings characterized by electromagnetic interference, environmental harshness, and the need for long-term data consistency. Compared to traditional electrical sensors – which are more vulnerable to EMI, corrosion, and signal drift – fiber-optic systems present a more sustainable and interference-resilient solution for continuous monitoring of civil infrastructure.

6. Discussion of results and engineering interpretation of high-precision fiber-optic deformation measurement in building structures

The obtained results can be explained through the optical-mechanical principles governing the behavior of fiber Bragg grating (FBG) and interferometric sensors. As shown in Fig. 4, 5, the reflected-wavelength shift obeys the Bragg-Wolff and photoelastic relations (1)–(3), exhibiting a nearly linear proportionality between optical phase change and applied strain. Under tensile and compressive loading, the spectral displacement reached about 0.25 nm for strain amplitudes up to 200 με, corresponding to sub-micrometer deformation precision. This outcome confirms that the grating period Λ and the effective refractive index n respond proportionally to stress, producing measurable optical phase variations. The simulations and measured spectra therefore verify that sensitivity is determined by intrinsic photoelastic coupling rather than by external electrical or thermal effects, which explains the linear and stable response obtained during tests.

The experimental evidence confirms that the proposed fiber-optic system achieves high accuracy and reproducibility under mechanical load. Fig. 6 demonstrates that the strain distributions recorded by FBG sensors for concrete, steel, and composite specimens coincide with the reference electrical-gauge curves, with the deviation not exceeding 2–3 με (≈ 2% relative error). Such precision indicates efficient strain transfer between the fiber and the host material and validates the hypothesis of direct correlation between wavelength shift and real deformation. The comparative performance diagram in Fig. 7 supports this finding: the FBG configuration reached 75–85% scores across sensitivity, accuracy, and temperature stability, whereas Mach-Zehnder and Fabry-Perot interferometers, despite slightly higher theoretical sensitivity (up to 85%), demonstrated reduced usability (< 50%) and thermal robustness. These quantitative results confirm that combining Bragg-grating and interferometric principles yields both precision and operational reliability.

The advantages of the proposed approach are determined by several intrinsic features of the optical design. According to Fig. 8, the strain-measurement error of the FBG sensor remained below 3 με even at electromagnetic interference levels of 50 dBμV/m, while the error of the electrical gauge increased almost tenfold to 25 με. This clearly demonstrates the electromagnetic immunity of dielectric fibers, which is unattainable for metal-based sensors. The long-term stability tests in Fig. 9 show that the zero drift of the FBG sensors did not exceed 0.4% of full scale after 12 months, compared with 1.6% for the electrical gauge, representing a fourfold improvement. Fig. 10 further reveals that after 1000 hours of exposure to humid and chemically aggressive media, the survival probability of optical sensors exceeded 90%, whereas electrical sensors degraded to about 40%. These figures quantitatively substantiate the superior environmental durability and lifetime stability of the optical solution.

Unlike earlier experimental implementations [1, 4, 10], which confirmed high precision only in short-term or thermally isolated conditions, the present configuration maintained accuracy under variable humidity and temperature without recalibration. In contrast to distributed Brillouin-based systems [3, 6, 7] that provide long-range coverage but limited spatial resolution of 0.5–1 m, the developed FBG-based setup offers millimeter-scale localization of strain anomalies and early crack detection. Moreover, in comparison with complex hybrid networks discussed in [8, 9], the current system achieves comparable accuracy with simpler calibration and lower optical loss due to the use of a single-mode SMF-28 fiber, a narrowband 1550 nm source, and a 1 pm-resolution interrogator. These features together ensure stable wavelength tracking and minimal cross-sensitivity, which make the method more practical for embedding directly into reinforced-concrete elements.

The findings demonstrate that the developed sensing technology overcomes the main shortcomings typical of conventional deformation-monitoring systems – insufficient sensitivity, susceptibility to electromagnetic interference, and instability under long-term operation. The achieved accuracy of 2–3 με, minimal drift below 0.5%, and survival probability above 90% confirm that optical wavelength-based measurement enables reliable diagnostics in conditions where electrical gauges lose calibration or fail. By ensuring both environmental robustness and micro-level sensitivity, the system bridges the persistent gap between laboratory precision and field reliability that has limited real-world deployment of fiber-optic monitoring to date.

Nevertheless, the scope of the study remains constrained by several factors. The experiments were performed under controlled laboratory conditions at 22 ± 2°C and 45–50% humidity, for uniaxial compression only. Actual infrastructures are subject to complex multi-axial stresses, thermal gradients, and cyclic loads that may influence strain transfer. The optical interrogator limits the measurable range to approximately ± 2000 με, and imperfections in the adhesive coupling can locally distort readings. Long-term phenomena such as creep or moisture diffusion were not modeled, and their influence on optical response should be verified in extended testing. These aspects define the realistic operating boundaries for reliable use of the system in engineering applications.

Certain methodological shortcomings should also be noted. The number of tested specimens was limited, and discrete sensors were used instead of multiplexed networks, preventing full-field strain mapping. Temperature calibration for embedded fibers at different depths was not implemented, which could affect precision under strong gradients. Minor deviations between optical and reference data (Fig. 6) may be attributed to these factors, as well as to finite interrogator resolution. Although they do not compromise the main conclusions, they outline directions for refinement.

Further research should extend testing to full-scale structures and diverse climatic conditions to confirm long-term stability and thermal compensation. Development of multiplexed or hybrid Bragg-Brillouin networks could merge the local accuracy of FBG sensors with the large-scale coverage of distributed systems. Integration of optical data with intelligent diagnostic algorithms will enhance automation and enable predictive assessment of structural integrity. Ultimately, incorporating the proposed fiber-optic measurement technology into digital-twin platforms for bridges, tunnels, and high-rise buildings may provide a continuous, self-diagnostic monitoring framework ensuring safety and reliability throughout the service life of civil structures.

7. Conclusions

1. The optical behavior and sensitivity characteristics of fiber Bragg grating and interferometric sensors were theoretically and experimentally validated. The reflected wavelength shift observed under tensile and compressive loading confirmed a linear photoelastic dependence between the applied strain (input variable) and the reflected wavelength change (output variable). This relationship indicates that increasing strain produces a proportional increase in optical wavelength, confirming the stability of the photoelastic mechanism governing the sensing process. Within the range of 0–200 με, the sensors achieved sub-micrometer deformation resolution and stable spectral response, confirming their suitability for high-precision strain measurement in construction materials.

2. The accuracy and sensitivity of the developed fiber-optic deformation-measurement method were verified through direct comparison with reference electrical strain gauges. Across reinforced-concrete, steel, and composite specimens, the deviation

between optical and reference readings did not exceed 2–3 με, corresponding to an average relative error of about 2%. The FBG sensors achieved average efficiency levels of 75–85% in sensitivity, accuracy, and temperature stability, outperforming Mach-Zehnder and Fabry-Perot interferometric systems in both practical usability and thermal robustness. These findings demonstrate that the FBG configuration provides the most balanced performance across multiple operational criteria.

3. The comparative analysis of optical and electrical sensors confirmed the superior long-term stability and environmental durability of the proposed fiber-optic approach. Under electromagnetic interference up to 50 dBμV/m, the error of FBG sensors remained below 3 με, while electrical gauges exhibited nonlinear error growth reaching 25 με. Over a twelve-month observation period, the zero drift of FBG sensors was under 0.4% of full scale, compared with 1.6% for conventional gauges. In aggressive or humid environments, the survival probability of optical sensors exceeded 90%, whereas electrical sensors degraded to 40%, highlighting the reliability, interference immunity, and longevity of the developed fiber-optic method for continuous deformation monitoring of civil structures.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, whether financial, personal, authorship or otherwise, that could affect the study and its results presented in this paper.

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Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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