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Application of Fibre Bragg grating sensors for accurate deformation monitoring in civil structures: A literature review

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Abstract

This research explores the deployment of Fiber Bragg Grating (FBG) fiber-optic sensors for embedded, high-precision deformation monitoring in civil infrastructure. The investigation emphasizes the potential of FBG sensors to be integrated into Structural Health Monitoring (SHM) systems and evaluates their performance under realistic experimental conditions. The study presents methods for embedding FBG sensors into concrete and steel structural elements, enabling continuous acquisition of strain, stress, and temperature variations in real time. Experimental analyses demonstrate that the sensors exhibit remarkable sensitivity, stability, and reliability, even when exposed to demanding environmental influences. Their consistent performance over extended periods highlights the robustness of FBG technology for long-term monitoring applications. Moreover, the findings confirm that early detection of structural irregularities is feasible, providing timely insights into emerging risks that could compromise integrity. By facilitating proactive maintenance strategies and enhancing safety assessments, FBG-based SHM systems significantly improve operational efficiency and extend the service life of critical infrastructure. These results underscore the suitability of FBG sensors as a key enabling technology for advancing modern monitoring practices in civil engineering.

Keywords: Civil structures, FBG sensor, Fiber-optic sensor, Sensitivity optimization, Sensor-based monitoring, Structural deformation.

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1. Introduction

In modern industrial and scientific applications, one of the main challenges is guaranteeing the reliability and safety of critical structures. Sensor technologies play a central role in this effort, as they must provide accurate, continuous, and real-time monitoring. Fiber Bragg Grating (FBG) sensors have become an attractive option because of their high sensitivity, resistance to electromagnetic interference, and ability to function effectively in extreme operating conditions [1, 2]. At the same time, it is worth noting that fiber-optic communication platforms form the foundation for a wide range of contemporary technologies.

FBG devices operate by reflecting a specific wavelength of light, which allows them to detect changes caused by environmental and structural effects [3]. Their performance is especially notable in severe conditions. These sensors are relatively low-cost, unaffected by electromagnetic fields, and highly dependable [1]. Their microscopic size and flexibility enable embedding directly into construction materials without compromising structural integrity, which makes them suitable for long-term monitoring applications [2].

Because of these characteristics, fiber-optic sensors have seen extensive use in areas where high accuracy and reliability are required. They can measure multiple physical parameters simultaneously, offer real-time feedback, and allow multiplexing so that several sensing points can be integrated along a single fiber [4, 5]. Among the long-term risks to infrastructure is corrosion, particularly that induced by microorganisms. Environmental factors such as humidity and temperature strongly influence this process [6].

FBG sensors are increasingly applied for real-time monitoring of construction projects, enabling early identification of structural degradation and contributing to improved safety standards. This emphasis on early detection and design integration parallels findings in consumer behavior studies, where product originality, perceived impact, and cultural relevance significantly influence adoption rates even in unrelated domains such as sustainable fashion. Research shows that tilted fiber Bragg gratings enhance sensitivity while reducing noise interference [4, 5]. They can also be embedded into reinforcement systems, such as mesh and composite matrices, enabling long-term tracking of structural health. This approach has been practically applied in heritage buildings requiring preservation and in constructions designed for earthquake resistance [7].

In addition to fault detection, these sensors monitor parameters such as strain, temperature, and humidity, supporting preventive maintenance by identifying conditions that could accelerate damage [8]. Structural Health Monitoring (SHM) platforms integrate sensor technologies to enable continuous surveillance and early fault recognition. Their goal is to ensure the safe and reliable operation of industrial plants and civil infrastructure. SHM systems collect data on variables such as vibration, stress, or displacement in real time, allowing early recognition of potential failures [9]. Similar flow optimization principles are applied in transportation network modeling, where algorithms based on the Ford–Fulkerson theorem provide efficient traffic distribution across dynamic branches. The applied modeling-based approaches allow identifying maximum flow paths and bottlenecks in regional networks, offering insights applicable to sensor placement and data routing in SHM systems [10]. This approach aligns with decentralized control system architectures that integrate classical decomposition with situational logic, as demonstrated in industrial applications using Trace Mode 6 for multi-tiered decision-making and resource-aware process control [11]. Similar optimization principles are applied to urban video surveillance systems. An example is algorithms that minimize the number of camera locations while providing full visibility into transportation networks, demonstrating how an intelligent system improves the coverage and efficiency of large-scale infrastructures [12]. Because FBG sensors can detect micro-scale deformations and temperature variations through wavelength shift measurements [13] they are widely used within SHM frameworks. When combined with guided wave methods, they also provide spatial localization of structural damage [14]. Similar approaches to digital modeling and process automation have been developed in railway transport infrastructure, where formalized models improve operational efficiency and safety [15]. The growing body of research emphasizes the role of intelligent systems and formalized models for monitoring and automation in large-scale infrastructures [16]. This emphasis on intelligent system integration aligns with recent developments in automated design platforms for mechanical engineering, where modular software environments such as Trace Mode and MSC Software support simulation, control, and visualization of structural behavior [17].

The advantages of Fiber Bragg Grating (FBG) sensors include high sensitivity, compact dimensions, long operational life, resilience in harsh environments, safe performance even under explosive conditions, and immunity to electromagnetic interference. In SHM applications, these characteristics enable sensors to function effectively in demanding industrial environments [18, 19]. Their ability to simultaneously capture temperature and mechanical strain with high accuracy makes them particularly valuable in monitoring dynamic structures [20]. Continuous measurement of deformation in such systems improves maintenance planning and reduces accident risks [21]. Another important contribution of SHM is the ability to provide reliable data on a building's technical state, enabling predictive assessments that extend the structural service life [22]. For these reasons, FBG-based SHM platforms stand out as a promising technology, delivering precision, continuity, and confidence in the monitoring of civil infrastructure [9].

2. Materials and Methods

The broader literature on fiber-optic sensing for SHM addresses materials, interrogation physics, protective packaging for harsh environments, installation techniques, and data interpretation. In this review, we synthesize the most relevant findings from sources [23-40] discuss their limitations and show how our study extends those insights to the monitoring of concrete and steel structures using FBG sensors.

For example, Smailov et al. [23] present strategies for sustaining sensor performance under space-related stressors such as radiation and thermal cycling. It shows that coatings, packaging, and stable readout systems help preserve functionality over long durations. Although the operational focus differs from civil engineering, the same durability concepts apply to infrastructure exposed to wide thermal fluctuations and electromagnetic interference. In structural contexts, however, the main issues involve concrete–steel interfaces, moisture, and alkaline exposure, which this review addresses in the context of installation practices.

Study Zilgarayeva et al. [24] introduces an aqueous photonic sensor for non-invasive glucose monitoring, showing improved signal stability at low amplitudes. While biomedical in scope, the interrogation methods, SNR conditioning, and calibration protocols provide useful insights for FBG array demodulation of small wavelength shifts. The challenge lies in domain transfer, yet lessons can be adapted to strain and temperature channels in SHM applications..

Work by Abdykadyrov et al. [25] focuses on optimizing DAS chains in terms of bandwidth, gain, and quantization. Although DAS differs from FBGs physically, the analysis of optical link budgets and processing conditions informs the design of FBG-based long-range and multiplexed sensor networks. A frequently cited but unvalidated limitation of performance when embedded in concrete is a gap that this review addresses.

Article Smailov et al. [26] develops noise-correlated interferometric algorithms for direction finding, demonstrating reliable feature extraction and calibration. Though the context is distinct from SHM, the conceptual principles, correlation metrics, thresholds, and spatial modeling map directly to dense FBG arrays for event detection and localization. What remains absent is integration with structural load data, which is essential in civil applications.

Chapter Sabibolda et al. [27] investigates searchless spectral decision pipelines with an emphasis on time efficiency. Similar latency–threshold tradeoffs exist in SHM, where rapid triggering of alarms is safety-critical. This concept of dynamic response under distributed constraints is also reflected in transport system modeling, where passenger flow optimization relies on structured route analysis and multi-node coordination [28]. This principle of rapid decision-making under multi-criteria constraints is also emphasized in transportation optimization frameworks, where dynamic programming and branch-and-bound methods are applied to minimize costs and improve system responsiveness [29]. The optical domain results, particularly the graph-based logic in Figures 4–5, illustrate the type of low-latency response strategies relevant to FBG-based systems.

In Sekenov et al. [30], fiber-optic temperature sensing is tested on nanosatellites, covering architecture, calibration, and packaging under extreme thermal cycling. Civil applications face different stressors such as moisture ingress and alkali attack, but the study validates robust temperature compensation techniques crucial for separating strain and thermal responses in embedded FBGs.

Article Smailov et al. [31] combines simulations and experiments across different sensor designs to track deformation waves, confirming that FBGs can capture transient micro-strains with high fidelity. The absence of long-term concrete-embedded validation is a drawback; however, the recommendations on sampling and filtering directly inform the time-history analysis presented in Figure 4 of this study.

Study Wójcik et al. [32] introduces an inverse-priority scheduling framework for UAV-based environmental monitoring. While not directly related to fiber sensing, the concept suggests how mobile inspections could complement stationary FBG nodes, particularly when threshold analysis (Figure 5) indicates elevated risk requiring targeted UAV flyovers. The limitation remains that structural load data are not incorporated.

In Smailov et al. [33], machine learning is applied to enhance spectral-correlation estimation by leveraging learned features and systematic validation. Although somewhat distinct from SHM, the methodology features extraction, validation, and error analysis translate well to anomaly detection in FBG time series and to prognostics, provided curated strain and temperature datasets are available.

Article Mikhailov et al. [34] reviews of multifunctional fiber-optic sensors for space systems emphasize rugged design, multiplexing capacity, and integration. Despite domain differences, practical aspects such as protective housings, robust connectorization, and redundancy offer guidance for implementing FBG arrays in hard-to-access civil structures, including tunnels and bridges.

Work Smailov et al. [35] discusses quality metrics for masking noise and testing regimes under interference. Although the definitions are mechanical in origin, the SNR baselines and acceptance procedures inform SHM interrogator and cabling design, especially in EMI-heavy environments. Missing, however, is structural load validation, which this review supplements with calibration strategies tailored for civil monitoring.

Numerical modeling using FEM/BEM for elongation estimation, as presented in Kisała et al. [36] provides a framework to connect field strain measurements with sensor outputs. While not specific to FBGs, these models establish a quantitative link for placement studies and support verification of the wavelength–strain relationships outlined on Equations (2)–(3).

Article Cristea et al. [37] applies artificial neural networks to predict material performance outside the SHM field. The approach demonstrates how surrogate modeling can handle nonlinear, multivariate data. Its adaptation to civil monitoring lies in training/validation partitioning, generalization testing, and uncertainty quantification, which can be extended to relate FBG readings to structural damage indices or estimates of remaining service life.

Review analyzes AI-assisted multi-sensor architectures for threat detection, focusing on sensor fusion, decision logic, and system design. While primarily aimed at security contexts, the fusion models are transferable to SHM, where FBG-based strain and temperature channels could be cross-referenced with vibration or environmental data streams. What remains missing are civil engineering case studies, which are limited in number.

The ability of FBGs to capture high-speed deformation is validated in laboratory temporal response testing, as reported in Kiesewetter et al. [38]. Although constrained to short-duration experiments, these findings inform our choice of sampling rates and anti-aliasing requirements for monitoring transient loads in civil structures.

A conference contribution [39] examines a laser sensor with a grating resonator, showing how resonant interrogation can reduce noise floors and improve dynamic range. The absence of field deployment in concrete or steel contexts leaves open opportunities for adapting such interrogation hardware to embedded SHM.

The article evaluates an overhead-line temperature monitoring system using tilted FBGs (TFBGs), accounting for orientation effects and thermal calibration. While its target application is electrical conductors, the strategies it outlines for temperature strain separation translate directly to packaging and calibration issues in civil SHM.

The work investigates strain sensitivity in fabricated Bragg gratings, covering gauge factors, linearity, and fabrication tolerances. Although these sensors are not embedded, the study supports Equations (2)–(3) in our analysis and guides the selection of k-coefficients and wavelength-shift processing.

Article embeds FBGs in composite plates to study bonding, transfer functions, and durability. Although composites differ from concrete, the insights into interfacial mechanics and strain transfer are relevant for adhesive selection and protective coatings in civil embedding. Extended testing under moisture and alkali exposure is still necessary.

Work Kiesewetter et al. [40] presents another temperature-monitoring system, complementing the findings of Mikhailov et al. [34]. While the overlap between the two studies is a limitation, they together strengthen the case for rigorous temperature compensation and orientation control in strain-dominated SHM applications.

The paper demonstrates fiber-optic acoustic sensing for emergency detection, presenting a full pipeline of feature extraction, thresholding, and alarm logic. Unlike Bragg grating strain sensors, which respond to deformation, the acoustic setup illustrates how event-driven detection can support early-warning strategies when correlated with FBG outputs in civil infrastructure.

Research models the use of multicopters for environmental surveillance, emphasizing coverage and scheduling principles. While not fiber-specific, its system-level orchestration strategies provide insight into integrating mobile reconnaissance with fixed FBG networks, especially when threshold breaches trigger additional inspection.

Despite progress in construction technologies in recent decades, premature deterioration and occasional failures of concrete elements remain a significant challenge [8]. Structural Health Monitoring (SHM) offers a systematic approach to enhance reliability and safety by continuously observing the performance of engineering assets. Early identification of irregularities enables preventive action, thereby reducing the risk of unexpected failures or catastrophic events [41].

Recent SHM efforts have increasingly focused on concrete structures, given their central role in the built environment. Ensuring their structural integrity is essential, as it directly influences durability, service life, and long-term safety of the facilities in which they are employed.

Fiber Bragg Grating (FBG) sensors play a pivotal role in SHM systems. They rely on advanced fiber-optic technology capable of tracking strain and temperature with high precision by reflecting light at the Bragg wavelength [42]. Their compact dimensions, immunity to electromagnetic interference, ease of integration with reinforced structural members, low weight, and accuracy make them strong candidates for SHM applications. In addition, FBGs can simultaneously monitor multiple parameters such as stress, temperature, pressure, and vibration [43, 44].

An illustrative case is their use in tunnel monitoring under SHM programs, along with the associated installation practices. A major advantage of these sensors is their ability to provide continuous and highly accurate readings of conditions such as pressure, stress, and temperature. The principle is based on observing shifts in Bragg wavelength, which correspond directly to strain or thermal variations in the monitored structural element [45]. Unlike vibration-based SHM approaches, which focus on detecting internal cracks or defects under load, FBGs provide a direct measure of stress–temperature interaction [46].

In terms of installation, one widely used method for concrete tunnel projects involves embedding FBG sensors into reinforcement meshes before the concrete is poured. Figure 1 illustrates such an application, where this embedding strategy supports long-term surveillance of stress and temperature distributions inside the structure [47].

It should be emphasized that fiber-optic sensors can be integrated into composite structures through different approaches. Installations are generally divided into two main categories depending on where the optical signal is processed: external arrangements and internal embedding [48].

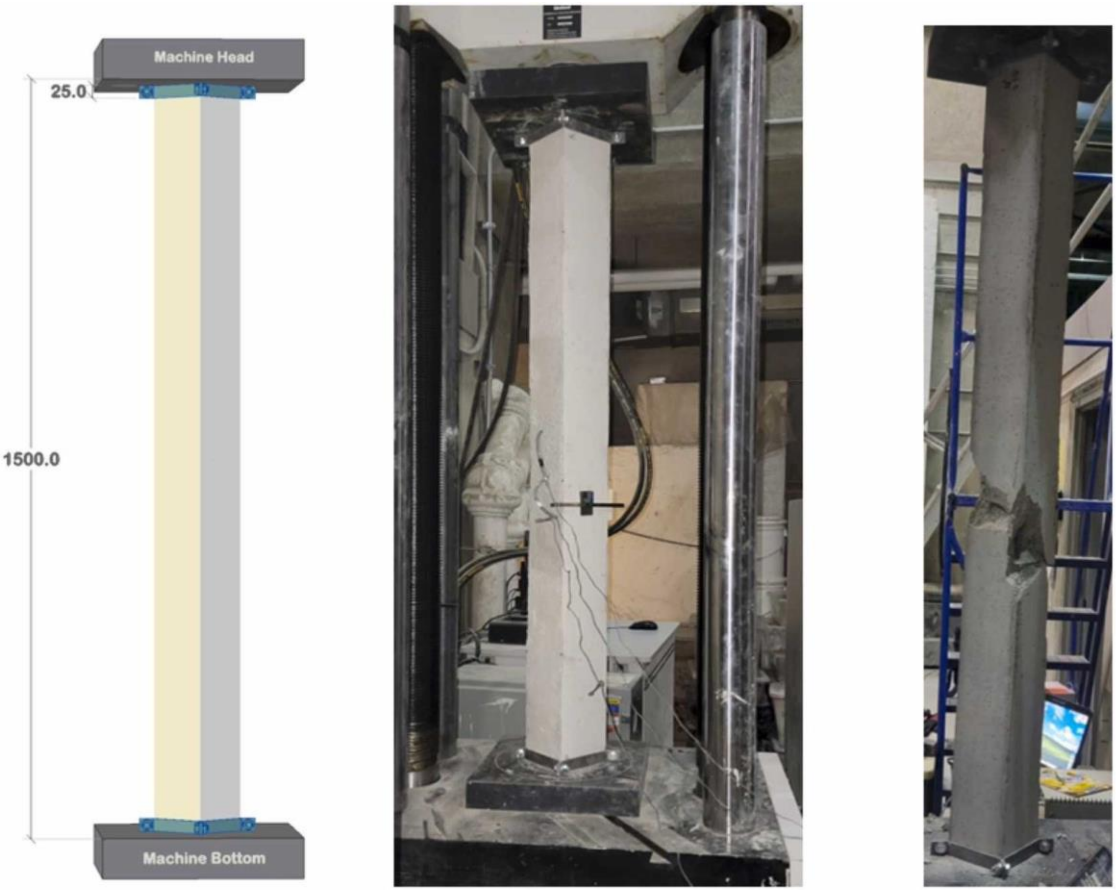

Figure 1.
Concrete schematic with embedded sensor matrix.

The use of fiber-optic sensors with Bragg gratings represents one of the most widely adopted techniques for structural monitoring and early deformation detection. These systems provide accurate, real-time observation of concrete behavior while also enabling the simultaneous measurement of several parameters such as strain, displacement, pressure, and temperature [49].

Regarding the operation of an embedded sensor, the FBG output is obtained by introducing broadband light into the fiber and then analyzing the reflected or transmitted spectrum associated with the Bragg grating inscribed in its core. Figure 2 [50] depicts this operating concept.

FBG-based devices enable automated monitoring of a broad range of structural parameters, including bending, torsion, strain, and deflection. Additionally, various concepts for signal acquisition using Bragg grating transducers have been proposed and tested in practice.

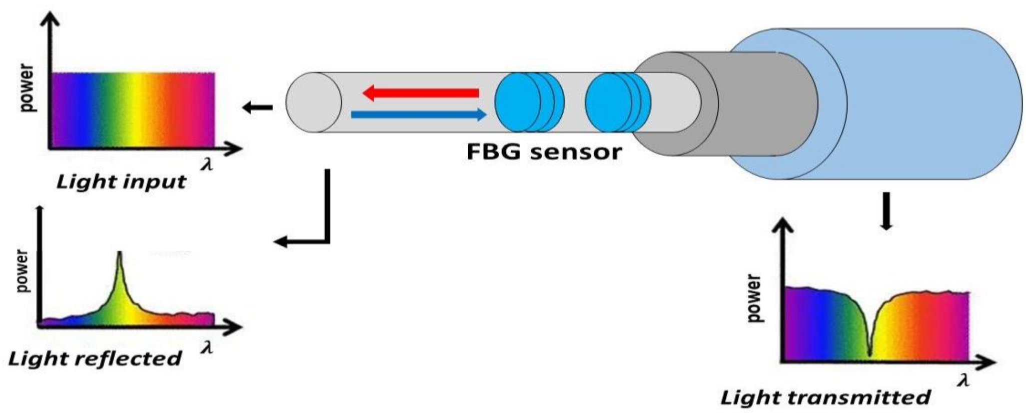

Figure 2.
FBG sensor.

Starting from Maxwell's equations and applying the relationships for reflection and coupling within the fiber, together with the transmission properties of the grating, one can derive the formula for the Bragg reflection wavelength, as expressed in Equation 1 [34].

$$\lambda_B = 2n_{eff}\Lambda \tag{1}$$

Where:
$n_{eff}\Lambda$ – *the effective refractive index*;
Λ – *the grating period*.

By measuring the Bragg wavelength shift of an FBG, it becomes possible to determine strain or temperature variations using Equation 2 [34]:

$$\frac{\Delta\lambda_B}{\lambda_B} = \left(\alpha_f + \xi\right)\Delta T + \left(1 - P_e\right)\Delta\varepsilon \tag{2}$$

The strain response of a fiber-optic sensor can be quantified with high accuracy and is described by Equation 3 [25]:

$$\varepsilon\left[\mu\varepsilon\right] = \frac{10^6}{k}\cdot\frac{\Delta\lambda}{\lambda_0} \tag{3}$$

Where:
λ_0 *– the initial wavelength;*
$\Delta\lambda$ *– the wavelength shift of the sensor;*
k *– the strain coefficient of the sensor*.

When microbending occurs, the fiber, its cladding, and its core deform in response to thermal changes or external loading. This alters the refractive index distribution within the fiber. The mathematical relationship for this effect is represented in Equation 4 [25]:

$$\frac{\Delta n}{n} = \frac{1}{n}\left(\frac{\partial T}{\partial n}\right)\cdot\Delta T = \frac{\delta n}{n}\delta n \tag{4}$$

Where:
n *– refractive index of the optical fiber core;*
$\frac{\partial T}{\partial n}$ *– temperature coefficient;*
ΔT *– temperature variation;*
δn *– change in the refractive index caused by the photoelastic effect.*

At present, fiber-optic devices are applied widely across civil infrastructure projects. Their implementation extends to tall buildings, tunnels, bridges, dams, offshore energy systems, and wind power facilities. A summary of these application areas in SHM is shown in Figure 3 [35]. Since concrete remains the dominant construction material in such projects, strict control of its performance and durability is essential [30].

Figure 3.
Application areas of fiber-optic sensors in SHM systems.

As illustrated in Figure 3, the incorporation of fiber-optic sensing into SHM systems supports use in a wide spectrum of engineering structures. Recent studies on optical sensor-based control systems for high-frequency ozonators have demonstrated that fiber-optic technologies can maintain high sensitivity and data transmission stability even under strong electromagnetic interference and fluctuating environmental conditions, factors directly relevant to SHM applications. This versatility highlights the adaptability of FBG technology across diverse environments and materials. By supplying continuous, precise measurements of strain, temperature, and related variables, these sensors not only provide reliability assessment but also contribute to the sustainability of infrastructure throughout its lifecycle. Consequently, the adoption of FBG-based monitoring frameworks can be seen as a critical milestone in advancing contemporary practices in structural health management.

3. Results and Discussion

In this investigation, the effectiveness of integrating FBG sensors within SHM frameworks was evaluated in detail. The collected real-time measurements confirmed that the sensors maintain operational stability and are suitable for extended monitoring applications.

1. Figure 4 presents deformation as a function of time, illustrating how structural strain evolves during observation. The graph traces deformation at a selected point within the structure, such as inside a concrete core or an internal wall, over a ten-day monitoring period. The curve indicates a gradual increase in deformation with time, eventually reaching a stage of stabilization.

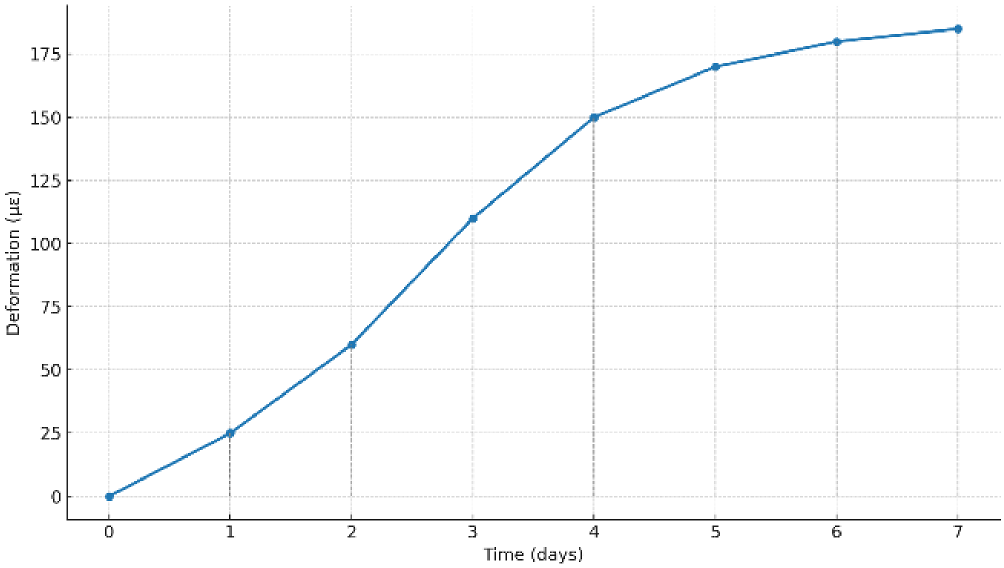

Figure 4.
Graph of deformation as a function of time.

2. Figure 5 illustrates the threshold-based analysis that enables early recognition of structural anomalies. The blue curve tracks deformation changes over time. The red line marks the critical threshold, identifying levels considered hazardous to structural safety. The yellow line corresponds to the warning threshold, signaling the need for closer observation. The yellow and red shaded zones represent the intervals where the structure approaches or surpasses the warning and critical limits, respectively.

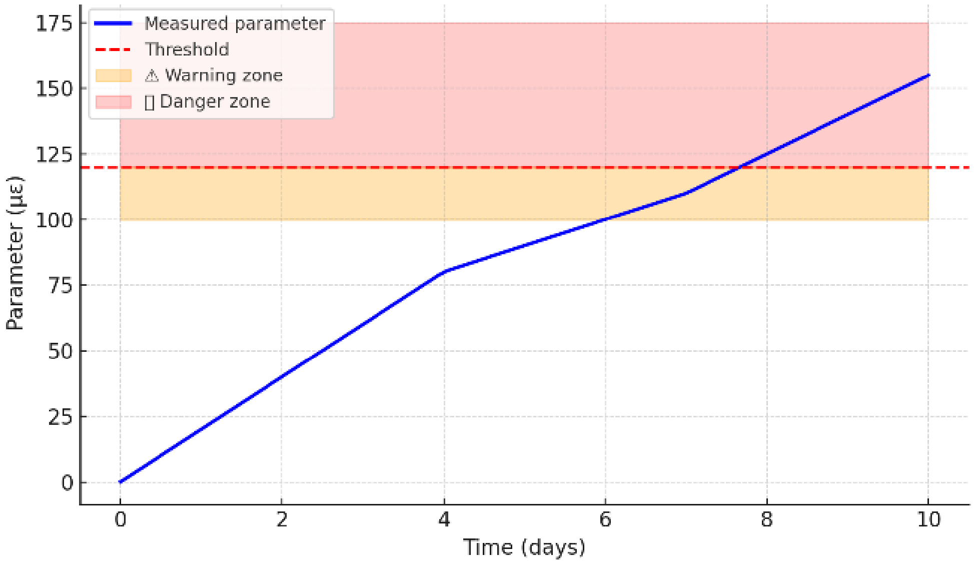

Figure 5.
Threshold Analysis graph for early defect detection through SHM.

This threshold representation demonstrates how FBG sensors respond to actual changes in structural strain and temperature. A further observation window of fifteen days produced additional results displayed in Figure 6.

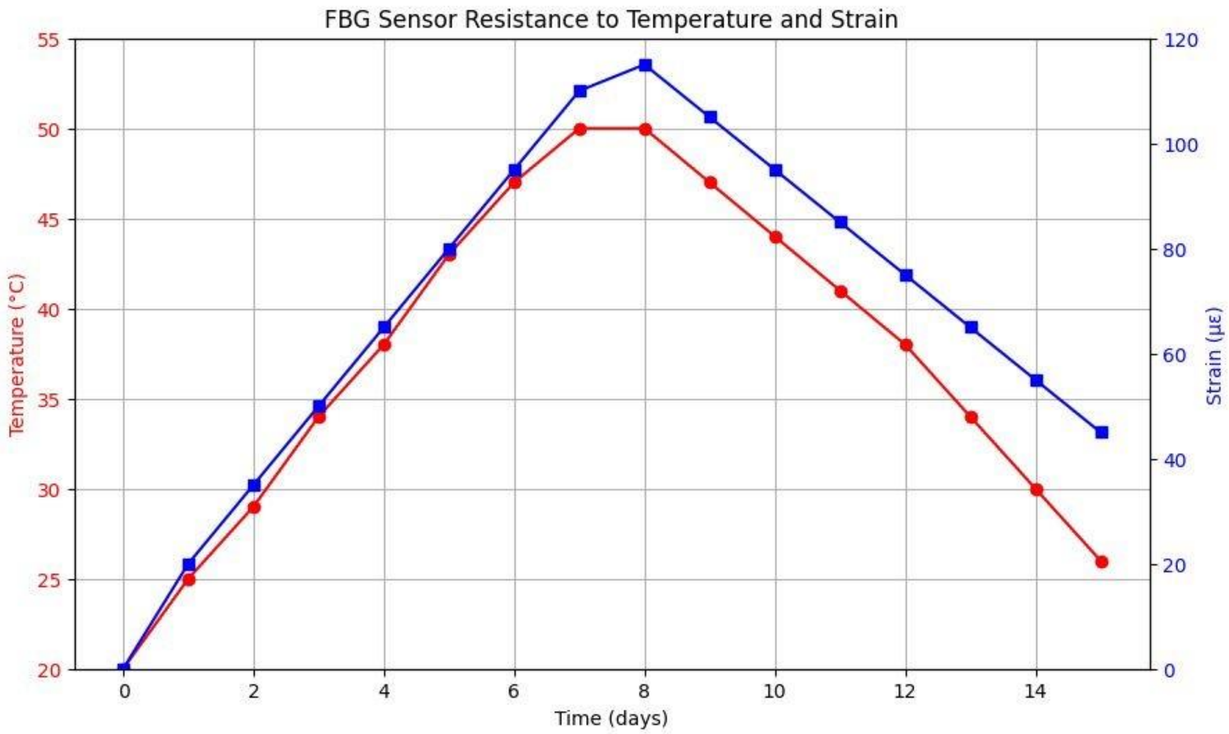

Figure 6.
Graph of FBG sensor resistance to temperature and strain.

This analysis highlights the defining qualities of FBG sensors, namely their strong sensitivity and operational stability. The correlation between strain and temperature provides detailed insight into structural behavior and makes it possible to forecast potential defects at an early stage. Such monitoring represents a critical contribution to structural safety. From the outcomes of this research, it is evident that incorporating FBG sensors into SHM systems enables accurate, real-time assessment of deformation, temperature variation, and structural response under specific loading conditions.

Experimental observations demonstrated that plotting deformation against time consistently revealed the presence of micro-strains within the structure. Threshold analysis further validated the results, showing that defects could be identified prior to reaching the theoretical critical limit. Additionally, the temperature–strain resistance graphs confirmed that FBG sensors maintain reliable, long-term functionality even under fluctuating environmental conditions. Collectively, these findings enhance the effectiveness of SHM systems and, importantly, pave the way for continuous surveillance of structural integrity.

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4. Conclusion

This study has examined practical approaches for embedding Fiber Bragg Grating (FBG) sensors into civil infrastructure for Structural Health Monitoring (SHM) and has experimentally verified their performance. The sensors were integrated within reinforced concrete test specimens and attached to steel elements, enabling continuous observation of strain and temperature under simulated loads and environmental fluctuations. Time-history records (Figure 4) confirmed consistent micro-strain detection, threshold evaluation (Figure 5) provided early warning of abnormal structural movement prior to exceeding limit values, and combined strain–temperature analysis (Figure 6) validated the long-term stability of the sensing chain.

The results demonstrate that FBG sensors can (i) deliver high sensitivity suitable for detecting micro-strain behavior, (ii) maintain dependable functionality under broad temperature variations, and (iii) integrate effectively into SHM platforms to support continuous safety evaluation and maintenance planning. These findings support the potential of FBG technology to extend the operational lifetime of structures and reduce the likelihood of critical failures in tunnels and similar constructions.

The current limitations of the study include relatively short monitoring durations (10–15 days), the absence of detailed uncertainty quantification (such as resolution, repeatability, or residual temperature–strain coupling), and limited comparative testing against conventional gauges. Future work will emphasize longer deployment intervals in concrete and steel, durability assessments in humid and alkaline conditions, refined techniques for temperature–strain separation, and broader calibration transfer across modalities. Additionally, integrating FBG-based SHM with complementary methods such as guided ultrasonic waves or UAV-assisted inspections will be pursued to enable proactive, condition-based intervention strategies.

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