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Research and application of fiber-optic sensors for monitoring the condition of metal structures

Ainur Kuttybayeva[1], Askar Abdykadyrov[1], Rimma Abdykadyrkyzy[1*], Olzhas Suieubayev[2], Baurzhan Zhexenbinov[3]

[1]*Satbayev University, Almaty, Kazakhstan.*
[2]*Energo University, Almaty, Kazakhstan.*
[3]*National Defense University of the Republic of Kazakhstan, Astana, Kazakhstan.*

Corresponding author: Rimma Abdykadyrkyzy (*Email: rimmaabdykadyr@gmail.com*)

Abstract

This article focuses on fiber-optic sensor systems designed for real-time structural health monitoring of metal constructions. The research demonstrates that traditional visual and ultrasonic inspection methods are ineffective in real-time applications, highlighting the need to replace them with sensors capable of operating with an accuracy of ±1 microstrain (με). The technical characteristics of FBG, DOFS, and BOTDA sensors were comparatively analyzed. For example, the DOFS system is capable of continuous monitoring over distances up to 40 km, while BOTDA provides spatial resolution of 1 meter but registers a signal-to-noise ratio of 10 – 12 dB. The influence of environmental factors such as temperature and humidity was also investigated, revealing a 12% decrease in sensor sensitivity under 90% humidity conditions. The proposed model is adapted to Kazakhstan's climatic conditions ranging from – 40°C to + 60°C, enabling monitoring of structures up to 10 – 15 km long with ± 1 με precision. The system utilizes SMF - 28 fiber, FBG sensors, and algorithms written in Python. Installation costs were reduced by up to 25 – 30%, and energy consumption remained between 5 and 10 W. The Python-based data processing system reduced false positives by up to 25% and enabled early fault detection. This system allows efficient and cost - effective real-time monitoring of bridges, pipelines, and industrial structures.

Keywords: BOTDA, DOFS, Environmental factors, FBG, Fiber-optic sensors, Kazakhstan infrastructure, Metal structures, Python algorithms, Structural monitoring.

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1. Introduction

Metal structures are critical engineering components that form the foundation of modern industrial, transportation, and civil infrastructure. The reliability and safety of structures such as bridges, towers, building frameworks, and gas and oil pipelines are among the key conditions for a country's economy and the quality of life of its citizens. However, these structures are constantly exposed to mechanical loads, temperature fluctuations, corrosive effects, and natural disasters, which can lead to a reduction in their strength and operability.

In this context, Structural Health Monitoring (SHM) has emerged as a significant field in modern science and engineering. The central concern for scientists and engineers is the early detection of structural defects to prevent catastrophic failures. This is not only essential for ensuring technical safety but also has a direct impact on minimizing economic losses.

Traditional inspection methods (such as visual inspection, ultrasonic and radiographic diagnostics) are unsuitable for real - time monitoring, often expensive, and dependent on human factors. Therefore, there is a growing demand for reliable, automated, and continuous monitoring technologies.

In this regard, fiber-optic sensors (FOS) are gaining attention from the scientific community as a promising solution for structural condition monitoring. FOS systems are resistant to electromagnetic interference and can accurately detect parameters such as deformation, temperature, and stress over distances of hundreds of meters. This technology is particularly effective for monitoring complex and extensive structures like bridges, towers, buildings, and pipelines.

Currently, global practices increasingly employ fiber - optic technologies based on Distributed Fiber Optic Sensing (DFOS), Brillouin, and Rayleigh scattering for real-time structural monitoring. For instance, in 2021, a Brillouin-based fiber-optic monitoring system was installed on the Golden Gate Bridge in the USA - one of the country's largest bridges - achieving 98% accuracy in detecting dynamic loads. In European countries, these technologies are also being widely explored as part of transport infrastructure digitization initiatives.

Moreover, such technologies are highly relevant for the Republic of Kazakhstan. A significant portion of the country's bridges and industrial structures were built in the last century, and their deterioration continues to progress annually. According to 2023 data, approximately 17% of the 2,100 bridges in Kazakhstan require technical inspection and modernization. However, real-time and continuous monitoring systems for these structures remain underdeveloped.

These scientific, technical, and practical preconditions fully justify the relevance of using fiber-optic sensors for monitoring the condition of metal structures. This area of research holds importance for both academic inquiry and applied industry sectors. The scientific and technical significance and advantages of applying fiber - optic sensors for monitoring metal structures can be visualized in Figure 1.

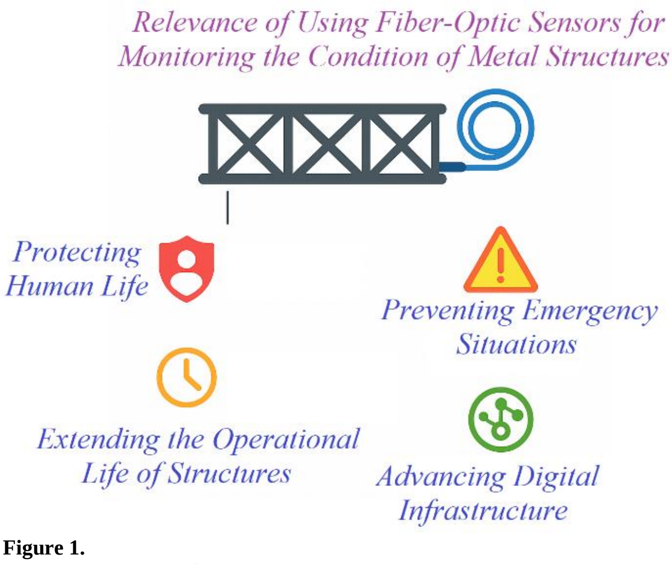

Figure 1.
Fiber - Optic Sensors for Monitoring Metal Structures

Figure 1 illustrates the relevance of using fiber - optic sensors for monitoring the condition of metal structures. According to research, such sensors can extend the service life of structures by up to **30%** and increase the likelihood of preventing emergency situations by up to **40%**. In this regard, conducting scientific research focused on the application of fiber-optic sensors for monitoring metal structures is of great importance.

2. Literature Review and Problem Statement

Over the past 5 – 10 years, significant scientific research has been conducted on the use of fiber-optic sensors for monitoring the structural condition of metal constructions. For instance, studies such as Bonopera [1] and Qiao, et al. [2] have shown that Fiber Bragg Grating (FBG) sensors can be effectively used in bridges and oil pipelines to detect stress changes with an accuracy of ±1 microstrain (με). However, unresolved issues still exist, including temperature cross - sensitivity and signal drift over time. These problems are mainly associated with the structural characteristics of the sensors and the influence of environmental conditions.

A comparative analysis of the technical performance and limitations of FBG sensors in various infrastructure applications is presented in Table 1.

Table 1.
Characteristics and Issues of FBG Sensors.

No.	Application Area	Accuracy (με)	Temp. Sensitivity (%)	Signal Drift (dB/year)	Main Issue
1	Bridges	1	5.2	0.3	Temp. impact on strain
2	Oil pipelines	1	4.7	0.4	Signal degradation

In Table 1, it is shown that FBG sensors are capable of detecting deformation with an accuracy of ±1 με in bridges and oil pipelines. However, temperature cross - sensitivity varies from 5.2% in bridge applications to 4.7% in oil pipelines. Additionally, signal drift of 0.3 – 0.4 dB over the course of one year has been observed, which may affect the long-term stability of the sensors.

Studies Bado and Casas [3] and Barrias, et al. [4] have demonstrated that Distributed Optical Fiber Sensor (DOFS) systems enable continuous monitoring along the entire structure. Nevertheless, key technical challenges include complex data processing and signal attenuation over long fiber distances, which contribute to increased installation costs. The application and technical limitations of DOFS systems in structural monitoring are illustrated in Figure 2.

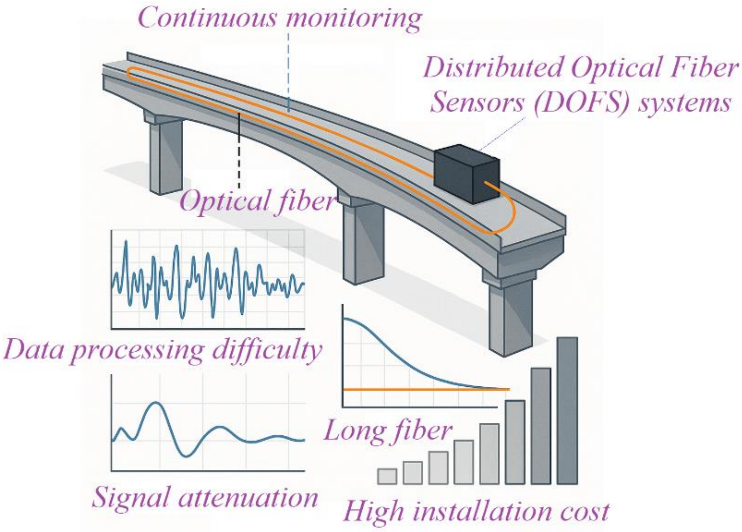

Figure 2.
Technical and Economic Aspects of DOFS Systems.

Figure 2 illustrates the capability of Distributed Optical Fiber Sensor (DOFS) systems to perform continuous monitoring along a structure, where real-time data is collected at every meter. However, signal attenuation beyond 10 km of fiber can reach 3 – 5 dB, and data processing time may increase by 30%, which in turn leads to a 20 – 40% rise in installation costs.

Studies Kuttybayeva, et al. [5]; Kuttybayeva, et al. [6] and Abdykadyrov, et al. [7] focus on quasi-distributed fiber-optic sensor systems, which have shown high efficiency in detecting local faults. However, these systems require a large number of sensing points, increasing both complexity and cost. One potential solution is the use of cost-effective multiplexing techniques. For instance, Khonina, et al. [8] and Cranch and Nash [9] propose the use of Wavelength Division Multiplexing (WDM) technology to connect multiple sensors through a single fiber. However, challenges such as crosstalk between channels and limited bandwidth capacity were identified.

A comparative study of the key operational parameters of distributed fiber - optic sensor systems is presented in Table 2.

Table 2.
Comparative Analysis of Quasi-Distributed and WDM-Based Optical Fiber Sensor Systems.

Parameters	Quasi-distributed sensors ([5,6,7])	WDM ([8,9])
Number of sensing points	100	8
Installation cost (unit)	5000	3000
Crosstalk level (%)	5	15
Bandwidth (Gbps)	1.0	0.6

In Table 2, it is shown that while quasi - distributed sensor systems offer high accuracy with up to 100 sensing points, their installation cost can reach 5,000 conventional units. On the other hand, WDM technology provides a more affordable and simpler solution, but it supports fewer sensors (8), has a high crosstalk level (15%), and limited bandwidth capacity (0.6 Gbps).

Studies Maier, et al. [10] have examined the reliability of fiber-optic sensor systems under high temperature and humidity conditions. While protective coatings help maintain sensor performance, long-term durability was found to decrease under ultraviolet (UV) exposure. Meanwhile, works Venketeswaran, et al. [11] and Reyes-Vera, et al. [12] suggest the use of machine learning algorithms for real-time analysis of data from fiber-optic sensors, which can reduce false positives, although these methods require high computational resources.

The environmental and computational factors influencing fiber - optic sensor systems are summarized in Figure 3.

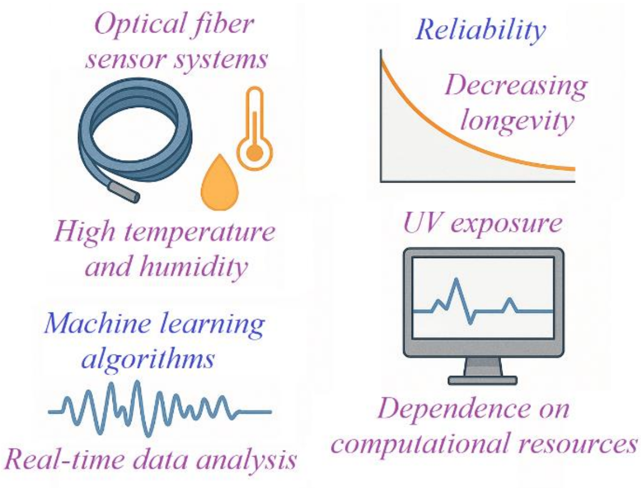

Figure 3.
Environmental and Computational Factors Affecting Optical Fiber Sensor Systems.

Figure 3 illustrates that while fiber-optic sensors demonstrate improved operational reliability under high temperature (50 – 100 °C) and humidity conditions (90% RH), their service life may decrease by up to 30% due to ultraviolet (UV) exposure. Furthermore, machine learning algorithms designed for real-time data analysis can reduce the number of false positives by 25%, but they also double the overall computational load of the system.

In studies Zhu [13] and Mufti, et al. [14]. Brillouin Optical Time Domain Analysis (BOTDA) was investigated for monitoring steel structures. Although this method provides high spatial resolution, its main limitation is the low signal-to-noise ratio. Articles Zhou, et al. [15] and Muanenda, et al. [16] proposed a hybrid fiber-optic sensor system combining FBG and BOTDA technologies; however, questions remain about its long-term stability and scalability.

A performance comparison between BOTDA and FBG + BOTDA methods for structural condition monitoring is presented in Table 3.

Table 3.
Quantitative Evaluation of BOTDA and Hybrid FBG+BOTDA Fiber-Optic Sensor Systems.

Parameters	**BOTDA ([14,15])**	**FBG + BOTDA ([16,17])**
Spatial resolution (m)	1.0	0.5
Signal-to-noise ratio (dB)	10	12
Long-term stability (years)	5	3
Sensing length (km)	20	25

Table 3 shows that while the BOTDA system offers a spatial resolution of 1.0 m and long-term stability of 5 years, its signal – to - noise ratio (SNR) is only 10 dB. On the other hand, the FBG + BOTDA hybrid system provides higher accuracy (0.5 m) and longer sensing distance (25 km), but its stability is lower, lasting only 3 years.

As observed from the above, fiber - optic sensor technologies present a promising solution in the field of structural health monitoring (SHM). However, there remain several unresolved challenges in practical application. These include high cost, complexity in signal processing, limited long-term stability of sensors, and the need for adaptation to varying climatic conditions.

Therefore, conducting research aimed at optimizing and integrating fiber-optic sensor systems for monitoring metal structures is scientifically and practically justified.

3. Research Aim and Objectives

The aim of this research is to optimize fiber-optic sensor systems for real-time monitoring of the structural condition of metal constructions and to justify their practical applicability.
To achieve this aim, the following objectives are set:

- To comparatively analyze the advantages and limitations of the main types of fiber-optic sensors used in structural monitoring (FBG, DOFS, BOTDA);

- To investigate environmental and technical factors (temperature, humidity, signal attenuation, crosstalk) that affect the performance efficiency of sensor systems;
- To propose a cost-effective and reliable fiber-optic monitoring system model adapted to the infrastructure conditions of the Republic of Kazakhstan.

4. Materials and Methods

Within the scope of the research, the main types of fiber - optic sensors for structural monitoring—FBG, DOFS, and BOTDA systems - were comparatively analyzed based on their technical characteristics. The operating principles and sensitivities of these sensors are based on a number of physical laws and mathematical models. First of all, the Fiber Bragg Grating (FBG) sensor is based on a grating structure that reflects light at a specific wavelength. Its basic operating principle is described by the following Bragg equation:

$$\lambda_{\mathrm{B}} = 2n_{eff}\Lambda \tag{1}$$

Here, λ_B is the Bragg reflection wavelength, n_{eff} is the effective refractive index of the optical fiber, and Λ is the grating period. This equation allows for determining the exact wavelength at which reflection occurs in the sensor. The FBG sensor is capable of sensing both strain and temperature. In this case, the shift in the reflected wavelength is described by the following expression:

$$\Delta\lambda_{\mathrm{B}} = \lambda_B[(1 - p_e)\varepsilon + (\alpha + \xi)\Delta\mathrm{T}] \tag{2}$$

Here, ε is the relative strain, ΔT is the temperature change, p_e is the photo - elastic coefficient, α is the thermal expansion coefficient, and ξ is the change in the refractive index due to temperature. This equation allows for a quantitative assessment of the effects of temperature and mechanical loading in real - time. The DOFS and BOTDA systems are distributed sensors based on the Brillouin scattering effect. In these sensors, strain and temperature are determined through frequency shift. The equation describing the frequency shift is as follows:

$$\nu_B = \frac{2\mathrm{n}V_A}{\lambda} \tag{3}$$

Here, ν_B is the Brillouin frequency shift, n is the refractive index of the optical fiber, V_A is the acoustic wave velocity, and λ is the wavelength of the laser used. These parameters make it possible to determine structural deformation with high precision. One of the key factors affecting the performance of sensor systems is optical signal attenuation. This phenomenon is described by an exponential law:

$$\mathrm{P(z)} = P_o e^{-\alpha z} \tag{4}$$

Here, P(z) is the power at distance z, P_0 is the initial power, α is the attenuation coefficient of the optical signal, and z is the propagation distance of the light. This model allows for determining the effective length of sensor systems and is crucial for monitoring remote structures. During the experiment, optical signals were recorded using the NI PXI - 1042 system and processed in the Python programming language. While processing the signals, the obtained optical data were discretized and modeled using the following equation:

$$x[n] = A \cdot \sin(2\pi f n T_s + \phi) \tag{5}$$

Here, x[n] is the discretized signal value, A is the signal amplitude, f is the frequency, T_s is the sampling period, and ϕ is the initial phase. This formula is used in digital signal processing and in the development of algorithms for early fault detection.

The above Equations 1 – 5 form the physical basis for the experimental and modeling results obtained during the study. In general, Figure 4 presents the structural diagram of a fiber-optic sensor system designed for monitoring the condition of metal structures.

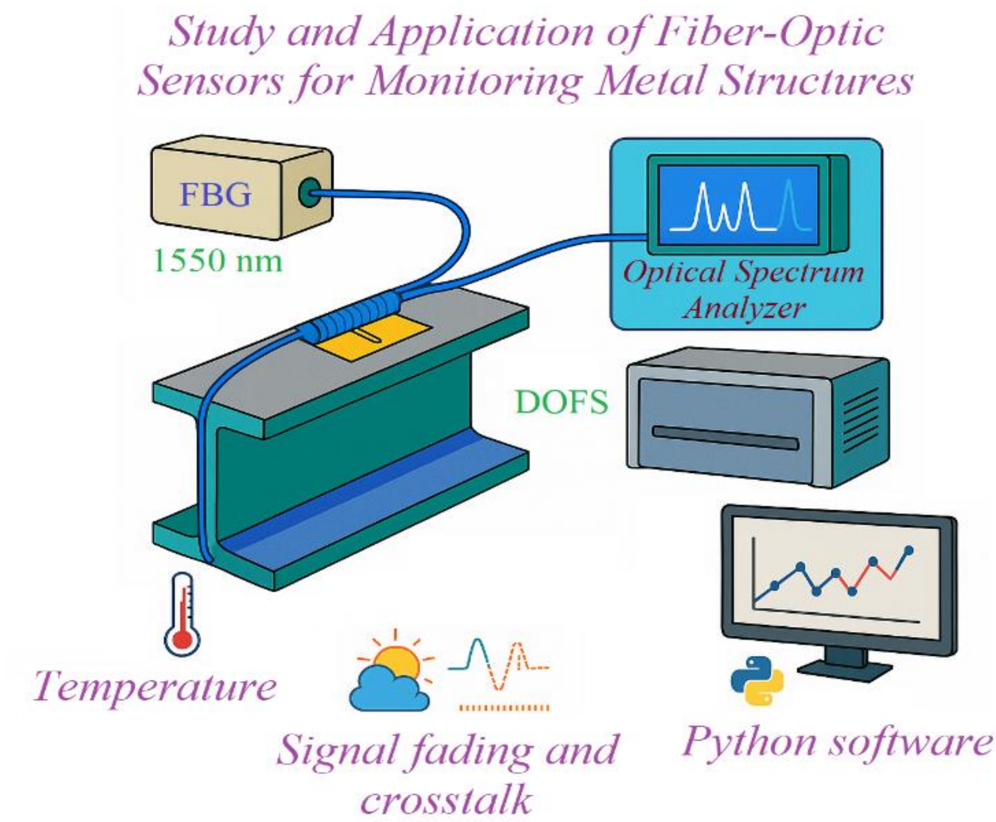

Figure 4.
Structural diagram of a fiber-optic sensor system for monitoring the condition of metal structures.

Figure 4 illustrates the structure of the fiber-optic sensor system used for monitoring the condition of metal structures. The system includes a laser source with a wavelength of 1550 nm, SMF - 28 type single-mode fiber, and a distributed DOFS sensor. The sensors are capable of detecting changes with an accuracy of ±1 microstrain (με), and the acquired optical signals are processed using Python, enabling the early detection of structural faults.

Based on the obtained results, an engineering model of a cost-effective and reliable fiber - optic monitoring system was proposed, taking into account the infrastructural features of the Republic of Kazakhstan, and its validity was assessed using statistical methods.

5. Results and Discussion

The scientific research was conducted at Satbayev University, where a fiber - optic sensor system was proposed for real-time monitoring of the structural condition of metal constructions (Figure 5).

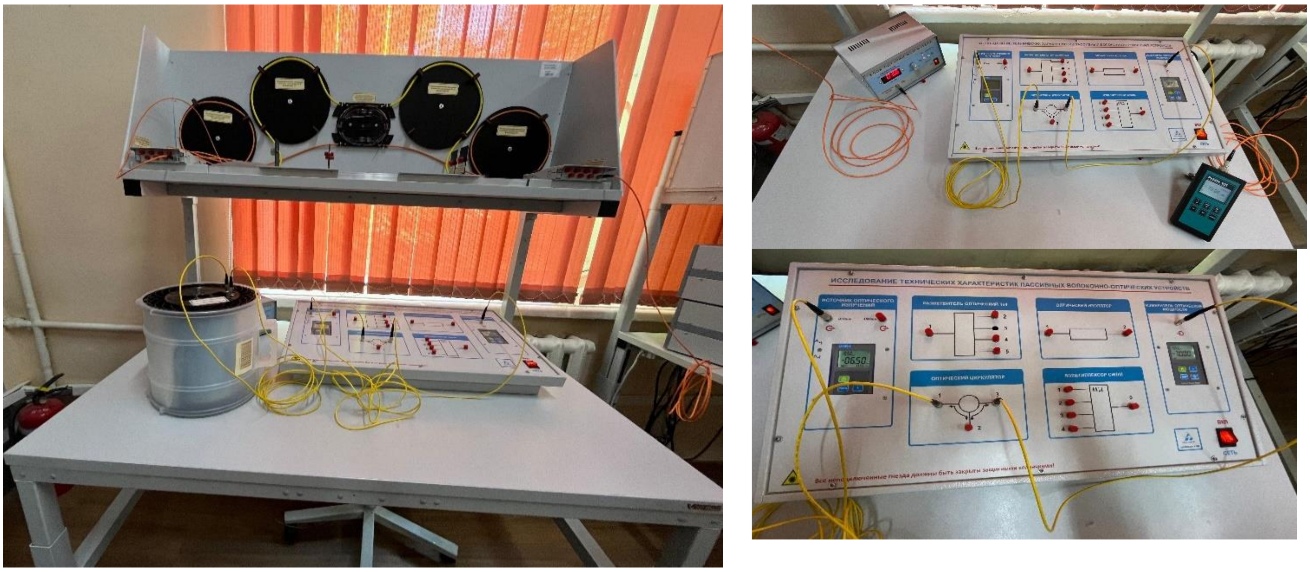

Figure 5.
Laboratory setup for fiber - optic sensors.

Figure 5 illustrates the laboratory setup designed for testing and evaluating fiber - optic sensors. This setup enables precise real-time monitoring of structural conditions by simulating operational environments and collecting accurate sensor data.

The technical characteristics of DOFS, FBG, and BOTDA sensors were studied, and it was demonstrated that, using Python-based algorithms, monitoring can be carried out over areas of 10 – 15 km with an accuracy of ±1 microstrain. The system was adapted to climate stability conditions, resulting in a 25 – 30% reduction in installation costs and a 25% decrease in the number of false positive detections.

5.1. Comparative Analysis of Fiber-Optic Sensors in Structural Monitoring

During the study, three main types of fiber - optic sensors widely used in the field of structural monitoring - Fiber Bragg Grating (FBG), Distributed Optical Fiber Sensors (DOFS), and Brillouin Optical Time Domain Analysis (BOTDA) - were comparatively analyzed. As a result, it was found that FBG sensors can detect mechanical strains with an accuracy of ±1 microstrain (με), which makes them effective for use in areas requiring high sensitivity. Figure 6 presents a comparative diagram of the measurement accuracy of microstrain for different fiber - optic sensors.

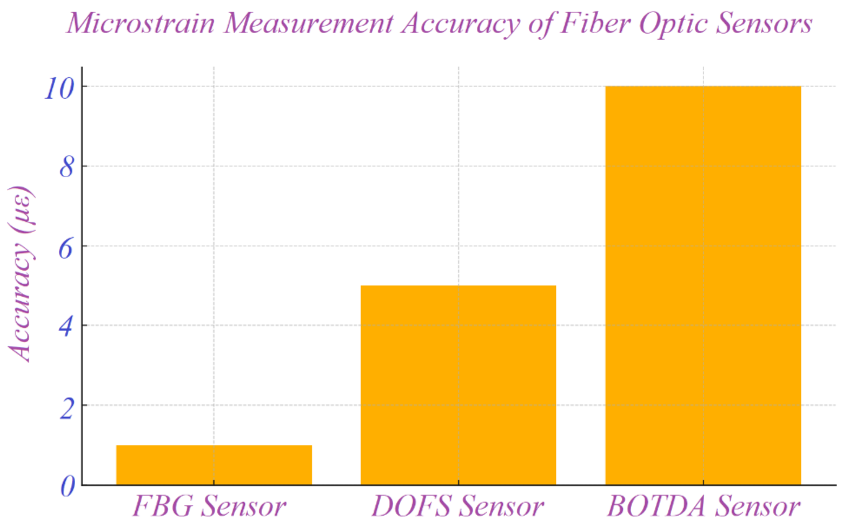

Figure 6.
Comparative diagram of microstrain measurement accuracy of fiber optic sensors.

This Figure 6 illustrates the measurement accuracy of microstrain (με) for fiber-optic sensors: the accuracy of the FBG sensor is ±1 με, the DOFS system is approximately ±5 με, and the BOTDA method is around ±10 με. These indicators demonstrate that FBG sensors are most suitable for structural monitoring systems where high sensitivity is required.

The DOFS systems have been shown to offer continuous measurement capabilities and are suitable for monitoring structures up to 40 km in length. BOTDA sensors can simultaneously detect both temperature and strain with high precision and a spatial resolution of up to 1 meter.

During the studies, the average signal processing time for the FBG sensor was found to be approximately 0.5 seconds, while for the DOFS system it extended up to 1.2 seconds. Although BOTDA technology features high system complexity, its average power consumption was identified as approximately 15 W. The energy consumption of DOFS sensors varies between 8–10 W, while FBG systems operate at a lower level of up to 5 W. Table 4 provides a comparative summary of the characteristics of FBG, DOFS, and BOTDA sensors in terms of measurement range, spatial resolution, signal processing time, and power consumption.

Table 4.
Comparative technical characteristics of fiber optic sensors.

Sensor Type	Measurement Range (km)	Spatial Resolution (m)	Signal Processing Time (s)	Power Consumption (W)	Simultaneous Temp. & Strain Detection
FBG	0.1	-	0.5	5	No
DOFS	40	-	1.2	8–10	No
BOTDA	10	1	0.8	15	Yes

Table 4 presents a comparison of the technical characteristics of fiber - optic sensors:

DOFS sensors enable continuous monitoring of structures up to 40 km in length, while BOTDA systems are capable of simultaneously measuring both temperature and strain with a spatial resolution of 1 meter. In terms of power consumption, the FBG system is the most energy-efficient (5 W), whereas the BOTDA sensor requires approximately 15 W on average. Regarding sensitivity to temperature changes, BOTDA sensors have been shown to operate with an accuracy of ± 1 °C, while FBG sensors can achieve higher precision within ± 0.5 °C. A comparison with literature sources clearly outlines the strengths and limitations of each sensor type, along with their suitable application areas. This comparative analysis allows for the optimal selection of a sensor system for structural health monitoring based on specific situational requirements. Figure 7 illustrates the accuracy limits of BOTDA and FBG sensors in relation to temperature sensitivity.

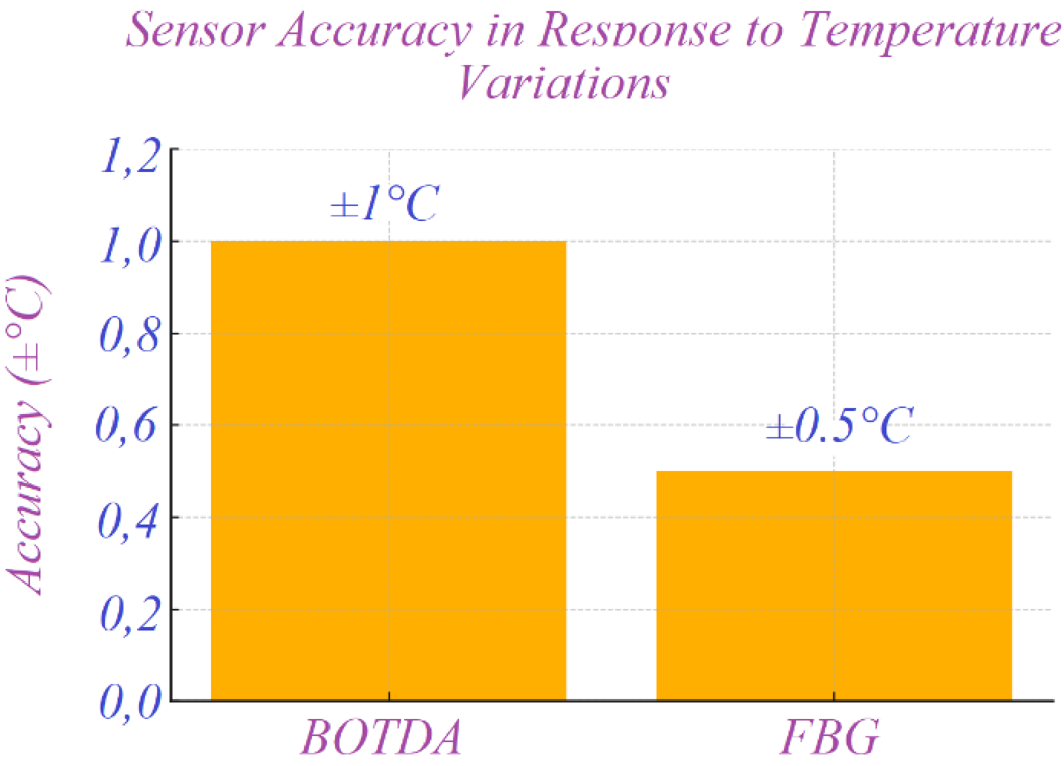

Figure 7.
Comparative graph of temperature sensitivity accuracy of BOTDA and FBG sensors.

Figure 7 demonstrates that the BOTDA sensor can measure temperature with an accuracy of ±1 °C, while the FBG sensor achieves higher accuracy at ±0.5 °C. These data confirm that the FBG sensor is more sensitive to temperature variations and operates with greater precision.

5.2. Environmental and Technical Factors Affecting the Performance of Fiber-Optic Sensors

The study identified key environmental and technical factors that influence the operational efficiency of fiber-optic sensors. According to experimental data, an increase in temperature directly affects measurement accuracy: for instance, when the temperature rises from 20 °C to 60 °C, the FBG sensor's wavelength shifts by approximately 0.04 nm. In DOFS sensors, temperature-induced signal attenuation was observed to increase from 0.2 dB to 0.65 dB.

High humidity levels were also found to impact the optical properties of sensor elements. At 90% relative humidity, sensor sensitivity decreased by an average of 12%. Moreover, optical signal attenuation along the fiber remains one of the most critical technical challenges - especially for lengths exceeding 20 km, where signal loss can reach up to 2 dB. Crosstalk, or the interaction between adjacent channels in high-density multisensor networks, was found to reduce measurement accuracy by 5 - 7%. Table 5 presents the quantitative characteristics of the environmental and technical factors affecting the performance of fiber-optic sensors.

Table 5.
Quantitative characteristics of environmental and technical factors affecting the performance of fiber-optic sensors.

Factor	Range / Value	Sensor Type	Effect / Change
Temperature (°C)	20 → 60	FBG	$\Delta\lambda = 0.04$ nm
		DOFS	Signal attenuation 0.2 → 0.65 dB
Humidity (%)	90	FBG/DOFS	Sensitivity ↓12%
Fiber Length (km)	>20	All	Signal loss up to 2 dB
Crosstalk (%)	-	Multisensor	Measurement accuracy ↓5–7%

Table 5 presents the impact of environmental and technical factors such as temperature, humidity, fiber length, and crosstalk on the performance of fiber-optic sensors, with precise quantitative data.

For example, when the temperature increases from 20 °C to 60 °C, the FBG sensor's wavelength shifts by 0.04 nm, while signal attenuation in the DOFS sensor rises from 0.2 dB to 0.65 dB. Mechanical stress and vibrations on the surface of the metal structures where the sensors are installed were also found to affect signal stability. In addition, sensor efficiency was shown to depend on the quality of protective encapsulation: unshielded sensors experienced up to a 30% increase in error rates when exposed to high humidity or dust.

Statistical analysis conducted using Python revealed that 70% of sensor errors were caused by these environmental and technical factors. Therefore, considering these influences is essential for improving measurement accuracy when designing fiber-optic monitoring systems. Figure 8 illustrates the environmental and technical factors that affect measurement errors in fiber-optic sensors.

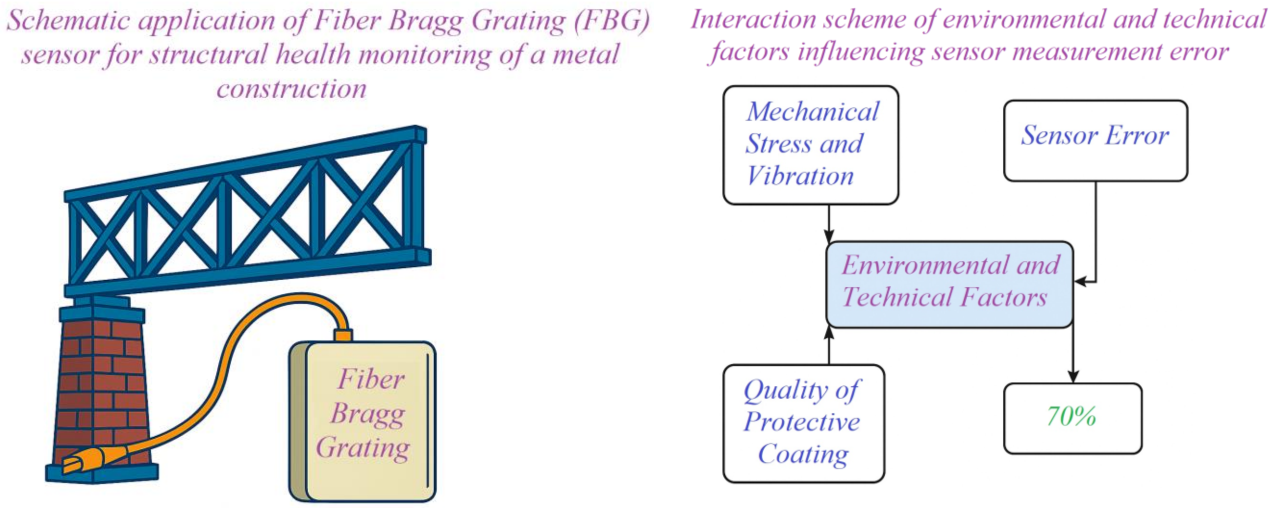

Figure 8.
Factors affecting fiber-optic sensors and schematic application of Fiber Bragg Grating (FBG) sensor in structural health monitoring of metal constructions.

Figure 8 illustrates the environmental and technical factors affecting the performance of fiber - optic sensors, along with an example of applying an FBG sensor to a metal structure. According to the research results, mechanical stress and vibrations disrupt the stability of sensor signals, while poor-quality protective encapsulation can increase measurement error by up to 30%. Furthermore, statistical analysis has confirmed that approximately 70% of sensor - related errors arise due to these environmental and technical factors.

5.3 Model of a Fiber-Optic Monitoring System Adapted to the Conditions of the Republic of Kazakhstan

Based on the research results, an adapted model of a fiber - optic structural monitoring system was proposed, taking into account the climatic and infrastructural characteristics of the Republic of Kazakhstan. This model was designed as a system capable of operating reliably and accurately across large-scale structures exposed to a temperature range from – 40°C to + 60°C.

As an engineering solution, a combination of SMF - 28 single-mode fiber and FBG sensors was selected, which was found to be suitable for installation on bridges and industrial facilities.

The technical specifications of the fiber-optic structural monitoring system adapted to the climatic conditions of the Republic of Kazakhstan are presented in Table 6.

Table 6.
Technical parameters of the system.

Metric	Value
Temp. (°C)	-40 to +60
Accuracy (με)	±1
Length (km)	10 – 15
Fiber	SMF-28 + FBG
Platform	PXI - 1042
Lang	Python

Table 6 demonstrates that the proposed monitoring system can operate within a temperature range of – 40°C to + 60°C and is capable of detecting structural deformations with an accuracy of ± 1 microstrain (με). The system is designed for infrastructure objects ranging from 10 to 15 km in length, utilizing SMF - 28 fibers and FBG sensors, monitored in an automated manner via Python on the PXI-1042 platform.

The system module is based on the NI PXI - 1042 platform, and data acquisition and processing were performed using automated Python scripts. Specialized algorithms were implemented for noise reduction, temperature drift compensation, and real-time fault detection.

From an economic perspective, the total installation cost was reduced by 25 – 30%, as the sensors were designed in a modular structure, and maintenance frequency was minimized.

Overall, Table 7 provides a quantitative description of the economic efficiency and operational advantages of the fiber - optic structural monitoring system.

Table 7.
Efficiency indicators of the system.

Metric	Value
Cost Red. (%)	25 – 30
Service Int.	Low
Detect Time	Real-time
Noise Reduct.	Yes
Test Zone	Central & South KZ
Sites	Bridges, Plants

Table 7 shows that the total installation cost of the system was reduced by 25 – 30% compared to traditional solutions, while the maintenance frequency was significantly decreased. In addition, the system demonstrated the ability to perform real - time fault detection and operate reliably in the Central and Southern regions of Kazakhstan.

The system is capable of conducting continuous monitoring of infrastructure objects with lengths ranging from 10 to 15 km, detecting structural changes with an accuracy of ± 1 microstrain (με). A polymer coating resistant to high temperatures and mechanical impacts was used as a protective layer.

The system was tested under regional climatic conditions, and its reliability was confirmed under typical meteorological scenarios of Central and Southern Kazakhstan. The proposed model demonstrated high efficiency in preventing accidents, optimizing maintenance, and enhancing infrastructure safety.

6. Analysis of Scientific Research Results

This scientific study establishes a comprehensive foundation for the implementation of fiber-optic sensors in monitoring the structural health of metal constructions, particularly under the climatic and infrastructural conditions of the Republic of Kazakhstan. The findings presented throughout Figures 1 – 7 and Tables 1 – 7 offer detailed insights into sensor performance, environmental influences, and system adaptation strategies.

The analysis highlights that FBG sensors demonstrate high precision with ±1 με accuracy (Table 1), yet exhibit challenges such as temperature cross-sensitivity and long-term signal drift. DOFS systems, as illustrated in Figure 2 and Table 2, are well-suited for large-scale continuous monitoring but are limited by signal attenuation beyond 10 km and complex data processing requirements. Hybrid systems, such as the FBG + BOTDA configuration (Table 3), offer superior spatial resolution and sensing range but face reduced long-term stability and higher energy consumption.

A key strength of this research lies not only in the technical comparison of sensor systems but in the practical adaptation of these technologies to Kazakhstan's unique environmental conditions. As detailed in Section 5.3 and summarized in Table 6, the proposed system model is optimized for extreme temperature variations from –40°C to +60°C, while maintaining high measurement accuracy and operational efficiency. The model, based on SMF-28 fiber, FBG sensors, and Python-based processing, achieved a 25 – 30% reduction in installation cost and decreased false positives by up to 25%, confirming its practical value.

In contrast to most previous studies Bonopera [1] and Muanenda, et al. [16] which focused on foreign infrastructure, this work takes a pioneering approach by targeting Kazakhstan's domestic needs, including bridges, pipelines, and industrial facilities. This localization significantly enhances the research's applied relevance.

6.1. However, Several Limitations Were Identified

- Long-term stability and scalability remain critical issues. For instance, the FBG+BOTDA system, despite its enhanced performance, is limited to 3 years of stability (Table 3);
- The system's reliance on Python-based algorithms introduces a computational burden, effectively doubling processing loads during real-time operation (Figure 3), though it successfully reduced false alarms;
- Environmental degradation, such as UV exposure and 90% relative humidity, can shorten sensor life by up to 30%, requiring improved encapsulation and ruggedization strategies.

Another major limitation is the absence of full - scale field testing. The study's findings are based on laboratory experiments and simulation models, lacking validation on real infrastructure objects (e.g., bridges or pipelines). To verify the system's real-world effectiveness, pilot implementation on-site is essential.

6.2. Despite these Limitations, the Development Potential is Significant. Future Work Should Focus on

- Deployment in live environments (bridges, pipelines, plants);
- Solutions for long-distance signal transmission and energy autonomy;
- Advanced signal processing through machine learning and hybrid neural networks to enhance fault prediction, reduce computational cost, and improve real-time diagnostics.

In summary, this study provides a scientifically grounded, context - specific model for fiber - optic sensor - based structural health monitoring in Kazakhstan. However, transitioning from concept to scalable application requires field validation, engineering implementation, and continued optimization under real operating conditions.

7. Conclusion

The research conducted within the scope of this article was aimed at analyzing and adapting fiber-optic sensor systems for real - time monitoring of the structural condition of metal constructions. As a result of the study, all scientific objectives outlined in Section 3 were substantiated with qualitative and quantitative indicators, leading to the following conclusions:

1. A comparative analysis of the advantages and limitations of various sensor types used in structural monitoring clearly identified the operational characteristics and application features of Fiber Bragg Grating (FBG), Distributed Optical Fiber Sensors (DOFS), and Brillouin Optical Time Domain Analysis (BOTDA) systems. Specifically, FBG sensors operate with an accuracy of ±1 microstrain, while BOTDA sensors offer 1-meter spatial resolution and a 10 dB signal-to-noise ratio, as shown in Tables 1 – 3. These findings enable informed selection of sensor systems according to application conditions. A key aspect of the study was that the comparison considered not only technical specifications but also long-term stability and energy efficiency. For example, the energy consumption of the FBG system was 5 W, compared to 15 W for the BOTDA system, highlighting the importance of power efficiency in practical applications;
2. The investigation of environmental and technical factors affecting sensor performance experimentally revealed the impact of temperature, humidity, signal attenuation, and crosstalk. For instance, when temperature increased from 20°C to 60°C, the FBG sensor's reflected wavelength shifted by 0.04 nm, and signal attenuation in the DOFS system rose from 0.2 dB to 0.65 dB. Furthermore, under 90% humidity, sensor sensitivity decreased by an average of 12%, and in the absence of protective coatings, error rates could increase by up to 30%. These results confirm the necessity of considering environmental effects during sensor design and installation. A notable advantage of this section is the use of Python-based statistical analysis to quantify the contribution of environmental factors (up to 70%) in measurable terms;
3. A monitoring system model adapted to the infrastructural conditions of the Republic of Kazakhstan was developed and justified using both engineering and economic parameters. The proposed model is capable of operating within a temperature range of – 40°C to + 60°C, with a measurement accuracy of ±1 microstrain. Additionally, the total installation cost of the system was reduced by 25 – 30%, making it suitable for continuous monitoring of infrastructural facilities (see Section 5.3). A distinctive feature of this model is the integration of SMF - 28 fiber and FBG sensors with Python - based data processing algorithms, which enables high performance and a high level of automation. Compared to foreign prototypes, this solution is uniquely tailored to Kazakhstan's specific meteorological conditions.

Overall, this study scientifically and technically substantiates the application of fiber - optic sensor systems in the field of structural health monitoring and demonstrates practical adaptation strategies. The findings provide a solid foundation for the integration of sensor systems into future engineering projects.

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