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Modelling and Application of Fibre Optic Sensors for Concrete Structures: A Literature Review

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Abstract This literature review examines the application of Fibre Optic Sensors (FOS) in the structural health monitoring of concrete buildings, an increasing issue in contemporary construction owing to the demand for safer and more resilient infrastructure. This review aims to evaluate the current state of FOS applications and estimate their efficacy. The study employed modelling and experiments with FOS to measure deformations in various concrete samples. FOS, which are thin fibres with an optical cable inside, was used in the study. The sensors were integrated into concrete structures to measure deformations. The research indicates that FOS, specifically Fibre Bragg Gratings, deliver higher reliability and accuracy in quantifying deformations in concrete, surpassing conventional approaches in precision and environmental durability. FOS are non-contact sensors that excel in extreme environments, including elevated humidity and temperature fluctuations, rendering them suitable for monitoring essential infrastructure such as bridges, tunnels, and buildings. The analysis highlights critical challenges, such as the necessity for advanced sensor integration techniques and better calibration procedures to guarantee consistent data accuracy. Moreover, it underscores the possibility of amalgamating FOS with additional monitoring systems to provide comprehensive, real-time structural health management solutions. Although FOS are now utilised in several concrete buildings, the study indicates that more research is necessary to enhance sensor technologies and investigate new applications, including the incorporation of artificial intelligence for data processing. This evaluation underscores the necessity of creating economical, scalable solutions for the extensive application of FOS in building projects.

Keywords Structural Condition Monitoring, Deformation, Spectrometer, Durability of Building Materials, Innovative Measurement Methods

1. Introduction

The modern construction sphere faces many challenges, one of which is ensuring the durability and safety of concrete structures. Concrete, being the main building material, is used in various structures such as bridges, buildings, dams and tunnels. The mechanical and physical properties of concrete, as well as its condition during operation, play a crucial role in the overall safety and reliability of these structures. In recent years, there has been a trend towards the use of advanced technologies to monitor the condition of building structures. Fibre Optic Sensors (FOS) enable continuous and accurate monitoring of various parameters of concrete structures. These sensors are capable of measuring deformation, temperature, humidity and other important indicators, which provide timely detection of potential defects and preventive maintenance. The study of the use of FOS for monitoring the condition of concrete structures is highly relevant, as it is aimed at improving safety and extending the service life of construction projects, which is of great importance for the sustainable development of infrastructure.

The main problem considered in this study is the need to develop effective methods and technologies for monitoring the condition of concrete structures. Despite significant progress in the field of construction and the use of new materials, the problem of premature wear and tear and the destruction of concrete structures remains a pressing issue. One of the key tasks is to develop and implement reliable methods for installing and operating FOS in concrete structures. It is also necessary to optimise the algorithms for processing the data received from these sensors to ensure accurate and timely detection of defects. It is necessary to analyse the impact of various factors, such as humidity, temperature and mechanical stress, on the accuracy and stability of measurements [1]. Another significant issue is the assessment of the cost-effectiveness of FOS compared to traditional monitoring methods. FOS has numerous limits even if it provides great precision and real-time monitoring features. FOS integration into concrete construction poses technical difficulties especially in guaranteeing the long-term stability of the sensors without sacrificing material qualities [2]. Measuring accuracy can also be affected by environmental elements like temperature variations, moisture, and mechanical forces. Moreover, the interpretation and processing of data need optimisation to improve dependability. Recent research concentrates on enhancing sensor durability, creating sophisticated data processing techniques, and combining FOS with other monitoring systems to help to solve these problems. Addressing these issues can greatly enhance the concrete construction monitoring systems, raise their dependability and safety, and lower their maintenance and repair costs.

Li et al. [3] believe that the introduction of FOS in construction faces several problems that require careful consideration and solution. Firstly, it is necessary to develop methods for integrating sensors into concrete structures to ensure their reliable operation without deterioration of material properties. This is a technical and engineering task that requires a special approach and research. In 2019, Halim et al. [4] conducted a review of FOS applications covering various structures, including buildings, mines, bridges, pipelines, tunnels, and dams. This review discusses the wide range of applications of FOS for monitoring the health and safety of various engineering structures. The researchers complemented and extended this review by providing in-depth research and new applications of FOS in construction.

Afzal et al. [5] believe that the integrated FOS system was used to monitor the deformation of structures during and after construction. The FOS system was used to monitor the deformations before, during and after the formwork removal stages. FOS was selected due to its advantages, such as invisibility, lightness and corrosion resistance. The deformation measurements were carried out over a period of 10 months on a 5-metre section of the suspended slab. This was used to track structural changes at various stages of construction and use in detail. Recent reviews of new developments, namely studies by Theodosiou et al. [6], Karayannis et al. [7], and Liu et al. [8] in the field of structural reinforcement in the construction industry provide important information for civil and mechanical engineers. In the wake of the recent earthquake in Almaty and accordance with legislation requiring the installation of monitoring systems at construction sites, the need to implement building condition monitoring systems has become urgent. According to the National Data Centre of Kazakhstan, seismic activity of up to 6.5 on the Richter scale was observed in the city in 2024 [9].

Given the seismic activity in the region, it is necessary to implement a health monitoring system in numerous buildings such as schools, hospitals and hotels. Moreover, it is necessary to develop sensors built into buildings that monitor various parameters, provide information for public warnings and even predict cracks, compressions, bends and deviations. This study integrates numerous advancements, such as vibration analysis, seismic monitoring, and multi-functional sensing, providing an examination of FOS capabilities, in contrast to earlier research that focused mostly on specific sensor applications. The innovation is in its methodical assessment of FOS performance under diverse environmental circumstances and its comparative examination of sensor technologies. This paper clarifies the economic factors and practical implementation difficulties of FOS, offering pragmatic insights for enhancing cost efficiency, sensor integration, and data processing techniques. Therefore, it facilitates the wider deployment of FOS in extensive infrastructure projects. This study aims to provide a comprehensive overview of the current state of knowledge on the application of FOS for structural health monitoring (SHM) of concrete structures. The review will explore the working principles, types, advantages, and applications of FOS, as well as their performance under various environmental factors. Additionally, the study will discuss future prospects and recommendations for further research in this area.

1.1. Literature Review

Fibre Optic Sensors (FOS) have emerged as a potential instrument in structural health monitoring (SHM) due to their sensitivity, durability, and capacity to work in severe settings. One of the key benefits of FOS is their capacity to give real-time, continuous monitoring of structural characteristics without direct contact with the concrete surface. This is especially beneficial for monitoring structures that are hard to reach or subjected to severe circumstances. Takahashi et al. [10] showed a bidirectionally applied polarizer-based FOS system for vibration position estimation, a system that is particularly suitable for monitoring dynamic deformations in high-rise buildings subjected to seismic activity. Similarly, Sun et al. [11] deployed a FOS-based jerk sensor to monitor seismic activity in high-rise structures, showing the promise of FOS in structural health monitoring in locations prone to earthquakes. These studies highlight how FOS systems may be used not only for typical deformation measurements but also for monitoring vibrations and dynamic motions, a vital issue for structures subjected to seismic pressures.

FOS are also applied for strain measurements in numerous forms of infrastructure, including pipelines, bridges, and tunnels. Qi et al. [12] focused on high-performance FOS for seismic monitoring in borehole applications, demonstrating how these sensors might be incorporated into borehole monitoring systems to detect ground movements and strain in real-time. The research of Bujugundla and Pradhan [13] expands the use of FOS to the biological arena, but its findings are important for the building industry as well. Their analysis underlines the versatility of FOS, illustrating how comparable sensor technologies have been implemented in multiple industries, giving insights into possible developments in structural health monitoring, particularly with respect to multi-analyte detection and sophisticated sensor designs. Furthermore, the amalgamation of FOS with additional technologies, including distributed acoustic sensing, has been investigated in studies such as that of Saharudin et al. [14]. Their work stresses the synergy of FOS and acoustic sensors, demonstrating how this combination can enable more complete monitoring systems that measure strain, temperature, and even identify early indicators of fractures and other problems in concrete buildings. The capacity of FOS to detect minute changes in strain and temperature with high precision is one of the primary characteristics of this technology. FOS-based monitoring systems can work in harsh environmental circumstances such as high humidity, temperature variations, and mechanical stress, which are generally challenging for traditional monitoring systems [15].

Elrawashdeh et al. [16] proposed an optimisation technique for current FOS displacement sensors, demonstrating how algorithmic innovations can enhance sensor performance. Their study underlines the relevance of algorithmic enhancements in boosting the accuracy and stability of FOS systems, particularly when subjected to unfavourable environmental variables. A significant benefit of FOS is its non-contact characteristic. Unlike typical strain gauges or accelerometers, FOS do not require direct physical contact with the concrete surface, which makes them excellent for monitoring structures that are difficult to reach, such as those situated in distant places or buried underwater. Moreover, their capacity to quantify strain at several sites along a single fibre enables a degree of spatial precision that is difficult to attain with conventional approaches.

As mentioned by Kadokura et al. [17], the adoption of a triaxial accelerometer based on fibre-optic technology allows for precise, multi-directional assessment of acceleration and displacement, offering a more comprehensive picture of the structural health. FOS furthermore has benefits regarding durability. Traditional sensors frequently require constant maintenance and calibration to preserve their accuracy, especially in areas prone to temperature fluctuations or mechanical vibrations. In contrast, FOS are often more resilient and have a longer lifespan, with many sensors being able to sustain their function over years without substantial deterioration. FOS systems create vast volumes of data that need to be evaluated in real-time to discover possible faults [18]. This requires sophisticated data storage and processing infrastructure, including the integration of machine learning or artificial intelligence to increase the accuracy and efficiency of the monitoring system.

Sun et al. [11] analysed the integration of FOS with seismic monitoring systems but also highlighted those additional developments are needed in data interpretation and decision-making algorithms to fully harness the potential of FOS for structural health management. A further constraint of FOS technology is the challenge of incorporating these sensors into current infrastructure. Although fibre optic sensors (FOS) are efficient when incorporated during the building phase, retrofitting them into existing concrete structures may be arduous and expensive. The research by Lyu et al. [19] suggests that the integration of FOS into existing buildings, particularly in the context of retrofitting for seismic monitoring, is feasible but requires careful planning and execution to ensure the sensors' effectiveness without compromising the structure's integrity. Despite the encouraging improvements in FOS technology, significant research gaps remain. Future research should focus on finding cost-effective solutions for the wider deployment of FOS in building projects.

As indicated by Qi et al. [12], the development of low-cost variations of FOS, as well as the standardisation of sensor installation procedures, might lessen the barriers to entry for smaller-scale building projects. Moreover, attempts to minimise the cost of data processing and storage, maybe by inventing more efficient algorithms, would make FOS a more economically viable alternative for continuous monitoring of infrastructure. Lastly, while FOS have proved their efficiency in monitoring deformation and temperature changes, additional study is needed to examine their potential in other areas, such as corrosion detection, moisture levels, and chemical changes in concrete. As emphasised by Bujugundla and Pradhan [13], FOS technologies in the biological area have already made steps in multi-analyte detection, indicating that comparable improvements may be adopted for use in construction to identify a larger spectrum of possible faults in concrete buildings.

2. Materials and Methods

Various materials and methods were used. The materials used were standard concrete cylinders with a diameter of 150 mm and a height of 300 mm. For different series of experiments, samples with different concrete compositions were used, including additives to increase strength and resistance to external influences. Multimode and single-mode FOS were used to measure deformations. These sensors were integrated into the concrete specimens during the manufacturing process. A high-sensitivity optical spectrometer was used to record and analyse the signals coming from the FOS. The spectrometer was used to record changes in wavelength caused by deformations in concrete samples. A computer with software for processing data was obtained from an optical spectrometer. Specialised software was used to interpret the results and plot the deformation. Standard concrete mix components were used: cement, sand, crushed stone, water and additives (plasticisers, superplasticisers and microfibre).

The methods included in vitro specimen preparation, sensor implementation, hydraulic press machine experiments, strain recording using FOS, data processing using specialised software and statistical analysis of the results. The concrete cylinders were prepared in the laboratory. FOS was integrated into each sample during the manufacturing process. The sensors were positioned along the central axis of the cylinders for the most accurate strain measurement. The samples were cured under standard conditions until the design strength was reached (28 days). A hydraulic pressing machine capable of applying axial loads of up to 2000 kN was used for the tests. The samples were subjected to uniaxial static and cyclic loads until failure or until the elastic limit was reached. The deformations occurring in the concrete samples when the load was applied were recorded by FOS, the signals from which were transmitted to an optical spectrometer. The spectrometer recorded changes in the wavelength of the reflected light, which was used to determine the amount of deformation. The signals from the optical spectrometer were analysed using specialised software. Deformation values were calculated based on changes in wavelength. The data were processed to obtain graphs of strain versus time and applied load. The sensors were calibrated to ensure their accuracy before the experiments began. The data obtained were compared with traditional methods of measuring deformations.

The experimental procedure included the preparation and installation of sensors in concrete samples, pouring the mixture and curing the samples, testing on the press machine, data collection and analysis, as well as summarising the results and conclusions on the methodology. The movement of concrete structures occurs throughout their entire service life, both during the pouring process and after complete curing. FOS can monitor structural deformations in real time, as well as accurately determine and measure their location and magnitude [20].

For the experiment, a concrete specimen with dimensions of 22×15×3 was prepared. The authors constructed a concrete beam including several layers of SM-3-2 m single-mode embedded optical fibres [21]. In addition, temporary or permanent protection for the optical fibres was not employed (Figure 1).

Figure 2 shows the typical output signals from six optical fibres placed through a concrete structure before and after applying lateral and total mechanical loads to a concrete span. These signals illustrate the condition of the beam before and after mechanical impact. The graph shows insignificant changes in the amplitude of the optical signal associated with the load Fv in the range from 0 to 500 kg, corresponding to the range of elastic deformations of the concrete span [22].

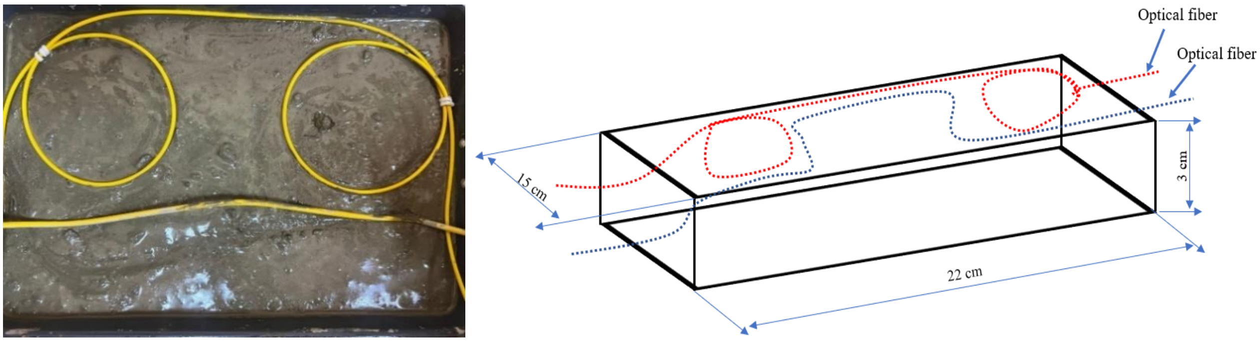


Figure 1. Optical fibre embedded in concrete

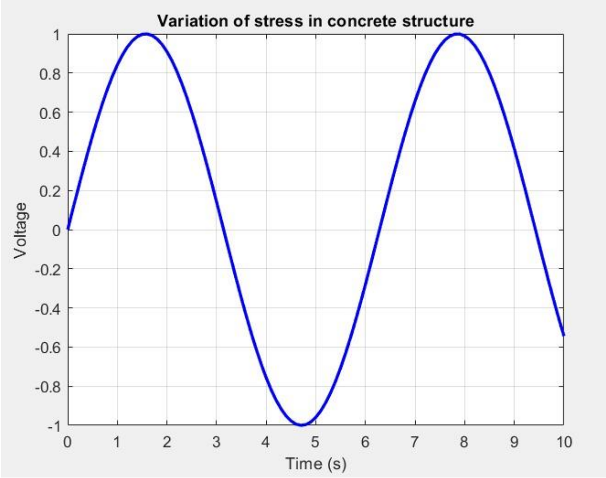


Figure 2. Stress variation over time in a concrete structure

The strain in FOS was calculated using the following expression (1):

$$\varepsilon[\mu\varepsilon] = \frac{10^6}{k} \times \frac{\Delta\lambda}{\lambda_0}, \tag{1}$$

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

The change in the phase of light $\Delta\phi$ due to temperature and voltage was modelled as a function of temperature and voltage as follows (2):

$$\Delta\phi = \phi_T \times \Delta T + \phi_S \times \Delta S, \tag{2}$$

where: ϕ_T and ϕ_S – coefficients determine the sensitivity of the sensor to temperature and voltage, respectively.

The concept of creating a method for monitoring defects in concrete roads involved the use of a single-mode fibre optic as a sensing element and a sensor integrated into the monitoring system (Figure 3). The optical fibre was subjected to mechanical stresses, which led to changes in mode properties, such as phase, frequency, and intensity of light passing through its core. All these changes were recorded in a single set of output data (Table 1). Signal processing and decision-making could be performed by photodetectors. Before starting the experiment, safety rules were observed. The basic physical principles of fibre-optic communication systems were studied, the internal structure of fibre-optic cables in fibre-optic and laser measuring systems was investigated, and deformed cables were analysed.

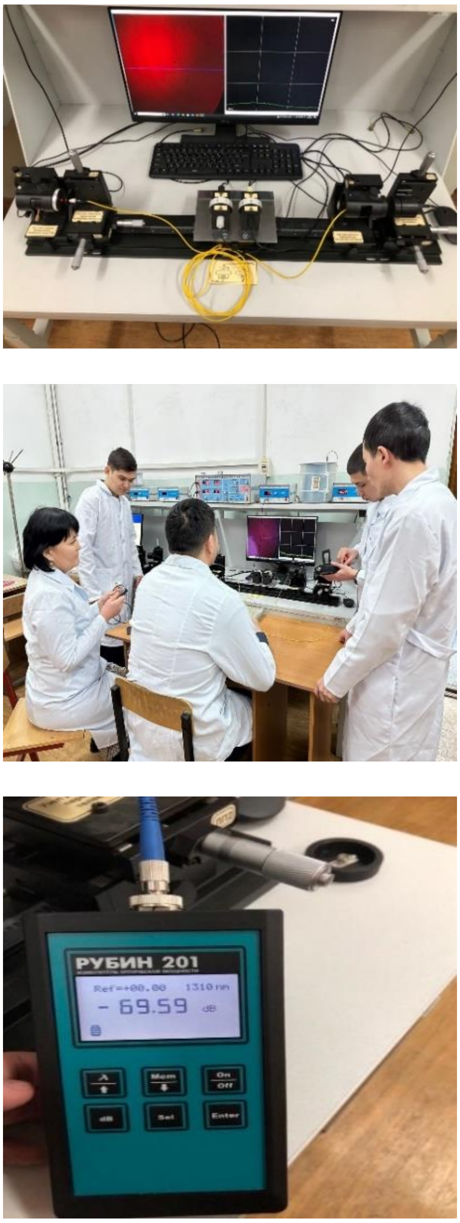


Figure 3. Study of the structure of a single-mode optical fibre

Table 1. Input and output values of a single-mode optical fibre

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

The structure of the concrete structure was also investigated using single-mode fibre. The results obtained for the concrete structure are shown in Figure 4. The input and output values of a single-mode fibre optic in a concrete structure are shown in Table 2.

Figure 4. Analysis of concrete structure using single-mode fibre optics

Table 2. Input and output values of single-mode fibre optics in a concrete structure

Input: 1310 nm	Output: 1310 nm
0.27 kHz – 6.50 dBm	63.04 dBm
100 kHz – 6.50 dBm	64.11 dBm
200 kHz – 6.50 dBm	65.74 dBm

The experimental results presented in Table 2 demonstrate the changes in the output signals of a single-mode optical fibre depending on the frequency of the input signal.

3. Results

With the increase in modern infrastructure and the rapid growth of construction volumes around the world, construction projects are facing increasingly challenging conditions. Ensuring safe construction work and reliable long-term use requires appropriate structures and facilities. Structural Health Monitoring (SHM) is an effective process for analysing the integrity of structures and predicting their behaviour during maintenance [23, 24]. A key aspect of a successful SHM approach is the correct selection and placement of sensors. The methodologies used cover a wide range, including electro-optical and electromechanical sensors, acoustic emission, fibre optics, remote sensing, imaging and vibration measurement. Concrete structures are widely used in construction due to their strength and affordability [25, 26]. However, concrete is subject to deformation and damage, which can reduce its integrity and strength. Various methods are used to assess deformation and damage in concrete structures, including traditional methods such as sensor-based strain measurement and modern methods such as fibre optic techniques [27].

Strain measurement methods are based on the use of FOS, which are thin fibres with an integrated optical cable. The deformation of the fibre changes the length of the optical cable, which leads to a change in the optical frequency of the light passing through the fibre [22]. This change can be measured with an optical spectrometer to determine the strain. FOS offer several advantages over newer strain measurement methods. First, FOS are non-contact sensors, which eliminates the need for physical contact with the concrete surface, making them convenient for measuring strain in hard-to-reach areas. Secondly, FOS are high-precision sensors capable of measuring stress with high sensitivity. Thirdly, FOS are robust sensors that ensure long-term operation. Modern methods of monitoring building structures are undergoing significant changes with the introduction of new technologies [28]. One of the most promising approaches is the use of FOS, which has high accuracy and durability. This section discusses the theoretical aspects of FOS application in the construction industry, including the basic principles of operation, advantages and prospects.

FOS are based on changes in the optical properties of the fibre due to external factors such as strain or temperature. The main types of FOS are interferometric sensors, Fibre Bragg Gratings (FBG) and scattering sensors [29]. Interferometric sensors measure changes in the phase of a light wave passing through an optical fibre [30]. The most common types of interferometers used in FOS include Michelson and Fabry-Perot interferometers [1]. These devices capture the smallest changes in the wavelength of light, which provides highly accurate measurements. FBG represents periodic changes in the refractive index in an optical fibre. When subjected to strain or temperature changes, the wavelength of light reflected from the grating changes, allowing these changes to be measured with high accuracy. FBGs are among the most widely used FOS due to their high accuracy and stability. Raman and Brullen scattering sensors are based on measuring changes in the intensity of scattered light. These methods are based on inelastic scattering of light that is altered by temperature or mechanical stress. Scattering sensors allow monitoring over long distances and can be used in environments where other types of sensors are difficult to use.

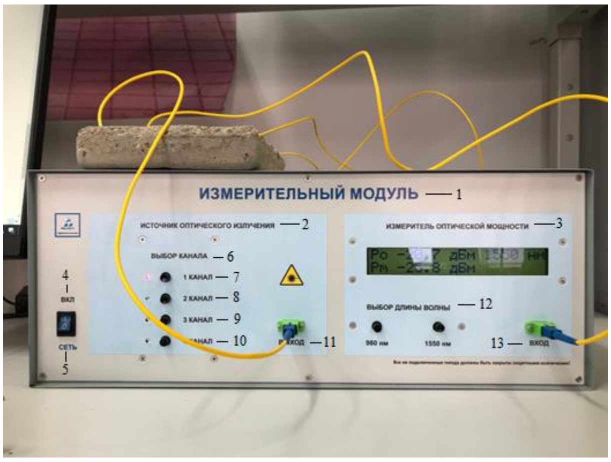
The use of FOS in the construction industry has several key advantages [31]. Firstly, FOS detects the smallest changes in deformation and temperature, which allows for the timely detection of potential problems in structures. This is relevant for monitoring critical facilities such as bridges, dams and high-rise buildings. Secondly, FOSs maintain their performance in harsh environments such as high humidity, temperature and mechanical stress [32]. This renders them ideal for use in building structures exposed to aggressive external factors [33]. Thirdly, FOS are non-contact sensors, which eliminates the need for physical contact with the measured surface. This is relevant for monitoring hard-to-reach areas of structures or for making measurements in conditions where the use of traditional sensors is difficult [34]. Finally, FOSs can be integrated into building structures during the construction phase, enabling continuous monitoring of the condition of the facilities throughout their entire service life, which contributes to the safety and durability of the structures.

FOS has been successfully used to monitor various types of structures, including bridges, tunnels, dams and buildings [35]. For instance, FOS was used to monitor deformations and vibrations in bridges, enabling timely detection of damage and prevention of emergencies. In one study, FOS was used to monitor the condition of a bridge over the Huangpu River in Shanghai, which helped identify critical points of deformation and prevent possible structural collapse [8]. FOS is also used to monitor deformations and temperature changes in tunnels to monitor their condition and prevent accidents. In a study in Switzerland, FOS was used to monitor the condition of the Gotthard Base Tunnel, which allowed for the timely detection and removal of potentially dangerous structural changes [20, 36]. Similarly, FOS has been used to monitor deformation and temperature changes in dams [37]. In a study conducted in the USA, FOS was used to monitor the condition of the Hoover Dam, which allowed for the timely identification and removal of potentially hazardous changes in the structure [6]. FOS has also been used to monitor deformation and temperature changes in buildings. In a study conducted in Japan, FOS was used to monitor the condition of a high-rise building in Tokyo, which provided timely identification and elimination of potentially dangerous changes in the structure [3].

The introduction of FOS in the construction industry presents new opportunities for enhancing the safety and durability of structures [38, 39]. The prospects for FOS application include the development of new methods and technologies, such as integration with structural management and forecasting systems. This can significantly improve the monitoring and management of construction projects. For instance, the use of artificial intelligence and machine learning to analyse data from FOS can improve the accuracy and efficiency of monitoring. FOS can be integrated with other monitoring systems, such as vibration monitoring systems and acoustic emission sensors, to provide a more complete picture of the condition of structures and improve their safety. FOS can also be applied in new areas, such as monitoring the condition of subsea structures and pipelines, which opens up new opportunities for their use in various industries [40]. The development of standards and regulations for the use of FOS in the construction industry can help promote their wider adoption and improve the safety of construction projects. For instance, the creation of international standards for the use of FOS in monitoring bridges and buildings could facilitate their wider use in different countries.

Employment of FOS in the construction industry is a promising area that combines high measurement accuracy with resistance to external influences [41]. The introduction of FOS in the monitoring of building structures can significantly improve their safety and durability, which is especially important for modern construction projects [42, 43]. Further research in this area is needed to develop new methods and technologies that will improve the monitoring and management of building structures. FOSs work based on the interaction of a light signal with the fibre through which it passes. Interferometric sensors measure changes in the phase of a light wave caused by external influences such as deformation or temperature changes. Such sensors can use Michelson or Fabry-Perot interferometers to detect changes. FBGs are periodic changes in the refractive index of an optical fibre that reflect light at a specific wavelength [1]. As the voltage or temperature in the fibre changes, the wavelength of the reflected light changes, allowing these changes to be measured with high accuracy. Raman and Brillouin scattering sensors measure changes in the intensity of scattered light. These methods are based on the inelastic scattering of light, which changes under the influence of temperature or mechanical stress.

The occurrence of cracks in concrete structures has a direct impact on their strength and service life. SHM is becoming an increasingly important part of concrete structure maintenance, complementing traditional visual inspections [21]. Effective monitoring of the condition of concrete structures is essential for early detection of problems and appropriate remedial action [44]. In recent years, several SHM methods have been developed for concrete structures, including the use of FOS, piezoelectric materials and radioactive materials such as X-rays and gamma rays [45]. These methods provide more accurate and sensitive data, allowing for earlier diagnosis of real-world conditions and appropriate measures to maintain integrity and safety [46]. The use of FOS allows for continuous monitoring of changes in the concrete structure, which is especially important for preventing complex damage and ensuring the durability of concrete structures (Figure 5).



Note: 1 – measuring module; 2 – the source of optical radiation; 3 – optical power meter; 4 – on; 5 – network; 6 – channel selection; 7 – channel 1; 8 – channel 2; 9 – channel 3; 10 – channel 4; 11 – output; 12 – wavelength selection; 13 – input.

Figure 5. Determining the strength of embedded optical fibre in a concrete structure

In the construction industry, concrete is highly prone to be affected not only by deformations but also by moisture and temperature [47]. To observe these factors, the following experiment was conducted (Figure 6). The results reflect measurements and interpretation of the change in the wavelength of reflected light as a change in temperature. A physical model describing the interaction of light with the optical fibre was used to describe the process more accurately, taking into account the change in the periodic structure of the optical fibre as the temperature changes. Methods for analysing the spectral characteristics of the reflected light, including the measurement of the Bragg peak shift or the change in the amplitude of the scattered light, made it possible to determine the temperature with high accuracy. Thus, the condition of concrete structures was studied based on the Bragg effect.

The temperature of the concrete-based optical sensor was determined through various parameters and factors, including changes in power, laser temperature, laser power and Peltier element temperature. How each of these factors affects the temperature of the sensor was investigated: increasing the gain power of the sensor was considered a significant parameter, as it determined the amount of energy transferred through the sensor, measured at 102 mW. An increase in power increased the number of photons, indicating an increased impact on the optical sensor. Similarly, the energy delivered to the optical sensor by the laser current increased the temperature by 39.2 ℃. The increase in laser current directly contributed to the increase in light generation output, with a significant increase to 129.3 mA, thus increasing the load on the sensor. Peltier elements were used to efficiently cool or heat the optical sensors. Controlling the temperature of the Peltier element helped maintain optimal temperature conditions for the optical sensor, reducing thermal disturbances to 103.2 mA. Taken together, these parameters were interrelated and required careful consideration to optimise the temperature stability and measurement accuracy of the optical sensors in concrete structures.

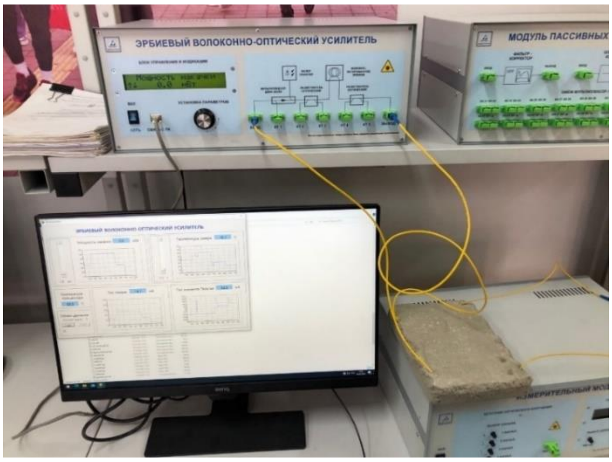


Figure 6. Temperature determination of optical sensors based on concrete

Temperature and stress effects on FOS performance were modelled using linear relationships for the coefficient of thermal expansion and Young's modulus for stress (Figure 7). Temperature changes were assumed to cause a linear change in the length of the fibre, which in turn affected the phase of the light passing through it [48, 49, 50]. The coefficient of thermal expansion of the optical fibre was denoted as α [1/°C]. The stress value determined that the optical fibre changed its dimensions (stretched or compressed), resulting in a change in the phase of the light. The Young's modulus of the fibre material determined how much it deformed when a force was applied and was denoted as E [Pa]. The optical fibre was assumed to have an initial temperature of T0 and was not subjected to any stress S0. It was then subjected to changes in temperature ΔT and stress ΔS [51, 52, 53]. The change in the phase of light passing through the fibre was considered proportional to these changes in the measurements [54]. By linearly increasing the temperature from 20 ℃ to 40 ℃ and the voltage from 0 to 1000 Pa, a graph showing the change in the phase of light as a function of these two parameters is created. The values of $\phi T=0.05$ [phase/℃] and $\phi S=0.01$ [phase/Pa] are set [55].

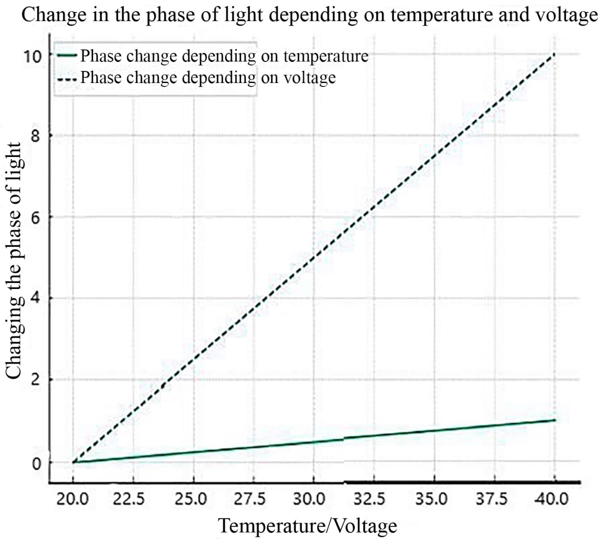


Figure 7. Graph of light phase change in FOS

The graph shows the phase change of light in FOS over an extended temperature range from 20℃ to 40℃. The light phase change with temperature now represents a wider range of changes, while the phase change with stress remains unchanged for comparison [56]. This demonstrates how the sensor adapts to a wider range of monitoring conditions in concrete structures.

FOS have substantial benefits for monitoring concrete infrastructure, including high precision and durability in adverse conditions [57]. However, their deployment entails expensive implications. The initial expense of implementing FOS, including the sensors and their requisite integration into physical structures, may be elevated in comparison to conventional monitoring techniques. Moreover, specialised equipment for data collection and processing contributes to the budgetary strain. Nonetheless, these initial expenditures can be mitigated by long-term advantages, including decreased maintenance and repair costs, early identification of structural problems, and an increased lifespan of infrastructure. Ultimately, the financial benefits derived by circumventing significant repairs and probable failures may render FOS a more economically feasible choice, particularly in essential or large-scale projects.

4. Discussion

This study provides a comprehensive and critical review and comparison of various microcrack detection methods using FOS. Particular attention is devoted to the identification of areas for further development of detection methods. The study also evaluated the compatibility and reliability of the latest FOS in detecting damage in concrete. This study offers a comprehensive overview of the current state of the art and future development of FOS technologies in the field of damage detection in building structures. A method for measuring relative humidity in high-performance concrete mixtures using femtosecond laser technology was discussed, involving the use of Bragg grating in a low-mode CYTOP polymer optical fibre (with three main modes). The sensor was characterised for temperature, strain and relative humidity, showing improved response coefficients compared to similar sensors. This technique opens new possibilities for accurate moisture monitoring in high-strength concrete mixtures, which is an important aspect of their durability and structural stability.

Monsberger and Lienhart [58] also employed Distributed Optical Fibre Sensors (DOFS) but based on Rayleigh backscatter optical frequency domain reflectometry to monitor structural deformations. The experiments use polyamide optical fibres bonded directly to the surface of the reinforcement and protected by a layer of silicone. This allows accurate strain measurement and monitoring of crack formation and development. The study above showed the high accuracy of FOS in measuring strains in concrete structures, confirmed by comparison with conventional methods. The experiments demonstrated that FOS can effectively capture strain changes within concrete, allowing for timely identification of potential problems and preventing structural failure. The strain measurements obtained with DOFS were equivalent in accuracy to conventional electric foil sensors. Errors in crack location and crack width were minimal, emphasising the high accuracy of DOFS. Both studies confirm the high accuracy and reliability of FOS for monitoring the condition of concrete structures. The study above focuses on laboratory testing and emphasises the importance of calibration and data processing to obtain accurate results.

Berrocal et al. [59] described the use of fibre optic technology for monitoring building structures. Their study aimed to analyse existing methods and sensors used for SHM, with a focus on FOS and their application in concrete structures. The study above uses FBG and other FOS to measure strains in concrete structures. The sensors are integrated into concrete specimens and changes in the optical frequency of light passing through the fibre are used to determine the strains [60, 61]. The results of this study showed the high accuracy of FOS in measuring deformations in concrete structures. The experiments demonstrated that FOS can effectively capture the strain changes occurring within concrete, which enables the timely detection of potential problems and prevents structural failure. FOS also showed high stability and reliability even when exposed to unfavourable environmental factors such as moisture, temperature and mechanical loads. The researchers also emphasised the high accuracy of FOS used for monitoring concrete structures. The authors describe cases of successful application of FOS for measuring deformations and detecting defects in various structures, including bridges, buildings and tunnels. The results show that FOS can provide high measurement accuracy and data reliability in real-world applications.

The study conducted above and the review study on DOFS by Sakiyama and Garrecht [62] were devoted to the study of the use of FOS for monitoring the condition of building structures. The main objective of the above study was to apply FOS to measure deformations in concrete specimens and to evaluate the accuracy and reliability of these measurements in the laboratory. The review study focuses on analysing current research and methodologies for applying DOFS to monitor various engineering structures, including bridges, buildings, roads, geotechnical structures, tunnels, pipelines and wind turbines. In this study, FBGs are used to measure deformations in concrete cylinders subjected to static and cyclic loads. The sensors are integrated into the concrete structures and measure changes in the optical frequency of light passing through the fibre, allowing for accurate deformation detection [63]. The DOFS Review describes various methods and technologies for applying DOFS to monitor deformation, temperature and vibration in building structures. The focus is on the minimal invasiveness, high accuracy and ease of deployment of DOFS, as well as the ability to measure with very fine spatial resolution (down to 0.63 mm). The experiments demonstrated that FOS can effectively detect changes in deformation within concrete, which ensures timely detection of potential problems and the prevention of structural failure. In the study on the mechanism of strain transfer between the host material and optical fibre, a new analytical model is considered that addresses the imperfect adhesion between the layers. The study aimed to establish a general formula for the strain transfer from a cracked concrete material to an optical fibre in a multilayer system. This study includes wedge splitting tests on concrete specimens equipped with embedded and surface-mounted fibre optic cables.

The results of the study from the file showed the high accuracy of FOS in measuring deformations in concrete structures. The experiments demonstrated that FOS can effectively record strain changes occurring within the concrete, which allows for the timely detection of potential problems and prevention of structural failure. FOS has also shown high stability and reliability even when exposed to adverse environmental factors such as moisture, temperature and mechanical loads. A study on the strain transfer mechanism demonstrated that the proposed strain transfer model correctly describes the process of strain transfer from cracked concrete to optical fibre [64]. Experimental results showed that the model can accurately predict the amount of crack opening near the location of the optical cable and track the response of the optical cable through the strain lag parameter. The study from the film focuses on laboratory tests and emphasises the importance of calibration and data processing for accurate results. The study on strain transfer mechanism demonstrates the successful validation of the new strain transfer model and its applicability for crack monitoring under realistic service conditions. Both studies emphasise the need for further development and integration of FOS with other monitoring systems, such as piezoelectric sensors, acoustic emission systems, and remote sensing technologies, to improve the safety and durability of construction projects. Complementing FOS in real-time deformation analysis, piezoelectric sensors can identify mechanical stress and strain changes in concrete buildings. By recording high-frequency stress waves produced by microstructural changes, acoustic emission devices offer an understanding of material fatigue and fracture propagation. Remote sensing technologies, such as LiDAR and satellite monitoring, offer extensive structural evaluations and longitudinal performance monitoring. Integrating these systems enables a more thorough and dependable method for structural health monitoring, hence improving predictive maintenance techniques and mitigating the risk of structural breakdown.

5. Conclusions

Based on the literature review, several key conclusions can be drawn regarding the use of FOS for monitoring the condition of concrete structures. Laboratory experiments have shown the high accuracy and reliability of FOS in measuring deformations in concrete structures. In particular, the use of FBG and other FOS ensure accurate recording of deformation changes occurring within concrete. This opens new opportunities for the timely detection of potential problems and prevention of structural damage. Experiments have confirmed that FOS can operate stably and reliably even when exposed to adverse environmental factors such as moisture, temperature and mechanical stress.

The results of the study emphasise the importance of calibration and accurate processing of the data obtained with FOS. Accurate strain measurement requires correct sensor setup and calibration, as well as the use of advanced data processing techniques. This is especially important under severe operating loads, where measurement accuracy is critical to ensure the safety and durability of structures.

An important conclusion is the confirmation of the possibility of using FOS in real-world applications. Laboratory experiments conducted as part of this study demonstrate that FOS can be successfully integrated into concrete structures to monitor their condition. This is especially relevant for objects where traditional measurement methods are difficult or impossible, such as bridges, tunnels, high-rise buildings and other engineering structures. FOS can be used in hard-to-reach areas, providing continuous monitoring of the condition of structures and timely detection of potential problems.

Future research should prioritise the integration of FOS with structural management and forecasting systems to improve predictive capacity and optimise infrastructure maintenance. A possible avenue is the creation of hybrid monitoring frameworks that integrate FOS with machine learning algorithms and digital twin technologies. Machine learning algorithms can analyse extensive information from the FOS in real time, discerning patterns in structural behaviour and forecasting possible faults prior to their occurrence. Digital twins, which are computerised copies of real things, can use continuous data from FOS to model different stress situations, check how well structures work in different situations, and make maintenance plans better. Furthermore, the integration of FOS with wireless sensor networks and cloud-based data platforms can enhance remote monitoring and centralised data analysis, increasing accessibility for engineers and decision-makers. Implementing standardised protocols for FOS integration with Building Information Modelling systems will promote interoperability and data-driven decision-making in construction management.

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