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SHM-3

CHALLENGES AND POTENTIAL OF FIBER OPTIC SENSORS FOR STRUCTURAL HEALTH MONITORING OF BRIDGES: A REVIEW

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ABSTRACT

Structural health monitoring (SHM) has gained significant attention in the field of civil engineering due to effective maintenance of structures, particularly bridges. However, traditional SHM methods have limitations in providing accurate and continuous data, which has led researchers to explore new technologies, one of which is fiber optic sensor (FOS) monitoring. This paper provides a comprehensive review of the use of FOS in bridge SHM, highlighting the challenges and potential of this technology.

FOS are convenient for SHM due to their high accuracy, immunity to electromagnetic interference, and capability of working in harsh environments. They are particularly suitable for quasi-distributive and distributive measurement systems on capital civil engineering structures. FOS can be utilized to measure various parameters, including deformation, temperature, and strain. In bridge constructions, FOS can be installed in multiple locations.

Deformation measurements using FOS can provide accurate information on the displacement and deflection of the bridge, which can help in detecting abnormalities or damages. Temperature measurements using FOS can detect effects of thermal load on bridges, which can cause significant damage. Strain measurements using FOS can help describe the stress distribution in the bridge, which can be used for maintenance purposes.

FOS-based SHM systems can provide real-time and continuous data, which can help in detecting any potential problems at an early stage and preventing catastrophic failures. The use of FOS in SHM of bridges has been extensively researched and demonstrated in various studies. However, challenges such as installation, calibration, and interpretation of the data require further research.

The paper will discuss the potential of FOS-based SHM systems in improving the safety and reliability of bridge constructions. It will also highlight the challenges related to FOS installation, calibration, and data interpretation and provide insights into future research directions for developing more robust and cost-effective FOS-based SHM systems.

Keywords: Fiber optic sensors; Structural health monitoring; Bridges; Strain; Displacement

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1. INTRODUCTION

Over the past decades, fiber optic sensors (FOS) have been used both experimentally and practically for measurements on various types of structures (bridges, dams, tunnels, towers and other large scale structures). They have been most commonly used to monitor the behavior and physical state of structures over time [1], [5], [17], [18], [20], [22].

FOS have been used for detecting different types of effects as mechanical strain, temperature effects, occurrence of corrosion, rotation, displacement, acceleration etc.

Their advantage over classical electrical sensors is that they allow long-term monitoring of large scale structures via an external database that doesn't need to be located at the structure. Some of the most relevant types of FOS for SHM of bridges will be described.

The most important advantages that all types of FOS have in contrast to typical electrical sensors are: lightweight (typical optical fiber is about 13 times lighter than a copper wire), small dimensions (outer diameter of an optical fiber is approximately 250 µm), immunity to electromagnetic interference, low attenuation compared to electrical sensors, immunity to aggressive environments (can be embedded in materials for long-term measurements), greater bandwidth (multiplexing possible for multimode fiber).

The main advantage of FOS is the ability to perform quasi-distributive and distributive measurements, allowing the entire fiber to serve as a sensor for long range, high resolution measurements.

2. USE OF FOS IN STRUCTURAL HEALTH MONITORING (SHM) OF BRIDGES

2.1. FOS for measuring strain

FOS for measuring strain on bridges are commonly used for two purposes:

- for monitoring the effective force in prestressing cables used in suspension and cable-stayed bridges, as well as prestressing tendons in prestressed concrete [1]-[14];[10]
- for monitoring stresses along the girders at different locations in the cross-section of steel and concrete bridges [22], [23].

The failure of cables can have catastrophic consequences on the structure, therefore the effective force should be monitored with the available instruments.

Currently, there are three types of FOS sensors that have been used to measure cable forces, which are the Fiber Bragg grating (FBG) sensors, distributive FOS (DFOS) and interferometric sensors (most commonly the Fabry-Pérot interferometer (EFPI) and SOFO sensors), [1], [2], [14].

Fiber Bragg Grating sensors for measuring strain in cables (FBG sensors)

Bragg gratings in FBG sensors experience wavelength changes in reflected light signal under both temperature cahnge and mechanical strain. These sensors are typically used in pairs for the sole purpose of isolating mechanical strain and temperature change. However, when FBG sensors are used solely for temperature measurement, they must be isolated from mechanical strain to provide quality data, [10].

The optical fiber’s structure for measuring strain of cables is modified in multiple ways for the purpose of protecting the fiber from harsh environments and for mounting it on the cables in different ways. Common modifications are shown in **Fig. 1** where it can be seen that the basic structure of the optical fiber remains intact, and that additional protective layers are added to it. These layers influence the sensitivity of the sensor, the transmitted effective strain and its design work life.

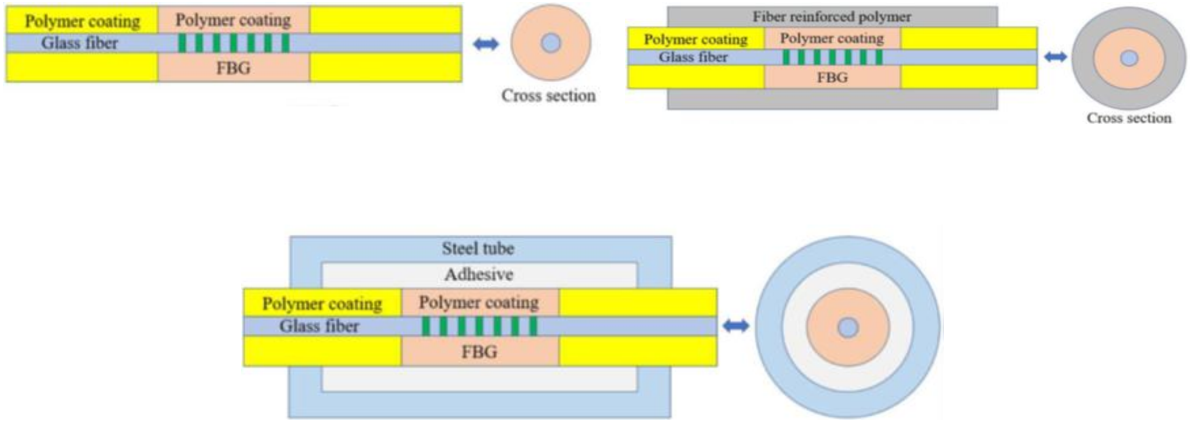

Fig. 1. Different type of FBG structure modifications: (a) protection with a polymer coating only, (b) protection with a localized layer of FRP, (c) protection using a steel tube, [10]

Mounting of FBG sensors for measuring strain in cables

According to the type of modification used in the FBG sensors structure, three types of mounting methods have been generally used in practice. In the first method FBG sensors are attached to the surface of the cables using only adhesives **Fig. 2(a)**, [1], [2]. In the second method the FBG sensors are placed inside the bundle of the cable wires **Fig. 2(b)**, [3]-[6], and in the third method the sensors are clamped to the cables **Fig. 2(c),** [7]-[9].

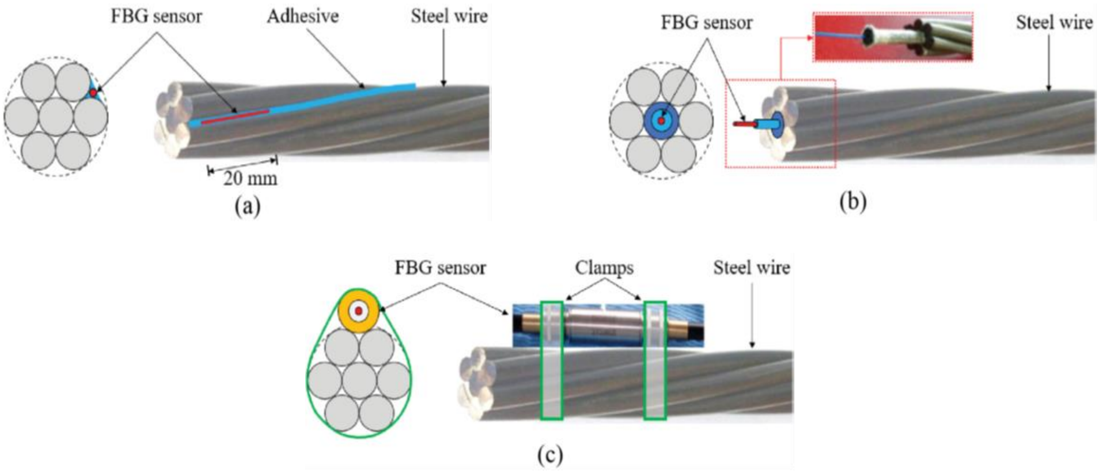

Fig. 2. Mounting of FBG sensors on tendons and cables: (a) attached to the surface by adhesives, (b) bundled by the wires of the tendon, (c) clamped to the cable [10]

Clamping of the sensors to the cable is only suitable when the cable is not located in the duct (stayed cables and suspenders) because the sensors can slide or un-bond due to friction with the tendon’s duct.

Assessing the force in the cables

Some external effects on the FOS that may result in erroneous measurements need to be monitored, such as: wavelength shift of the FBG due to coupled temperature and mechanical strain, reduction of strains in the FBG sensor due to the shear lag effect of the polymer coating **Fig. 3**, [10].

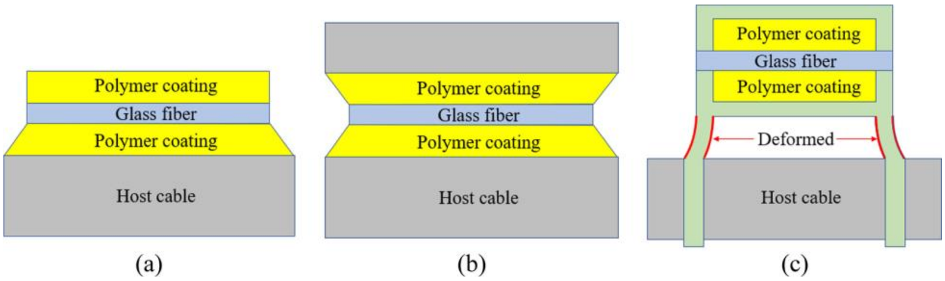

Fig. 3. Shear lag in FBG sensors: (a) attached to the surface, (b) bundled by the wires (c) clamped to the cable ,[10]

Temperature effects can be isolated by using another FBG sensor that is not exposed to mechanical stress, or even by using different types of sensors to monitor temperature, such as thermocouples. With these phenomena in mind, the stress in the cable can be determined from the relationship between the observed wavelength change in the Bragg grating and its mechanical strain. These FBG sensors can be used to assess the effective amount of prestress in prestressing tendons [11], [12], as well as for experimental confirmation of prestress losses predicted by calculations.

Distributed FOS sensors for measuring strain in cables

Two types of measuring technologies have been mostly used, both based on Brillouin scattering, the Brillouin Optical Time Domain Analysis (BOTDA) and Brillouin Optical Time Domain Reflectometry (BOTDR). The main difference between these two methods is that BOTDA uses a light wave to stimulate acoustic waves in the optical fiber (with the goal to scale the intensity of the Brillouin scattering), and BOTDR does not use light stimulating but relies solely on spontaneous waves. [2]-[10]

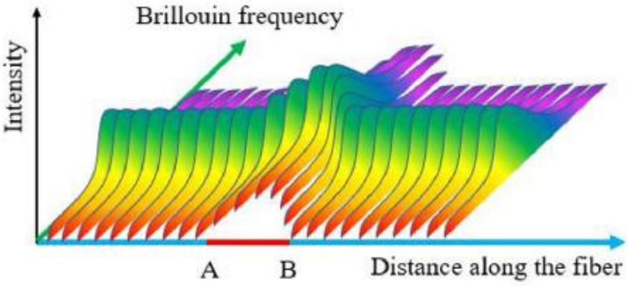

Fig. 4. Brillouin frequency (wave length) shift caused by external effects, [10]

Assessing the force in the cables

Since DFOS sensors have the simplest possible structure, it can be foreseen that all of the mounting methods shown in **Fig. 2** can be applied to deploy DFOS on the cables. The first two methods are the most used, as shown in **Fig. 5**, since the third method includes a large number of clamps.

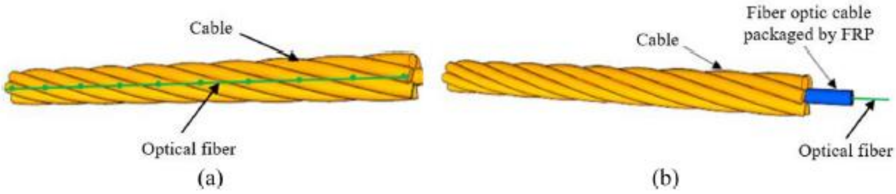

Fig. 5. Application of DFOS on cables: (a) Fiber attached to the surface of the cable and (b) fiber bundled by the wires of the cable, [10]

Unless attachment of the fiber to the cable surface can be done automatically, it is much more convenient to bundle the optical fiber together with the prestressing strands as shown in **Fig. 5 (b)**.

Since the DFOS sensors are sensitive to both temperature and strain changes, temperature compensation is required in real practices. For this cause two methods are generally used: (1) using another sensor that is isolated from mechanical strains, (2) using two different distributed sensing technologies for analyzing light scattering – for example coupling Optical Frequency Domain Reflectometry (OFDR) and BOTDA or BOTDR.

As with FBG sensors, strain transfer effect need to be had in mind with DFOS also. DFOS are often subjected to highly nonuniform strain fields which is mainly a consequence of the long measurement length. These sensors have been used for measuring cable forces for prestressed concrete tendons and bridge cables, [13]. When considering measurement of the bridge cable forces, DFOS were bundled with steel strands of the cable for the measurement of strain distribution along the cable, [14].

FBG and DFOS sensors for measuring strain in the cross section

The strain distribution in the cross-section needs to be measured at multiple locations for a detailed cross-section response, but along the dominant moment direction when the number of sensors is limited.

These sensors were used for SHM of a pedestrian bridge constructed at Princeton University in 2009-2010, [22]. The sensors installed were long-gauge FBG sensors and optical fibers for BOTDA sensing. In [23], FBG sensors were used for measuring strain distribution in welded joints of steel bridges at the connection of longitudinal and transversal stiffeners, **Fig. 6**.

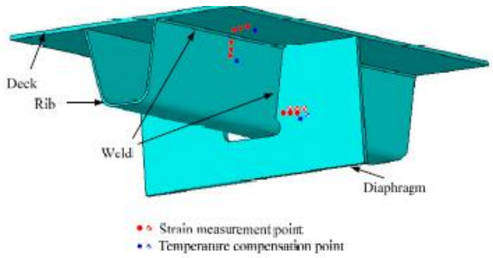

Fig. 6. Measurement points of FBG sensors for measuring strains near welds, [23]

Sensor layout

Proper sensor layout is required to obtain quality data that can be used to confirm theoretical behavior. In [22], fiber optic sensors were coupled with discrete sensors to compare the results of different technologies, **Fig. 7**. The sensors shown in **Fig. 7** were placed at the most heavily loaded sections, above the pier sections, and in the center of the spans. All sensors were attached to the rebar with ties prior to concreting.

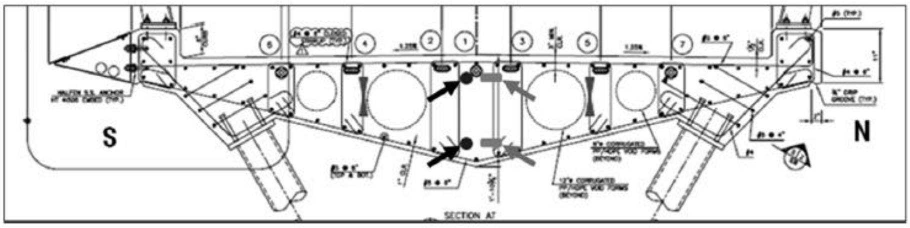

Fig. 7. Position of sensors in the cross-section of pedestrian bridge – Black arrows point to discrete sensors and grey arrows to distributed sensors, [22]

Conclusions of monitoring

Monitoring the strains in the section of the Princeton University Bridge allowed for high quality SHM of the structure, as well as for conclusions about the effective stiffness caused by cracking due to temperature and other loads. It was found that cracking occurred in the deck above the piers as a result of thermal effects during concrete curing, which reduced the effective stiffness of the section, **Fig. 8a**.

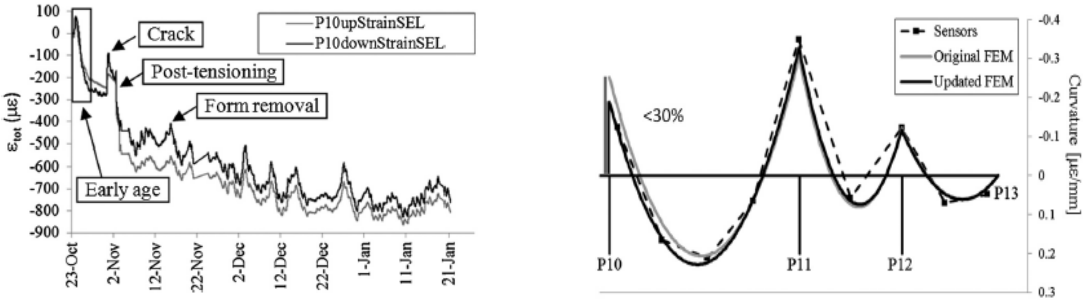

Fig. 8. (Left) Strain evolution showing early age, cracking, post tensioning and formwork removal; (Right) Bridge curvature diagram due to applied dead load, comparing measurements and FEM results, [22]

Curvature measurements at the sensor locations were used to fit a parabolic line and compared to the FEM curvature diagram. Measurements showed that the stiffness of the joint above the pier was approximately 30% less stiff than obtained by the original FEM model.

Monitoring the strains in steel plates near the welded joints described in [23] showed high resolution of data. After data analysis and separation of mechanical and temperature strains, live loads and stress caused by them could be monitored in real time, **Fig. 9**.

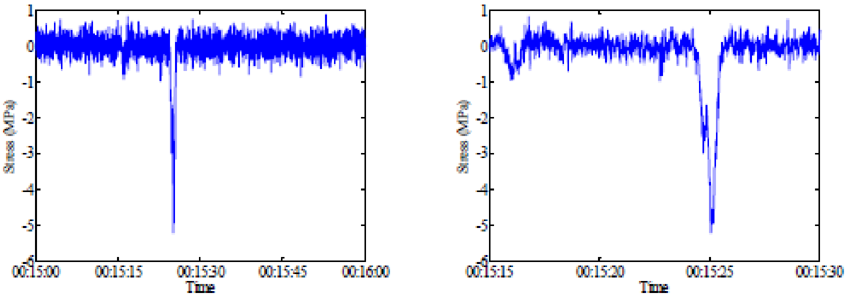

Fig. 9. Live-load induced stress time history in 1 h (left) , in 1 minute (right) [23]

2.2. FOS for measuring temperature

Measuring temperature distributions is as important for bridges as it is for any other structure. Because of the need for continuous temperature measurements on large objects, there has been intensive research of the use of distributed temperature sensors (DTS) based on Raman scattering. Other types of FOS researched for measuring temperature are quasi-distributed FBG sensors, and the Fabry-Pérot interferometric sensor. [15],[16],[19]

Distributed FOS for measuring temperature (DTS)

DTS sensors are mainly based on the principles of Raman light scattering. In contrast to Brillouin scattering, Raman scattering practically isn't dependent on mechanical strain. Temperature can be measured with Raman scattering by determining the ratio of the temperature dependent Anti Stokes component and temperature independent Stokes component of Raman scattering spectra.

A distributed FOS has also been used to measure temperature based on Brillouin scattering, but in these cases it is necessary to isolate the fiber from mechanical stress.

Fabrication of DFOS sensors

These sensors have been used in numerous experiments to measure the temperature of the structure during normal use or during accidental fires. Since DFOS are used, no special treatment of the fiber structure is required, although they are usually additionally protected with a buffer and a polymer sheath to increase the longevity of the fiber and to protect it from mechanical damage, abrasion, environmental exposure and stress as depicted in **Fig. 10**.

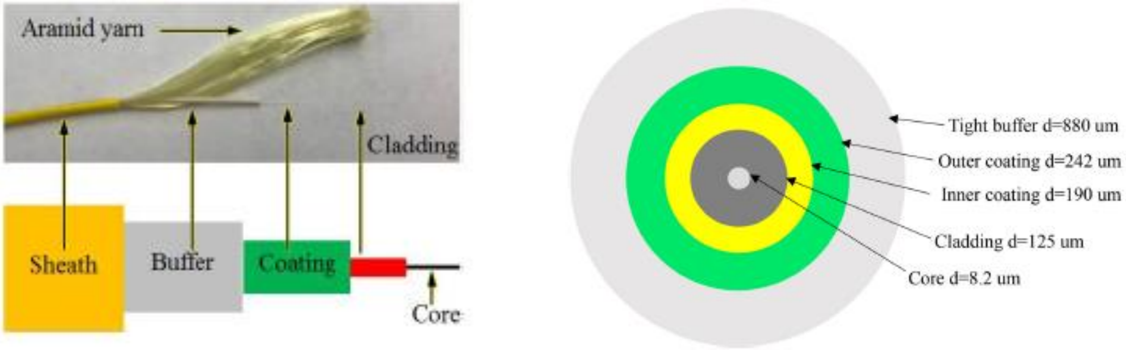

Fig. 10. DTS structure, (a) fiber appearance ,(b) cross section of the fiber with protective layers, [16]

Dimensions of the fiber layers gave a total outer diameter of 880 µm which is roughly 3.5 wider than the DFOS used for measuring strain (about 250 µm).

Measurement of temperature with DFOS

Temperature measuring DFOS shown in **Fig. 10** was used in papers [15] and [16] where steel-concrete composite slabs and beams were exposed to high temperatures from a simulated fire as shown in **Fig. 11**.

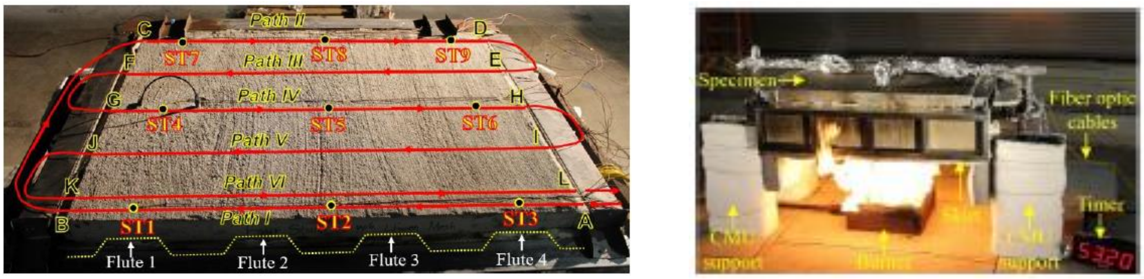

Fig. 11. (a) Layout of DTS in the concrete plate, (b) Fibers under temperature load [15]

In [15], the temperature measurement was based on the Brillouin frequency shift along the fiber with a bandwidth of 10.82 GHz to 11.67 GHz corresponding to a temperature range of 20°C to 1100°C. The DTS measurements were compared with discrete thermocouple (TC) measurements, and the comparison showed that the separate measurements were almost identical.

Quasi-distributed FOS for measuring temperature based on Bragg gratings

Fabrication of FBG sensors

Conventional FBG sensors, consisting of a core (with written Bragg gratings), cladding, and outer coating, can withstand temperatures of 300°C to 400°C before annealing. This temperature range is perfectly adequate for the design temperatures of most structures, but it cannot withstand the temperatures of fires. In [18], Bruno et al. tested three types of FBG sensors embedded in concrete and exposed to fire. While a regular FBG sensor annealed at 420°C, a regenerated type of FBG measured temperatures above 1000°C with high accuracy.

Measurement of temperature with FBG

These sensors have been used on many occasions. In [17], FBG sensors were used to measure temperature in a scaled tunnel and the measurements were compared with thermocouple results and predicted values. In [19], FBG sensors were used for road surface monitoring. It was concluded that temperature played an important role in measured deformation of asphalt layers. In bridges, when measuring strain in cables or within the cross section, these sensors are often used for temperature compensation of strain monitoring sensors or for direct temperature measurement, [10].

The most common resolution of FBG sensors for temperature measurement is 0.1°C with 1% accuracy, although higher resolution types are available for specialized measurements. In this regard, it appears that FBGs are more practical for shorter measurements than DTS because they have better resolution for shorter measurements.

2.3. FOS for detection of corrosion in reinforced concrete

Bridges, as structures, are always exposed to aggressive environments. They are exposed to snow, rain, chemicals from vehicles, high concentrations of salt poured on the asphalt, and other various types of chemicals. Different types of fiber optic sensors have been researched for corrosion detection and they can be classified as discrete corrosion sensing (FBG, LPFG, EFPI) and distributed corrosion sensing (BOTDR, BOTDA, OFDR), [20], [21].

FBG sensors for detecting corrosion

These sensors have an advantage that measurement can be performed using only one end of the optical fiber, because the reflected signal is used for demodulation. FBG sensors for detecting corrosion are classified in three groups according to process that is monitored: FBG sensing chemical reaction of corrosion, FBG monitoring expansion of steel bar and FBG sensing the expansion of concrete.

Chemical reaction detecting FBG

FBG sensors that detect chemical reactions have been intensely researched in the past two decades. They either directly sense the chemical reactions around the fiber or monitor the changes in the chemically altered cladding of the fiber. In the last modification of these sensors cladding is removed from a part of the fiber and replaced with a layer of polymer and hydrogel that is reactive to -pH values, **Fig. 12**, [20]. This protects the fiber and increases its sensitivity. The measurand in this type of sensor is the strain of the fiber due to the expansion of the corroded reinforcement. This causes strain in the fiber in the grating, resulting in a wavelength shift of the reflected light.

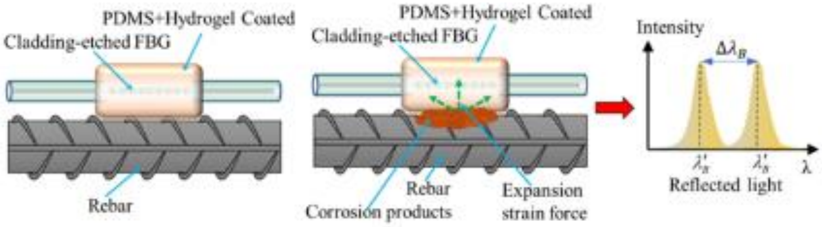

Fig. 12. Sensing principle of FBG corrosion sensor based on a chemical reaction – FBG coated with a layer of PDMS and Hydrogel, [20]

Steel rebar corrosion detecting FBG

These sensors work on the principle that the formed corrosion products have 2-6 times the volume of the original non corroded steel. Many types of modifications of this type of sensor have been used and have been explained in detail in [20]. The measurand of rebar corrosion detection FBG is the strain in the fiber caused by the expanding rebar located near the sensor or attached to the sensor as shown in **Fig. 13**.

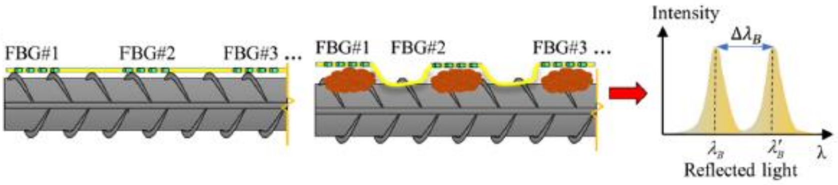

Fig. 13. Sensing principle of FBG corrosion sensor based on sensing steel rebar corrosion – FBG optical fiber periodically attached to the rebar, [20]

The sensitivity of this type of FBG sensor is highly dependent on the method and type of installation, as well as the chemical properties of the steel and surrounding concrete.

Distributed FOS for detecting corrosion

Two widely used distributed fiber optical sensing technologies are BOTDR and BOTDA, which are based on Brillouin backscattering. The advantage of BOTDR is that measurements can be made using only one end of the fiber, while BOTDA requires light waves to be injected into the fiber from both ends. While BOTDR is easier to use, the intensity of the backscattered light is much lower than that of BOTDA.

BOTDR/BOTDA fiber optic corrosion sensors

Since Brillouin wavelength shift depends on the strain and temperature change in the fiber, measurand of the fiber in both technologies is the corrosion-induced strain due expanding of the corroded steel or concrete covering it. This sensor was deployed by Sun et al., [21], to monitor corrosion initiation and concrete surface cracking in an concrete column using BOTDR demodulation technology (**Fig. 14**).

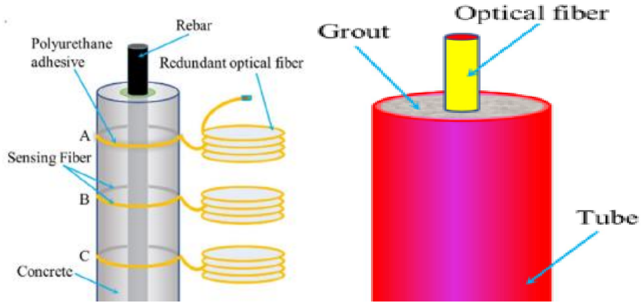

Fig. 14. Brillouin backscattering sensors: (Left) OF wrapped around cylindrical column, (Right) OF encased grout [21]

These sensors detect corrosion indirectly by measuring volume expansion. Their spatial resolution depends on the way they are installed, parallel or wrapped around a steel bar. It is usually about 0.5-1m. Their sensitivity depends on the chemical properties of the steel and the surrounding concrete, as well as the thickness of the coating.

3. EXISTING CHALLENGES WITH FOS AND OPPORTUNITIES IN THE FUTURE

Based on the above review, some challenges can be identified from the existing studies on fiber optic sensors as follows:

- The number of sensors that can be multiplexed in a row is limited by the number of channels of the interrogator (the device that collects data from the FBG FOS ~~fiber~~). The use of FBG sensors requires advanced data processing and analysis, and therefore requires highly skilled engineers.
- Durability of FOS under realistic environmental conditions is unknown. Degradation of sensors and their mounting packages needs to be considered in harsh environments. Methods for maintenance and repair of fibers need to be researched.
- More research needs to be conducted with the goal to investigate which type of FOS and what type of analysis is the best for specific applications of FOS.
- Even though FOS are much easier to use than traditional sensors, their high cost is one of the main obstacles for use in practice, as well as for research topics.

REFERENCES

[1] E. Li, J. Xi, J. Chicharo, T. Liu, X. Li, J. Jiang, L. Li, Y. Wang, Y. Zhang, The experimental evaluation of FBG sensor for strain measurement of prestressed steel strand, Proc. SPIE 5649 (2005) 463–469

[2] M. Perry, Z. Yan, Z. Sun, L. Zhang, P. Niewczas, M. Johnston, High stress monitoring of prestressing tendons in nuclear concrete vessels using fibre-optic sensors, Nucl. Eng. Des. 268 (2014) 35–40

[3] S.T. Kim, Y. Park, S.Y. Park, K. Cho, J.R. Cho, A sensor-type PC strand with an embedded FBG sensor for monitoring prestress forces, Sensors 15 (1) (2015) 1060–1070

[4] J.M. Kim, H.W. Kim, S.Y. Choi, S.Y. Park, Measurement of prestressing force in pretensioned UHPC deck using a fiber optic FBG sensor embedded in a 7-wire strand, J. Sens. 2016 (2016)

[5] T.C. Huynh, J.T. Kim, FOS-based prestress force monitoring and temperature effect estimation in unbonded tendons of PSC girders, J. Aerosp. Eng. 30 (2) (2017) B4016005

[6] J.M. Kim, C.M. Kim, S.Y. Choi, B.Y. Lee, Enhanced strain measurement range of an FBG sensor embedded in seven-wire steel strands, Sensors 17 (7) (2017) 1654

[7] H. Abdel-Jaber, B. Glisic, A method for the on-site determination of prestressing forces using long-gauge fiber optic strain sensors, Smart Mater. Struct. 23 (7) (2014) 075004

[8] S. Shen, Y. Wang, S.L. Ma, D. Huang, Z.H. Wu, X. Guo, Evaluation of prestress loss distribution during pre-tensioning and post-tensioning using long-gauge fiber Bragg grating sensors, Sensors 18 (12) (2018) 4106,

[9] H. Abdel-Jaber, B. Glisic, Monitoring of long-term prestress losses in prestressed concrete structures using fiber optic sensors, Struct. Health Monit. 18 (1) (2019) 254–269

[10] Y.Yao, M. Yan, Y. Bao, Measurement of cable forces for automated monitoring of engineering structures using fiber optic sensors: A review, Automation in Construction 126, 2021

[11] L.J. Butler, J. Xu, P. He, N. Gibbons, S. Dirar, C.R. Middleton, M.Z. Elshafie, Robust fibre optic sensor arrays for monitoring early-age performance of mass-produced concrete sleepers, Struct. Health Monit. 17 (3) (2018) 635–653

[12] O. Khandel, M. Soliman, R.W. Floyd, C.D. Murray, Performance assessment of prestressed concrete bridge girders using fiber optic sensors and artificial neural networks, Struct. Infrastruct. Eng. (2020) 1–15

[13] X. Tan, A. Abu-Obeidah, Y. Bao, H. Nassif, W. Nasreddine, Measurement and visualization of strains and cracks in CFRP post-tensioned fiber reinforced concrete beams using distributed fiber optic sensors, Autom. Constr. 124 (2021) 103604

[14] J. He, Z. Zhou, J. Ou, Optic fiber sensor-based smart bridge cable with functionality of self-sensing, Mech. Syst. Signal Process. 35 (1–2) (2013) 84–94,

[15] Y. Bao, M.S. Hoehler, C.M. Smith, M. Bundy, G. Chen, Measuring three-dimensional temperature distributions in steel–concrete composite slabs subjected to fire using distributed fiber optic sensors, Sensors 20 (19) (2020) 5518

[16] Y. Zhu, M. Klegseth, Y. Bao, M.S. Hoehler, L. Chloe, Genda Chen, Distributed fiber optic measurements of strain an temperature in long-span composite floor beams with simple shear connections subject to compartment fires, Fire Safety journal 121 (2021) 103275

[17] Lönnermark, A.; Hedekvist, P.O.; Ingason, H. Gas temperature measurements using fibre Bragg grating during fire experiments in a tunnel. Fire Saf. J. 2008, 43, 119–126

[18] Bueno, A.; Torres, B.; Barrera, D.; Calderón, P.; Lloris, J.M.; López, M.J.; Sales, S. Fiber Bragg grating sensors embedded in concrete samples for a normalized fire test. In Proceedings of the 21st International Conference on Optical Fiber Sensors, Ottawa, ON, Canada, 15–19 May 2011; Volume 7753, p. 77538.

[19] Kashaganova, G.;Kozbakova, A.; Kartbayev, T.;Balbayev, G.; Togzhanova, K.;Alimseitova, Z.; Orazaliyeva, S. Research of a Fiber Sensor Based on Fiber Bragg Grating for Road Surface Monitoring. Electronics 2023, 12, 2491.

[20] F. Tang, G. Zhou, H. N. Li, E. Verstrynge, *A review on fiber optic sensors for rebar corrosion monitoring in RC structures*, Construction and Building Materials 313, 2021.

[21] Y. Sun, B. Shi, S.-E. Chen, H. Zhu, D. Zhang, Y.i. Lu, Feasibility study on corrosion monitoring of a concrete column with central rebar using BOTDR, Smart. Struct. Syst. 13 (1) (2014) 41–53.

[22] B. Glišic, D.Hubbell, D. Sigurdardottir , Y. Yao, Damage detection and characterization using long-gauge and distributed fiber optic sensors, Optical Engineering 52(8), 2013.

[23] X. W.Ye, Y. H. Su, P.S. Xi, Statistical Analysis of Stress Signals from Bridge Monitoring by FBG System. Sensors 18, 2018.