Fiber Optic Sensors to Perform Structural Health Monitoring of Concrete Structures Affected by Internal Swelling Reactions

K. K. Santos Silva, F. A. N. Silva, T. Mahfoud, A. Khelidj, A. C. Azevedo, and J. M. P. Q. Delgado

Abstract Structural Health Monitoring (SHM) on concrete structures is an important issue in controlling its performance during its service life. Data obtained using this technology can provide valuable information for decision making about the needs for corrective interventions that can ensure the integrity and safety of concrete structures. When concrete structures exhibit internal expansions due to the several types of swelling reactions a strong surface mapping cracking process appears that can significantly affect its durability and performance. The paper presents the state-of-art of the use of fiber optics sensor to monitoring concrete structures with focus in the researches related with its use. Background of the theory regarding fiber optics sensors and advantages and limitations are also discussed.

Keywords Fiber optic sensors · Internal swelling reactions · Concrete structures

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K. K. S. Silva · F. A. N. Silva
Civil Engineering Department, Universidade Católica de Pernambuco, Recife, Brazil
e-mail: klayne.dos-santos-silva@2020.icam.fr

T. Mahfoud · A. Khelidj
GeM Laboratory, University of Nantes, Saint Nazaire, Nantes, France
e-mail: mahfoud.tahlaiti@icam.fr

A. Khelidj
e-mail: abdelhafid.khelidj@univ-nantes.fr

A. C. Azevedo · J. M. P. Q. Delgado (✉)
Departamento de Engenharia Civil, CONSTRUCT-LFC, Universidade Do Porto, Rua Dr. Roberto Frias, s/n, 4200-465 Porto, Portugal
e-mail: jdelgado@fe.up.pt

A. C. Azevedo
e-mail: antonio.costaazevedo@fe.up.pt

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1 Introduction

Concrete is one of the main structural materials, widely used worldwide and it is used in diverse types of works and construction projects. Good durability and performance to carry mechanical loads are some issues that justify its spread use. As a heterogeneous material, made with elements from different origins, concrete structures may present pathologies manifestations throughout their useful life due to applied loads and also due to its interaction with the environment. Over time, an important scientific understanding of the nature of this material has been developed, including the perception that certain problems may cause changes in its micro and macro structure with possibility of generating an early deterioration and even the failure of the material (Tseng 2002; Surahayo 2019a, b). The occurrence of such problems may result from inappropriate selection aggregates types and cement to make concrete mixtures or it can arise from some hydration products. Regarding the development of its compressive strength along the time, some concretes may show pathologies due to environmental action, unforeseen stresses and external loads or due to changes in its micro structure that can lead to a cracking process that reduce its durability and performance (Sims 2017).

Structural health monitoring (SHM) with a focus on concrete structures emerged with the need to increase the safety of structures and provide guidelines for efficient and cost-effective maintenance plans. Currently for the SHM approach, several point sensors are used, however, due to the complexity of the concrete structures, it often ends up being necessary to use a large number of sensors. Fiber optic (FO) technology is being increasingly implemented for monitoring concrete structures, as it can provide integrated detection of a high degree of sensitivity, durability and stability (Bukenya et al. 2014; Sakiyama et al. 2019).

Internal swelling reactions (ISR) describe chemical phenomena that have physical implications for concrete structures. These expansion mechanisms can be broadly classified as alkaline aggregate reaction (RAA) and delayed ettringite formation (DEF), which lead to the expansion of the affected concrete elements that generate a cracking process on concrete surface that propagate through or around aggregate particles and/or cement paste (Noel et al. 2017).

Currently, there are several test methods used to describe the behavior of structures affected by internal swelling reactions (ISR). On the other hand, they do not take into account that in real situations the concrete element is subjected to mechanical loads or what effects that loading produce in the expansion levels. Retrofitting or rehabilitation works on the concrete structural element, affected by expansion reactions, in spite being very expensive, are sometimes performed without even knowing whether the expansion has stopped or not (Selier et al. 2017). To evaluate the behavior of concrete structures under normal loading conditions and during their use, it is essential to use safe monitoring strategies that allow obtaining material quality indicators to make decisions on possible intervention processes before the damage process increases. A deeper understanding of concrete expansion levels and the loads applied to material is needed, as well as finding cost-effective means of monitoring concrete structures. Over time, new technologies have been investigated being one of the most promising fiber optics sensors (Noel et al. 2017; Selier et al. 2017).

2 Internal Swelling Reactions

Currently, a large number of concrete structures around the world are affected by internal swelling reactions. Several reactions can cause internal expansions on concrete and the most common ones are: the alkali-aggregate reaction (AAR) and the internal reaction of sulfate (hereinafter used to designate the delayed ettringite formation—DEF). One of the main steps to develop means of rehabilitation or retrofitting works of concrete structures is to have a comprehensive assessment of structural implications of ISRs (Noel et al. 2017; Custodio and Ribeiro 2019).

2.1 Alkali-Aggregate Reaction

The reaction between the aggregate and the alkalis has been called the “alkaline-aggregate reaction”. AAR’s first records were reported in the state of California in the 1930s by Thomas Stanton of the California State Highways Division. The identification of the problem was reported by the same researcher in 1940 (Stanton 1940). Stanton identified the expansion of the mortar bars and observed that this expansion was influenced by the alkaline content of the cement, the type and amount of reactive silica present in the aggregate, the presence of moisture and also the temperature levels (Sims and Poole 2017; Thomas et al. 2013).

The most common AAR in concrete is the alkali-silica reaction. It is a chemical reaction that occurs between amorphous silica present in reactive ions and hydroxyl in porous solution aggregates. ASR is a complex reaction three conditions must be met for it to occur: the presence of reactive aggregate, a high level of alkalis, cement component and enough moisture, around 80% in the concrete pores. Without one of these conditions, ASR will not occur. Initially the gel formed does not cause damage to the concrete because it fills existing pores, however over time this gel can increase in volume significantly and can generate internal stresses in the concrete structure, sufficient to break the affected aggregate and, consequently, the surrounding cement paste (Pan et al. 2012; Comi et al. 2012).

For the occurrence of AAR, water is a primary factor, as water works not only as a means of transport, but actively participates in the expansion process, considering that the silica gel absorbs water and expands (Martin et al. 2012).

2.2 *Delayed Ettringite Formation*

Although AAR and DEF have similar effects and they can appear in the structure in a combined way, these types of expansive reactions have completely different origins. The first reported cases of DEF occurred in some precast concrete elements subjected to heat treatment inadequate to the concrete composition and the environment. The main reported cases of DEF worldwide include railway sleepers and components with large volumes of solid concrete. Most of the reported cases also include bridges. The parts damaged by DEF were mainly solid structural elements (pillars, beams or pillars, etc.) in contact with water or subject to high humidity. The sulphate activity that occurs when concrete undergoes a thermal process in the early ages is known in several countries and has been the subject of several studies worldwide (Noel et al. 2017; Godart and Divet 2013; Godart 2017).

The formation of etringite occurs naturally in the cement hydration process, when the tricalcium aluminate (C3A) reacts with gypsum and forms the primary ettringite. When all the gypsum is consumed, the etringite can react even more with the remaining C3A and form monosulfate in the first days. Entringite can re-form later, after months or years, as long as there is a new source of sulfate is present in the solution of the cement paste pores. This way we have the so-called “delayed ettingite formation”—DEF—, which is usually associated with a damage sulphate attack on concrete (Yu et al. 2016).

The chemical reactions that lead to DEF occur among several ionic species available in the pore solutions of concrete when the preliminary etringite was inhibited by high temperature (above 70 °C). This temperature may be due to steam curing processes or the cement hydration process itself, which is an exothermic reaction (Karthik et al. 2016; Bouzabeta et al. 2012).

2.3 *Effects of ISR’s on the Mechanical Properties of the Concrete*

What justify the widespread use of concrete are its good properties of strength and deformation, namely: tensile strength, compressive strength and Young’s module. These properties change when there are internal swelling reactions in the material. On a macroscopic scale, the damage caused by AAR and DEF is considered to be similar, as they usually manifest disorderly cracks that resemble a map, although restrictions due to loads or structural reinforcements can modify the observed crack pattern. Regarding the mechanical behavior, the tensile strength and the elastic modulus of the concrete can be severely reduced with the development of the expansion, while the compressive strength is generally little affected (Comi et al. 2012; Bouzabata et al. 2012).

The ISRs generate a decrease in Young’s modulus in the first moments of the expansion. After it is observed an increase in modulus because both the hygroscopic gel formed by AAR and the etringite crystals formed by DEF fill the cracks formed, stiffening, this way, its structure. Regarding the compressive strength, AAR and DEF exhibit different effects. AAR occurs more slowly and the gel can promote the healing effect that can be efficient to stabilize or increase the compression strength of the concrete. DEF expansions occur more quickly and the healing process must not be able to fill in the cracks, leading to a decrease in compressive strength (Martin et al. 2012; Brunetaud et al. 2018).

3 Fiber Optic Sensors (FOS) for Health Monitoring of Concrete Structures

The occurrence of cracks in the concrete directly affects its useful life and durability. Structural health monitoring (SHM) becomes more and more necessary for concrete structures because it is, in fact, a way to complement the visual inspection that is often performed in concrete structures, but it is most of the time subjective and it is a good possibility to overcome such limitations. Monitoring concrete structures is extremely important to early identify problems and adopt the most appropriate recovery measure. In recent years, several SHM techniques have been developed for concrete structures using fiber optic sensors, piezoelectric materials and radioactive materials (X-rays and G-rays) (Hu et al. 2013; Sakiyama et al. 2019).

The use of fiber optic sensors is shown to be increasingly promising because they are characterized by their high sensitivity, durability, stability and small size when compared to traditional sensors. In addition, they can withstand high temperatures and other aggressive environments, which make them ideal for SHM of large concrete structures (Bao and Chen 2012).

3.1 Basic Concepts on Fiber Optic Sensors

Fiber optics sensors are basically an optical waveguide, which consists of the joining of filaments, which can be made of glass or polymers, and are used as a means of propagating light. It consists basically of a fiber optic interrogator that emits light down the FO cable and a photodetector that measures the light that comes back (Hisham 2018; Barrias et al. 2016).

Optical fibers are composed of three layers: the core, the cladding, and the coating (Fig. 1). The core has a high refractive index and is coated with polymeric layers whose refractive index is lower, so that total internal reflection occurs and losses do not occur during the process. The cladding, in addition to protecting against losses, also works to protect the core from contaminants and incorporates mechanical resistance to the material. The coating is used to prevent the occurrence of physical

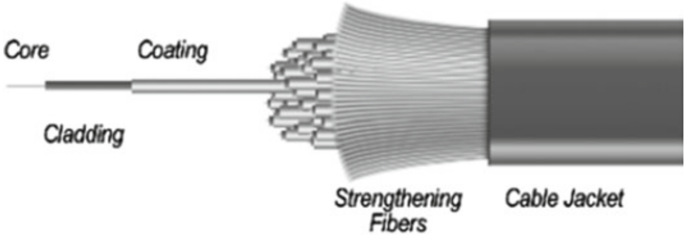

Fig. 1 Representation of the parts of fiber optics (Hisham 2018)

damage, considering that it is a fragile material (Hisham 2018; Giles and Spencer 2015).

The intensity of the light that passes or is reflected by the fiber optic is generally known and controlled by the emitter. A sudden decrease in the intensity of the light can indicate the appearance of a failure in the real structure, it can even indicate the break of the fiber due to the real damage of the structure (Giles and Spencer 2015).

3.2 Types of Fiber Optic Sensors

Optical fibers have properties that allow for different approaches with regard to the design of optical sensors. Currently, there are several types of fiber optic sensors that can be classified into basically three different categories: localized sensors distributed and multiplexed. These categories are based on the detection methods for each sensor (Kesavan et al. 2010).

Lau (2003) describes these categories one by one as follows:

(a) Localized sensors or point sensor: Localized sensors, as the name suggests, determine the use of a specific segment of an optical fiber, and are similar to voltage or temperature meters applied. The specific detection of the intensity modulation refers to the losses of light intensity that are directly related to the flexion or the micro curvature of optical fibers along any length extension. In this type of sensor, the active luminescent material at the distal end of the fiber responds to a temperature change applied to the optical fiber;

(b) Distributed sensors: The sensors can be designed to be able to make measurements in a spatial way, that is, the variable to be measured can be determined along the length of the fiber itself, this type of method is called distributed detection. The distributed sensors make full use of optical fibers, as each element of the optical fiber is used for measurement and data transmission purposes. These sensors are more suitable for application in large structures, as they have multipoint measurement capabilities. A distributed sensor allows the measurement of a desired parameter as a function of length along the entire fiber;

(c) Multiplexed sensors: Are generally built by combining several sensors to measure disturbances in a large structure, that is, the information is interpreted at specific points along the length of an optical fiber network. It is a complex technique where several researchers create innovative methods for the development of multiplexed fiber optic sensors. The most widely used multiplexed detection technique for measuring delays in the propagation time of light traveling in the fiber based on the change induced by measurement in light transmission. An optical time domain reflectometer (OTDR) is used primarily for this purpose. In this type of sensor, a pulsed light signal is transmitted to one end of the fiber, and the light signals reflected by several partial reflectors (splices) along the length of the fiber are recovered by the same end of the fiber.

As noted, there are several types of optical fiber sensors used in engineering for the most diverse purposes, among them the extrinsic Fabry–Perot Interferometric (EFPI) sensors and the Fiber Bragg Grating (FBG) sensors are being used more for long-term / structural monitoring of concrete structures (Kesavan et al. 2010).

3.3 Fabry–Perot Interferometric Sensor

The Fabry–perot fiber sensor is an in-line sensor device, which makes it very useful for a variety of applications. It is basically an optical cavity (called the FP cavity) that has high reflectivity mirrors with the reflective surfaces facing each other. Due to the high reflectivity, the transmission is spectrally selective and serves as an interference filter (Meggitt 2010).

In sensors of this type, light is reflected partially at the sensor input and then again at the distal end of the sensor (Fig. 2). If the light returning to the fiber entrance is in phase with the light being reflected at that point, constructive interference occurs. If the light is in the antiphase phase, destructive interference occurs. Adjusting the

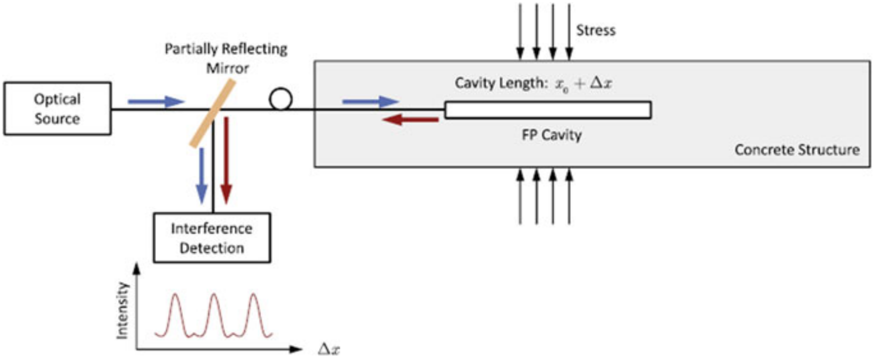

Fig. 2 Fabry–Perot Interferometric sensor (Yehia et al. 2014)

reflection coefficients at the sensor's final limits allows the sensor to be designed so that the light makes several passes. When all of these passages combine with the same phase, strong reflection occurs (Michie 2000).

The optical cavity changes in length when any voltage is applied to the structure in which the FOS is inserted. From the moment the light is injected into the cavity, this change in length causes a change in the pattern of interference of the optical signal coming out of the sensor, linking the structural deformation to the variations received in the optical intensity. FP-based sensors are very sensitive to changes in the length of the optical cavity and therefore are more sensitive to small structural changes than other FOS techniques (Yehia et al. 2004).

3.4 Fiber Bragg Grating Sensor

Among fiber optic sensors (FOS), Bragg fiber sensors, called FBG, are widely used and versatile. Basically, an FBG is a periodic variation in the refractive index along the fiber. This variation occurs due to the exposure of the nucleus to an intense pattern of optical interference (Taheri 2019).

Generally, the FBG's monitoring system consists of monitoring the wave of the "Bragg" response signal as a function of the variable being measured, such as temperature, voltage and others. The system has gratings in its composition (Fig. 3), which are a fundamental part of this type of sensor, because when a spectral source injects light into the fiber, these are Bragg grating that reflect, in response, a narrow spectral component corresponding to the measurement performed by each grating (Fig. 4) (Grattan and Sun 2000).

The main reason why FBGs are widely used is that, through this type of sensors, temperature and tension can be measured at a series of points along a fiber line, and have several advantages over conventional sensors (Pei et al. 2014).

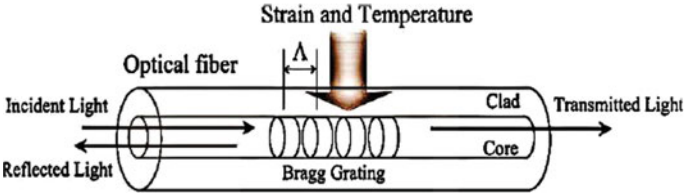

Fig. 3 Representative scheme of Fiber Bragg grating (Ramakrishnan et al. 2016)

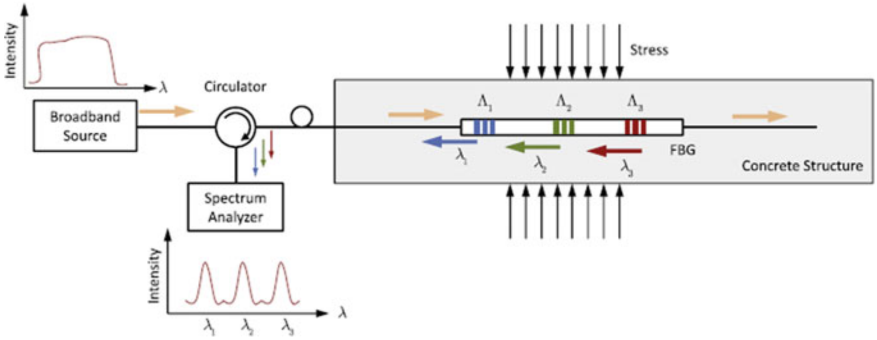

Fig. 4 Sensor representation of Fiber Bragg grating in a concrete element (Yehia et al. 2014)

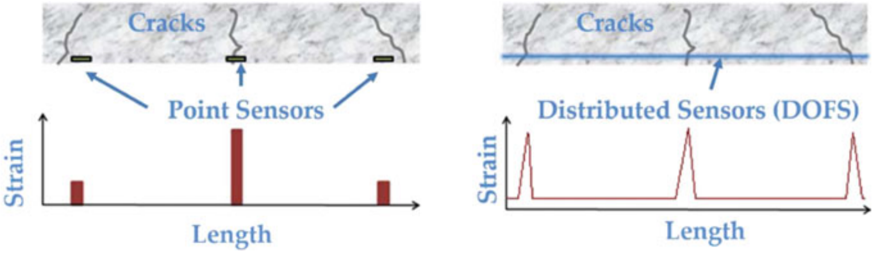

Fig. 5 Distributed sensor for crack detection (Barrias et al. 2018)

3.5 Practical Application of Fiber Optic Sensors in Concrete Structures

In the case of concrete structures, there are numerous places where cracks can occur, so that, in order to analyze the structure in a global way, the use of localized sensors becomes impractical, as it would require a very large number of point sensors, in this case, it becomes more appropriate to use sensors distributed (Bao et al. 2010) as shown in Fig. 5.

4 Tests with Embedded FOS in Concrete

4.1 Strain, Crack and Temperature Monitoring

The work developed by Yehia et al. (2014) used optical fibers to measure deformations due to physical changes, such as heat of hydration, as well as deformations due to cyclical and torsional loads. Concrete cylinders of 15 × 30 cm and beams of 175 cm in length and with a cross section of 35 × 55 cm were used. Fiber optic sensors

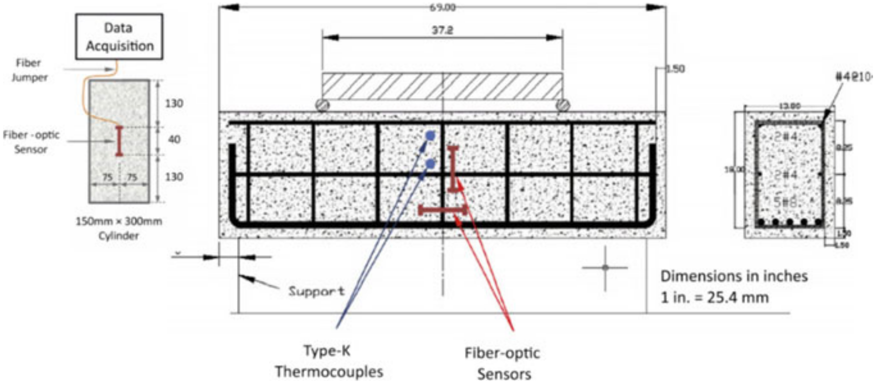

Fig. 6 Experimental setup: cylinder testing and beam testing (Yehia et al. 2014)

were inserted in the cylinders (1 in each) and in the beams (2 in each) as shown in Fig. 6. The FOS sensors used in the experimental investigation were the embedded fiber-optics (EFO), temperature-compensated and strain gauge for cylinder and beam testing, respectively. The sensors are based on Fabry–Perot interferometry.

To identify temperature variations during the hydration of the concrete, thermocouples were incorporated in the middle and on the surface of the beams, the embedded sensors could detect temperatures between 40 and 100 °C. All sensors were connected to the data acquisition system right after molding to record deformations due to the heat of hydration and also the shrinkage of concrete. The same procedure was used for both beams and cylindrical specimens. Monitoring was performed continuously during 7 days (Yehia et al. 2014).

In Fig. 7, it is possible to observe the performance of tests with cylindrical samples and concrete beams, and in the Figs. 8, 9 and 10, it is possible to see the results provided by the sensors, for each test performed on the concrete samples, as a function of time.

As a result, in the test made by Yehia et al. (2014) it was possible to observe in all tests, the FOS sensors showed instantaneous response to any changes in loading as well as temperature changes, which indicate the sensitivity and the ability of the FOS

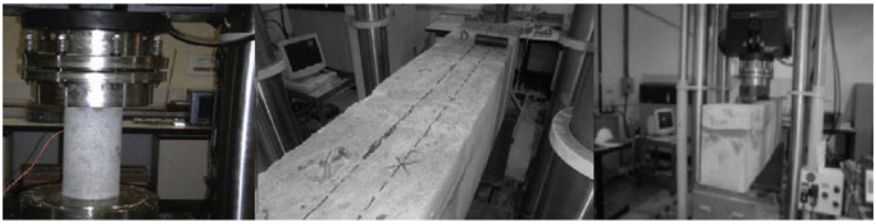

Fig. 7 Cylindrical specimen and beams during tests (Yehia et al. 2014)

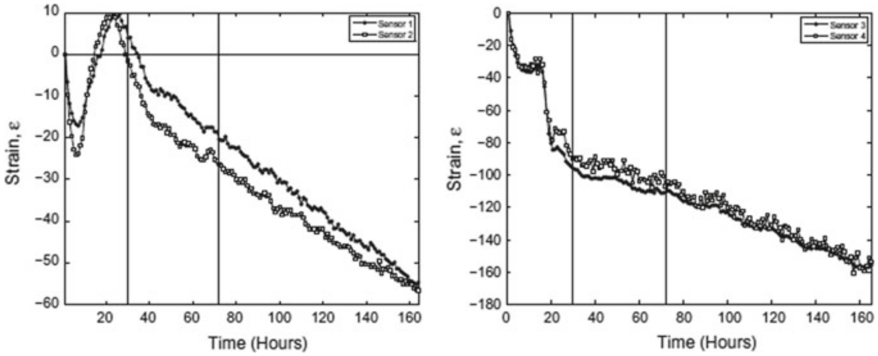

Fig. 8 Deformation result in the four cylindrical concrete samples presented by FOS (Yehia et al. 2014)

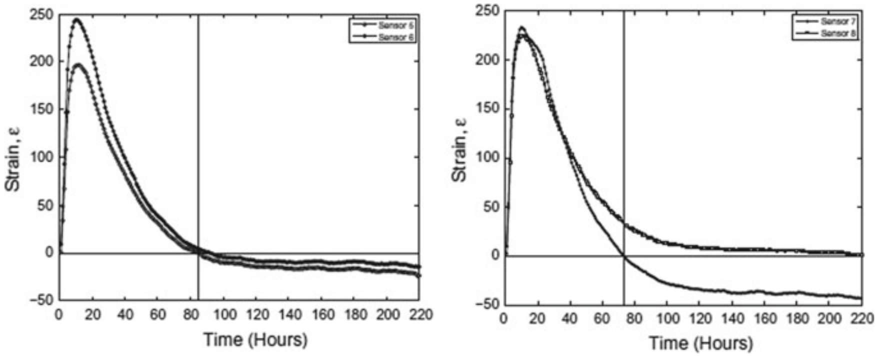

Fig. 9 Result of deformation in beams presented by FOS (Yehia et al. 2014)

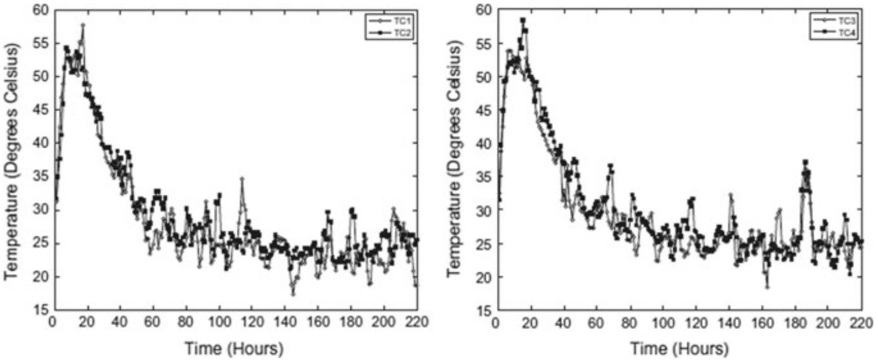

Fig. 10 Result of temperature variation in beams (Yehia et al. 2014)

sensors to record responses from the samples of concrete due to loading or during hydration.

Another work that uses FOS to analyze concrete strains is the work of Sienko et al. (2018). In this work, fiber optic sensors are used to investigate strains and cracks in a reinforced concrete element during a load test. Deformations are measured by analyzing the cracks that occurred during the load application. The crack dimensions were calculated based on the fiber deformation data obtained.

The FOS used were of the type single-mode telecommunication optical fibre SM 9/125 in a tight jacket (outer diameter of 0.9 mm), precisely to analyze the viability of this specific type of fibers, widely used in telecommunications, in the study of concrete structures.

The studied concrete element is 77 × 110x1050 mm (see Fig. 11a) and a 16 mm diameter steel bar inside, located in the middle of the cross section (see Fig. 11b). The optical fibers were placed along the length of the limb in six different positions (see Fig. 11c).

After processing the raw data, the author defined measurement bases in post-processing. The length of the bases taken was 10 mm and the distance between successive bases was 5 mm. This means that the sensor bases overlapped by half their lengths (see Fig. 12d).

Figure 12 shows the changes (deformations) of the fibers individually, according to each measurement base defined by the author (Pei et al. 2014), before the concrete cracked. It can be observed that the fibers B, D and F show greater variations in relation to the others, this is due to the fact that they are located close to the surface of the element, where due to the natural internal stresses, the surface shrinks.

The tensile stress was applied in an eccentric way, so that cracks were initially formed in the upper part of the element where there was the greatest stress and due to the progressive redistribution of the concrete they gradually developed on the lower surface. It was observed that all critical cracks appeared in the element up to a load

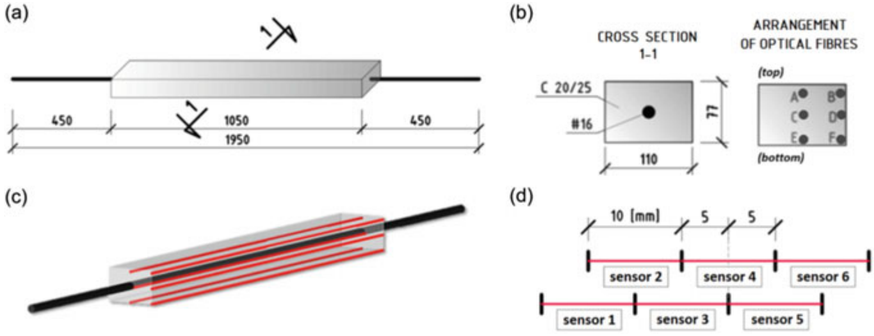

Fig. 11 **a** Specimen dimensions, **b** Cross section with the locations of optical fibres, **c** View of the member analyzed and **d** Arrangement of sensor bases along the length of the fibre (Sienko et al. 2018)

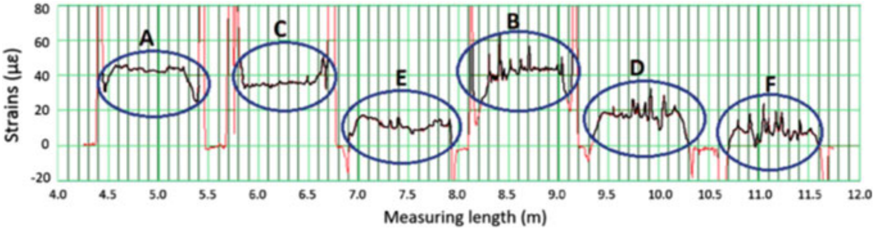

Fig. 12 Optical fibre strains recorded within individual measurement sections before the concrete became cracked (Sienko et al. 2018)

of 10 KN. From this information, the graphs referring to the behavior of the fibers for two load levels (6 kN and 10 kN) are shown in Fig. 13.

Significant changes in the signal presented by the fibers represent internal changes in the structural element. Figure 13a and b, are used as deformations measured by fibers closest to the most elastic surface (A and B). Note that there is a load of 6 kN, there are three characteristic locations of large deformations, confirming or appearing three cracks.

A load of 10 kN, the number of cracks identified by the doubled strain local ends. The measurements also show that the deformations that occur between a crack and another are very small.

In Fig. 13b for cracks 1 and 2, where the extreme stress values occur at the load level of 6 kN, but for load 10 kN, these deformations were smaller, but cover a wider area in the vicinity of the cracks. According to the author this occurs due to slipping on the surface where the contact between the fiber layer and the concrete is maintained, as well as between the jacket and the optical glass core.

The Fig. 13c shows the changes in the tension of the fibers glued to the steel bar. Figure 13d shows the changes in fiber tension in the middle of the element. Figure 13e and f shows deformations on a less elastic surface.

These deformations are positive or negative, depending on the degree of crack development along the shortest edge of the cross section. Based on the measured deformations (Fig. 13), the elongations of the fibers were determined on the measurement bases provided with a length of 10 mm (Fig. 14).

This work (Sienko et al. 2018) confirmed the usefulness of fiber optic technology to identify very small cracks (about 0.01 mm). This conclusion is of significant practical importance, as it refers to cracks that are difficult to identify using other methods. In addition, the research also confirmed the usefulness of optical fiber strain measurement technology for analyzing larger cracks and visible to the naked eye.

In another work, knowing the possibility of implementing the FOS in concrete, Horch et al. (2015) went beyond the existing laboratory studies and used sensors in the foundation element of a tall building. In the work in question, a system called "Backscattered Optical Reflectometry" (OBR) was used.

In this work (Horch et al. 2015), the configuration of the sensor system used has a spatial resolution of 5 mm, a temporal resolution of 50 Hz and a maximum detection

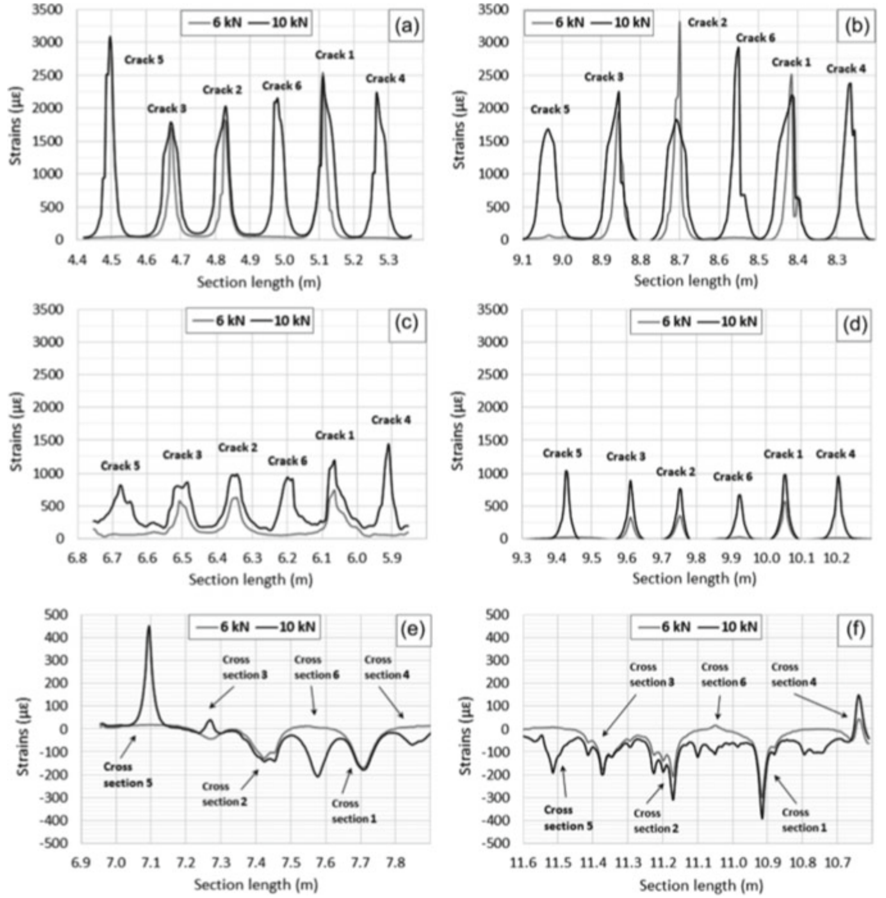

Fig. 13 Changes in FOS strains measured during the test: **a** Top center, **b** Top right, **c** On the reinforcing bar, **d** Center right, **e** Bottom center and **f** Bottom right (Sienko et al. 2018)

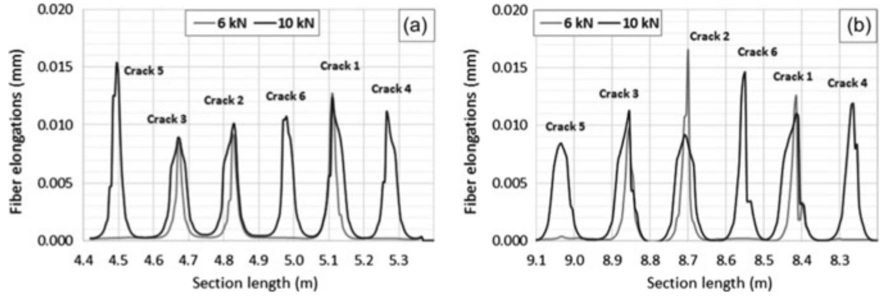

Fig. 14 Changes in elongations of selected FOS: **a** Top center and **b** Top right (Sienko et al. 2018)

Fig. 15 Three different sensor cables attached to the reinforcement (Horch et al. 2015)

of 20 m. As the structural element was 32 m. Altogether, 12 fibers were used coupled to the reinforcement (see Fig. 15), 8 for strain measurement (blue cables) and 4 for temperature (red cables). Regarding the 8 sensors, 4 had cables with a diameter of 3.2 mm and 4 with a diameter of 7.2 mm, in order to also compare the influence of the size of the cables in obtaining the results. The system is described in the Fig. 16.

After pouring, the reference measurement was made when the structure was 18 weeks old, then a reading was taken at 26 weeks and finally another reading at 34 weeks after pouring. For each measurement, temperature changes were measured once.

Regarding temperature measurement, according to the author, as the expected strain values are in the range of 10 μm / m, it is necessary to compensate the levels of thermal expansion of the concrete. Temperature sensitive fibers were used for this reason basically.

The values obtained from temperature presented in Fig. 17 presented large ranges of oscillation (noise), analyzed by the author as not consistent with reality, considering that the deformations did not show similar behavior, therefore, it was taken into account some alteration coming from the cables or the machine.

On the other hand, the temperature values oscillate around a constant average value throughout the foundation slab. The two horizontal lines in Fig. 17 show these average values. The author used these means to compensate for thermal expansion, so a constant stress displacement is calculated from the average temperature and subtracted from the measured strain values.

Figure 18 shows the values corresponding to the deformations after temperature compensation. It is seen that the absolute value of the voltage seems to increase. This is natural, as the load on the foundation increases as construction progresses.

For Horch et al. (2015) the purpose of the work was to demonstrate the use of fiber optic sensors distributed inside a real building as opposed to a laboratory installation. With the application in a real structure, some difficulties were observed, both in terms

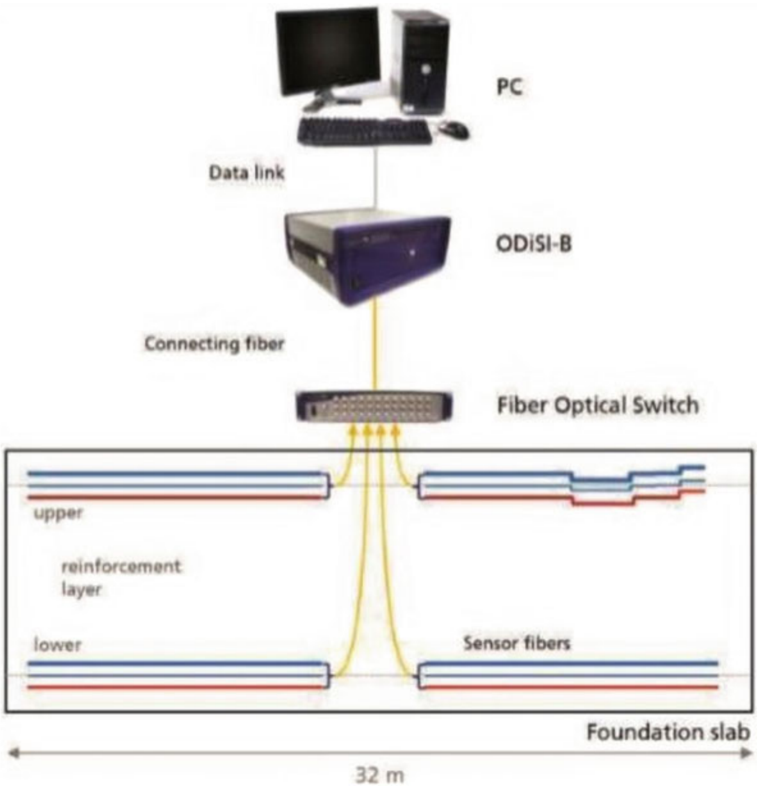

Fig. 16 Location of the sensor cables in the foudation slab and experimental setup (Horch et al. 2015)

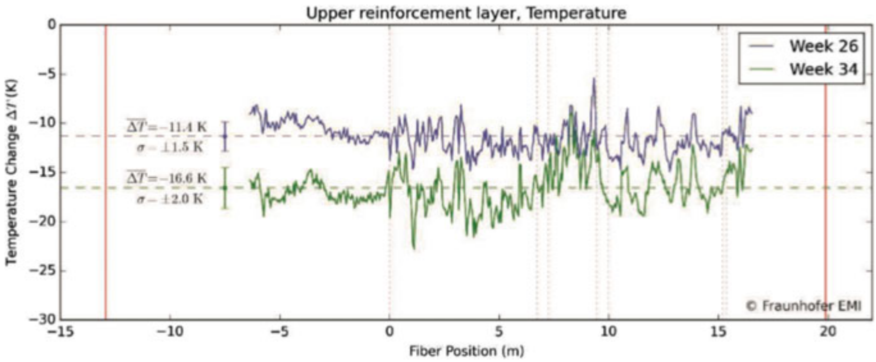

Fig. 17 Results of temperature measurements. The horizontal lines show the average of the temperature curves. The solid red lines indicate the dimensions of the foundation slab. Position 0 is the position where the fibers leave the slab. The dotted gray lines mark vertical sections of the sensor cable (Horch et al. 2015)

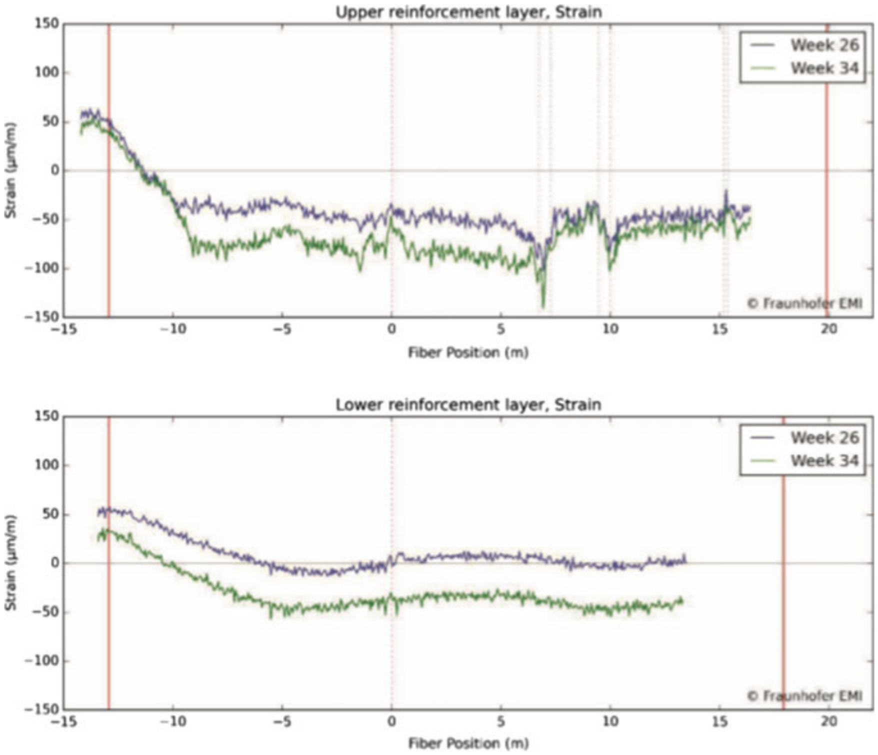

Fig. 18 Results of strain measurements at the upper and the lower reinforcement layer after compensation of temperature (Horch et al. 2015)

of logistics and in obtaining the results. The author states that the data should be better determined and that the factors related to the temperature and the influence of the different dimensions of the cables should be studied, considering that there was no coherent conclusion found by the author for these factors.

4.2 ISR's Monitoring

Fiber optic sensors can be used to measure deformations in concrete elements. It is well known that internal swelling reactions cause deformations due to the stresses caused by the hydration products (expansive gel, etringite crystals, etc.). The use of FOS specifically for the analysis of structures that present these types of pathology (AAR or DEF) is still very scarce.

One of the works that uses FOS to analyze one of the internal expansion reactions is the work of Dunant & Scrivener (2012). In this work it was performed an experimental study using sensors embedded in reactive and non-reactive concrete samples, with

Fig. 19 Samples in the loading frame (Horch et al. 2015)

the samples loaded in modified creep frames. In the concrete mixture procedures, reactive and no-reactive coarse aggregate were used. The concrete was cured at a temperature of 20° for 28 days. After that time the concrete was placed in a room with a controlled temperature of 38°. It is important to highlight that the reaction (ASR) was not accelerated. After this cure, the samples were placed in creep frames and subjected to 0, 5, 10 and 15 MPa stress levels.

Three standard cylindrical concrete specimens—height 335 mm, diameter 160 mm—were loaded in creep. In each column: a non-reactive sample on top and two reactive samples at the bottom (see Fig. 19). The load in each column was kept constant by hydraulic pressure, and the non-reactive samples allowed us to distinguish strains due to creep from the expansion induced by ASR.

For FOS monitoring the sensors embedded in each sample placed in the loading frame were:

- A temperature sensor;
- The elongation is measured using a *Fiber Bragg grating sensor* (length 67.5 mm);
- The temperature sensor allows the correction of small strain fluctuations due to variations of the ambient temperature.
- A longitudinal strain gauge (optical fibre length 100 mm) which functions in the same way as described above, but without a temperature sensor.
- A computer which logged the sensor values every 20 min. The resolution of both captors is 0.001 mm.

The scheme for installing the sensors in concrete is shown in Fig. 20. During the tests the samples were undisturbed and strain variations due to temperature fluctuations could be compensated. The low dispersion can be explained by the scale at

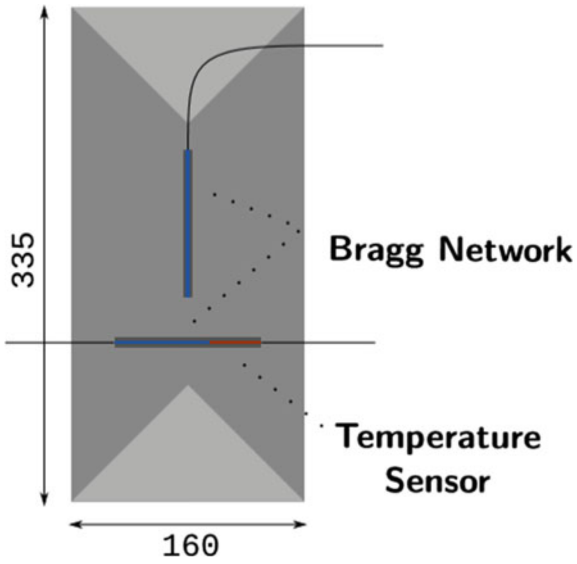

Fig. 20 Schematic of the sample instrumentation (Dunant and Serivener et al. 2012)

which cracking occurred. As the aggregates used are slow reacting aggregates, the cracks caused by the reaction are all micro-cracks in the aggregates and in the cement paste. No macroscopic cracks were observed at the surface of the samples during the duration of the experiments.

Figure 21a and b show how deformations occur, both due to the applied loads and the presence of ASR, simultaneously. Under load, a clear direction of propagation is favored: parallel to the load. When the load is further increased, the longitudinal expansion goes to 0, but the lateral expansion increases. This behavior is at odds with the idea of a "redistribution" of the expansion.

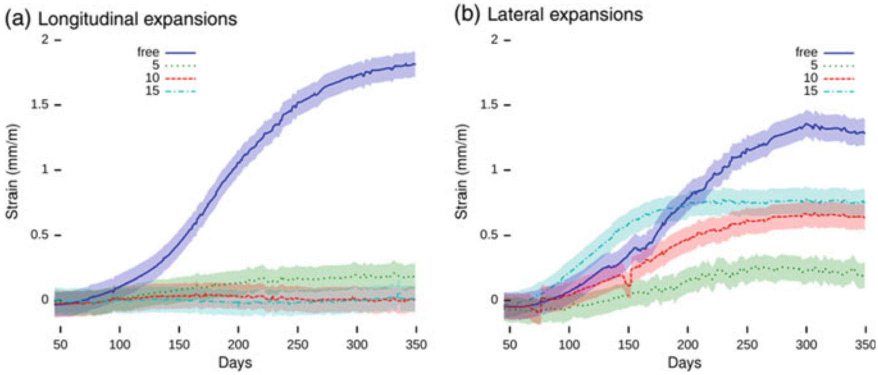

Fig. 21 A Longitudinal and **b** Lateral and expansions of samples due to ASR and load application (Dunant and Serivener et al. 2012)

Under the 5 MPa stress level, the cracking is more pronounced and its onset began often on the aggregate. Notable features of the crack patterns are that damage concentration are immediately around gel pockets, a network of cracks connecting the gel pockets. A dense pattern of short radial cracks immediately around the aggregates and relatively few main cracks which will grow to the edge of the samples.

The effects of uni-axial stress on the expansion of ASR reactive concrete were linked to the orientation and development of micro-cracks in the aggregates and paste. It is notably found that the expansion is not redistributed, but the applied load forces the orientation of the micro-cracks at the micro-structural level.

The expansions observed experimentally at 5 MPa is probably due to the very specific combination of mechanical properties of the materials, the aggregate type and the morphology of the cracks formed. As the strength of the material was not measured, this result does not indicate that the concrete is less damaged at this load.

Another experimental work that uses FOS to analyze one of the internal swelling reactions is the work of Rocha et al. (2013). This work was developed in two stages, in a laboratory and in a real structure. For laboratory tests, 12 samples of potentially reactive mortar were made for analysis of AAR. The specimens were made in metallic molds and had dimensions of 0.10 × 0.10 × 1.40 m. Before molding, optical fiber sensors were inserted into the molds, as shown in Fig. 22. A total of 12 fiber optic segments were placed: 6 sensing cables segments and 6 tight buffer segments.

The sensors used were distributed optical fiber strain sensors (DTSS). The prepared mortar was composed of potentially reactive aggregate and standard cement. Molding of specimens the mortar was prepared in a standard mechanical mixer with a trait of mixing 1: 2.24: 0.47.

The forms were filled with mortar carefully to avoid damage to the sensors. Demolding occurred after 7 days. To perform external measurements, metal pins were fixed on the lateral surface of each sample. Each group of pins was fixed at least 50 cm apart. External measurements were made to compare with internal optical fiber measurements (Rocha et al. 2013).

After demolding, the specimens were placed in a metal structure that facilitates handling and then in a tank with a 1 N NaOH solution (see Fig. 23) to accelerate

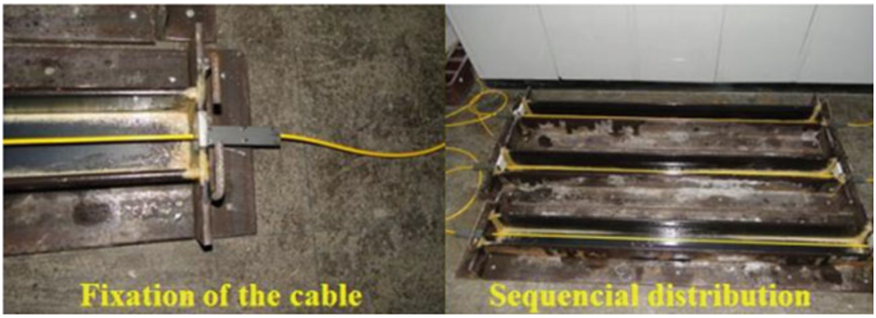

Fig. 22 Installation of the sensors in the molds (Rocha et al. 2013)

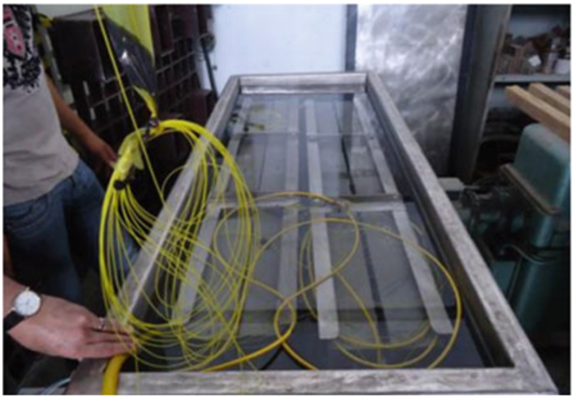

Fig. 23 Specimens in the tank (Rocha et al. 2013)

the reaction and a constant controlled temperature of 80 °C during the experiment. External measurements were made daily for 30 days (the duration of the experiment) and internal measurements, with the fiber optic system, were made every 30 min (Rocha et al. 2013).

In his work, Rocha et al. (2013) observed cable degradation due to the aggressiveness of the NaOH solution at high temperature. Although these factors are not considered in field installations, it is relevant in the analysis of laboratory tests, as it affects the condition of connection between sensors and the surrounding expansion mortar.

The results of the tight buffer data are not reliable after 10 days of measurement, while the cable, which is a more protected element, shows consistent results up to the 15th day of measurements (see Fig. 24). After these periods in each case, the information obtained is not relevant.

However, it was observed by the author that the expansion detected within the period in which the measurements were possible, is consistent with the measurements of the external pins. Its magnitude is smaller as expected, due to the gradient of deformation from the outer surface to the center of the sample. However, the important result is evidence of its ability to detect the evolution of AAR.

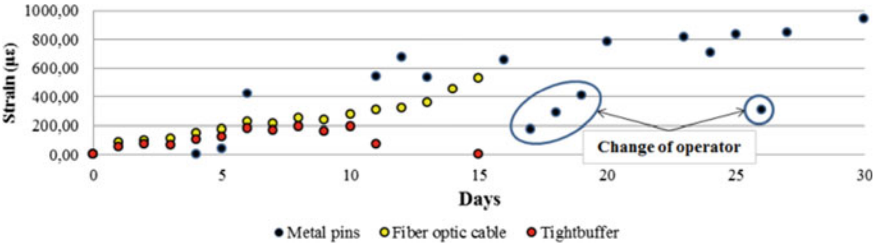

Fig. 24 Comparison of measurements of a large specimen—external metallic pins and optic sensors (Rocha et al. 2013)

Fig. 25 Peti Dam (Rocha et al. 2013)

According to the authors (Rocha et al. 2013), the first part of the experiment, carried out in the laboratory, served as a basis for understanding the measurement system that incorporates FOSs and only after the laboratory tests, the study began in a real structure. The structure in question is the Peti dam (see Fig. 25) that is located in the state of Minas Gerais, Brazil and was built between 1941 and 1945.

Unlike the studies previously presented in this work, in the case in question the installation of optical fiber sensors was done after the element already built. In this dam, structural abnormalities have been observed due to the reaction of the alkaline aggregate (AAR) since 1972. Eight preexisting vertical wells, with different depths, were instrumented with fiber optic sensors, with a depth of 3 to 30 m, distributed along the dam. One limitation encountered was the possibility of installing only in one direction. The column regions and the central section were instrumented, with a greater number of sensors on the left column, where greater degradation was reported. In this particular region, the DTSS and FBG sensors were applied. A schematic distribution of the DTSS cable is shown in the Fig. 26. The FBG sensors were installed on the left column next to the DTSS sensors in holes F5 and SR1.

For the installation of the sensors, some interventions were made in the holes, such as cleaning the well, anchoring the cable at the bottom and completely filling the well with a mixture of cement mortar.

Rocha et al. (2013) was observed that the Peti Dam is still showing evidence of a slow and continuous expansion due to the ARR. The installation of DTSS and FBG sensors in this structure offers a great opportunity for validating the use of optical fiber sensors for evaluation of expansions due to internal expansion reactions. Data readings can be taken in a few hours and are taken from a single point for the entire

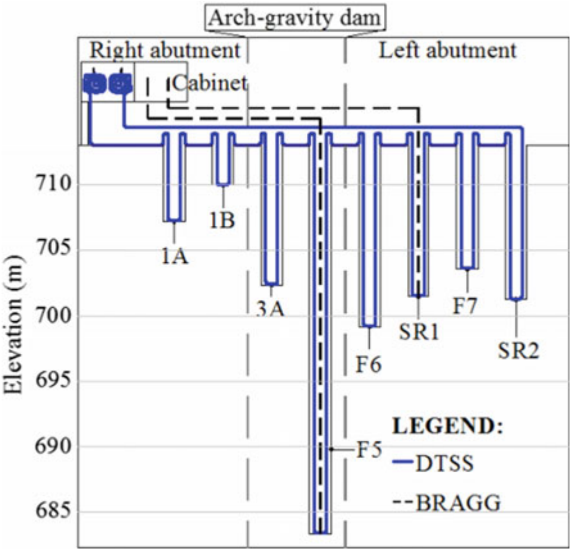

Fig. 26 Distribution of fiber optic sensors (Rocha et al. 2013)

installation. Also according to the authors, high spatial coverage and information density may be the main advantage of using FOS technology.

Finally, although no studies have been found using fiber optic sensors only for evaluation and monitoring of expansion by DEF, it is important to consider that although the origin of AAR and DEF are different, the effects on structures on a macroscopic scale are basically the same, both cause expansion in concrete elements, and often occur simultaneously. From the studies presented, it is possible to state that regardless of the internal reaction existing in the structure, the expansions can be detected through the FOSs.

5 Conclusions

FOSs technology has been successful for monitoring several types of concrete structures. The application of this type of technology has been increasingly frequent and promising. These are complex studies that need to be planned and done in a conscious way for the results to be valid. Most of the existing tests for this type of use of FOSs are made in the laboratory, however there are already tests on real structures, mainly on bridges and viaducts, and some tests on buildings (according to Horch's work (Barrias et al. 2018)), but on real scale there are important factors to be considered and the analysis of the results tries to be even more complex.

The aforementioned works highlight the potential in monitoring the performance of reinforced concrete structures with the use of FOSs. On the other hand, there are important challenges to be overcome, especially the aspects related to data processing and the need for a clearer and more objective presentation of the results to the academic community.

Moreover, the information about the equipment used and a justification for choosing the same ones is not always well detailed in the existing works. This fact greatly limits the possibility of reproduction of the same tests in lab or use this approach in real concrete works.

From the bibliographical review performed, one can say that there are currently several types of fiber optic sensors available on the technical market. These are usually sensors for multiple purposes and they have been effective in several works investigated, especially in the study of deformations of concrete elements.

Internal expansion in concrete may come from different internal swelling reactions and the investigation of FOSs to measure such expansion in an open filed to research—few studies have been found on this topic, although its use is promising. Most studies were conducted to measure deformations due, almost exclusively, to mechanical loads imposed on concrete specimens.

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