Distributed Optical Fibre Sensors for Strain and Temperature Monitoring of Early-Age Concrete: Laboratory and In-situ Examples

Rafał Sieńko, Łukasz Bednarski, and Tomasz Howiacki

Abstract Distributed fibre optic sensors (DFOS) provide new possibilities in structural technical condition assessment in comparison with traditional spot measurements. It is possible to analyze strains and temperature changes continuously over structural member length with spatial resolution starting from as fine as 5 mm. Thanks to the appropriate sensor construction and its installation before concreting it is possible to analyze material behaviour starting from its early stage, when thermal-shrinkage strains appear. This phenomenon depends on many factors, such as the type of concrete mix, dimensions of structural member, the way of concrete care, external conditions (temperature, humidity), formwork and constraints related to reinforcing bars or external friction and resulting with crack appearance. Stage of early-age concrete (hydration process) is thus very important for its final durability and performance. The article presents the very new measuring tools which allow for comprehensive analysis of concrete temperatures and strain state including all local nonlinearities (cracks). The attention was paid to hydration process, but sensors installed inside the structural members can be also effectively used during other phases such us: activation of prestressing tendons, construction stages or operation. Selected examples of laboratory tests as well as the unique in situ installations realized in Poland during last few years are presented and discussed hereafter. Except of traditional concrete, also other materials were examined, such as concrete made on lightweight sintered aggregate and fibre-reinforced concrete mixed with the ground.

Keywords Early-Age concrete · Optical fibres · Distributed measurements · DFOS · Strain · Temperature

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F. Kanavaris et al. (eds.), *International RILEM Conference on Early-Age and Long-Term Cracking in RC Structures*, RILEM Bookseries 31,
https://doi.org/10.1007/978-3-030-72921-9_7

1 Introduction

1.1 The Idea of Distributed Measurements

The main limitation of traditional extensometers and thermistors is the ability to carry out measurements only locally along defined measuring base (Fig. 1a). Sometimes some efforts are made to perform measurements along a given line by installing several sensors within this line (Fig. 1b), but this approach is expensive and thus occasionally used. Distributed optical fibre technology is based on light scattering and allows for strain or temperature measurements to be made with a spatial resolution starting from as fine as 5 mm along the length of the optical fibre [9]. From an engineering point of view such measurements can be considered as continuous in a geometric sense (Fig. 1c).

A number of studies concerning DFOS (distributed fibre optic sensing) have been conducted under laboratory and in situ conditions over the last few years. The attempts were made to find the best ways to embed fragile glass measuring fibres into a concrete [3, 4] detect and estimate crack width within concrete structural members [2, 16, 17] and analyse their strain and temperature distributions [6, 11] using different optical phenomena such us Brillouin [8] or Rayleigh scattering [1].

In all examples presented further optical backscatter reflectometer OBR 4600 manufactured by Luna Innovations (based on Rayleigh scattering) was applied for distributed measurements. The selected technical parameters of this device are summarised in Table 1.

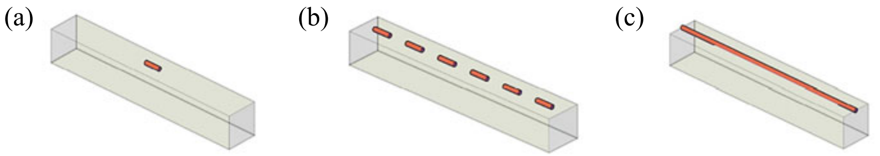


Fig. 1 The idea of measurements: **a** spot, **b** quasi-continuous, **c** distributed (geometrically continuous)

Table 1 Selected parameters of reflectometer used for distributed measurements

Parameter	Value	Unit	
Measuring range (standard mode)	70	m	
Optimal spatial resolution	10	mm	
Temperature resolution	±0,1	°C	
Strain resolution	±1,0	με	

1.2 Sensors Construction

Glass optical fibres used in the telecommunication field should be as pure as possible i.e. free from micro-imperfections that cause light wave energy losses over the length. The Rayleigh scattering phenomenon is one of the reasons and it occurs in every fibre cross section due to the particle structure of matter (heterogeneity of refractive index at micro-scale). However, this fact is favourable in terms of strain measurements. The light reflected from the imperfection of the glass structure moves backward relative to the original direction of motion. Scattering amplitude is a random but constant property for a given fibre and can by calibrated for mechanical or thermal strains by advanced reflectometers.

One of the most challenging tasks while constructing sensors for embedding into concrete is to provide appropriate strain transfer from surrounding medium (concrete) to the glass measuring core of the optical fibre. This phenomenon is influenced by the slip at the surface between the fibre external jacket and the concrete, as well as between the individual coatings and the optical glass core itself. Finite element (FE) analyses of this phenomenon are currently being conducted by a range of specialists in the field of structural mechanics and photonics together with the authors of this article.

One of the approaches is to use fibres with minimalized number of coatings (only with one primary coating applied directly in the production process of the fibre—see Fig. 2a), what reduce the risk of the slippage and thus the risk of disturbances. The limit strains for such standard SM telecommunication fibre could be more than ±5%, so they are able to measure even very wide cracks. What is more, in this case the presence of the sensor inside the member do not affect its behaviour at all (the fibre with negligible diameter of 250 μm and thus with negligible stiffness). However due to the fragility and the lack of resistance to shearing forces, this solution can be used only in laboratory conditions, where installation process could be performed with high precaution and precision.

Another option is to apply specially designed fibres with different coatings, which improve the adhesion between the concrete. Example of such fibre with coarse-grained silica coating is shown in Fig. 2b. Disadvantage of this solution is that the high stiffness coating and its unregular geometry reduces the measuring range of the sensor (which is then less than ±1%).

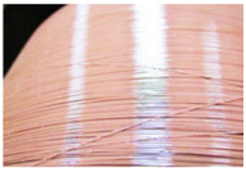
(a)  (b)  (c) 

Fig. 2 Example of DFOS measuring tools: **a** standard SM 9/125 fibre with acrylic coating, **b** with experimental coarse-grained silica coating, **c** integrated inside composite core (EpsilonSensor—[5])

The most advanced solution dedicated for laboratory and in situ installations is to integrate the glass optical fibre with composite core characterized by appropriate parameters (elastic modulus E, limit strains ε_{lim}, strength f and others). These parameters could be determined in two ways: making from a sensor the reinforcement ($E_{sensor} \gg E_{concrete}$) or not influencing the medium behaviour at all ($E_{sensor} \leq E_{concrete}$). Example of such dedicated solution is presented in Fig. 2c (EpsilonSensor [5]) with nominal diameter of 3 mm and elasticity modulus of 3 GPa.

The optical fibres are sensitive both to mechanical and thermal strains. For measuring temperature changes only, it is necessary to isolate the fibre from mechanical strains, e.g. by placing it inside the tube or use DFOS technique insensitive to mechanical strains (like Raman scattering). However, there are many important details which should be taken into consideration. That is why it is recommended to consult the choice of strain sensors and possible ways of compensation with experienced specialists, as these issues are crucial for quality of measurements and data interpretation.

1.3 Early-Age Concrete

Structural health monitoring (SHM) of the structures made of concrete is especially difficult task, because this material is very heterogeneous and subjected to the rheological phenomena over time. What is more, concrete members usually work within cracked state [12] which has important impact on corrosion development and the final durability. This process starts from hydration when thermal-shrinkage strains appear [18]. This phenomenon depends on many factors [19, 20], such as the type of concrete mix, dimensions of structural member, the way of concrete care, external conditions (temperature, humidity), formwork and constraints related to reinforcing bars or external friction and resulting with crack appearance. Stage of early-age concrete is thus very complex and important for its final durability and performance so works are ongoing to develop effective measuring tools able to provide reliable information about this phenomenon which is not yet sufficiently investigated and described in the literature.

2 Laboratory Tests

2.1 Lightweight Concrete Specimens

The specimens under consideration were made from concrete on lightweight sintered aggregate [7] in the Laboratory of Building Material and Structures at Krakow University of Technology. Some of them were prestressed after achieving the appropriate concrete strength to observe the influence of intensified creep. Optical fibres with silica-grained coating were installed inside the formwork by specially designed mounting frames (Fig. 3a), which were removed after concreting leaving the measuring fibres inside the specimens. This allowed for appropriate positioning the initially pretensioned fibres longitudinally near the lower and upper surface of the specimen. The measurements of early-age concrete strains were performed according to the planned schedule and are currently being processed.

2.2 Fibre-Reinforced Concrete Mixed with the Ground

Similar mounting solution of the DFOS sensors (composite rods integrated with measuring fibre) was used to create the specimen made from the fibre-reinforced concrete mixed with the ground (Fig. 3b). Early-age material strains as well as mechanical strains induced in three-point bending tests (performed in the Laboratory of Building Material and Structures at Krakow University of Technology) were measured continuously in geometrical sense and then used for designing the real structural element (slurry wall, see also chapter 3.2). Some exemplary results of thermal-shrinkage strains are presented on spatial visualization (Fig. 4a) in the time and specimen length domain.

2.3 Concrete 'Tomograph'

One of the most challenging tasks was to create the concrete 'tomograph' (Fig. 3c) enable to measure strains and temperature distributions in all directions and in many sections of the concrete massive specimen. It was formed as a cube with 36 cm side insulated with extruded polystyrene. One of the challenges was to not break the pure optical fibre only in its primary coating during concreting, so self-consolidating concrete was applied. This process finally was succeed providing thousands of measuring data during first few weeks of concrete hardening without any influence of embedded sensors on the concrete behaviour.

Four optical fibres were used: three for measuring strains along three orthogonal directions XYZ and one for measuring the changes in temperature. Fibres were traced in such a way that 5 measuring cross sections, each with 5 measuring traces, were created in each direction, what means that 75 optical paths with total length of 27 000 mm was installed within the cube. Assuming the spatial resolution of measurements equal to 10 mm, this solution replaces 2700 traditional spot strain sensors, which installation would not be obviously possible in such conditions.

This type of experiments and results was not yet described in the literature. All gathered data are currently being processed in detailed. Exemplary plot showing the possibilities of geometrically distributed measurements is presented in Fig. 4b for the fibre located on X direction over its all 25 measuring traces.

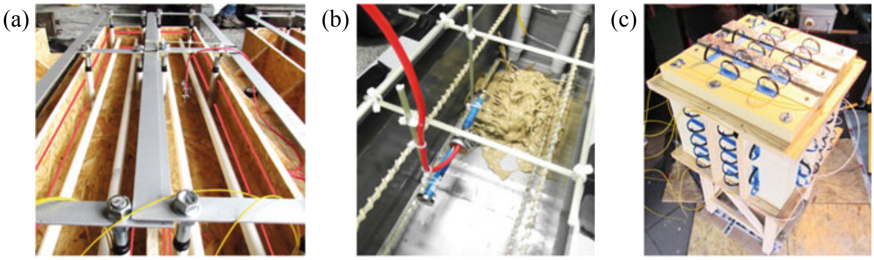


Fig. 3 Examples of laboratory specimens, where early-concrete strains were measured: **a** lightweight concrete, **b** fibre-reinforced concrete mixed with the ground, **c** tomograph for self-consolidating concrete (view during installation)

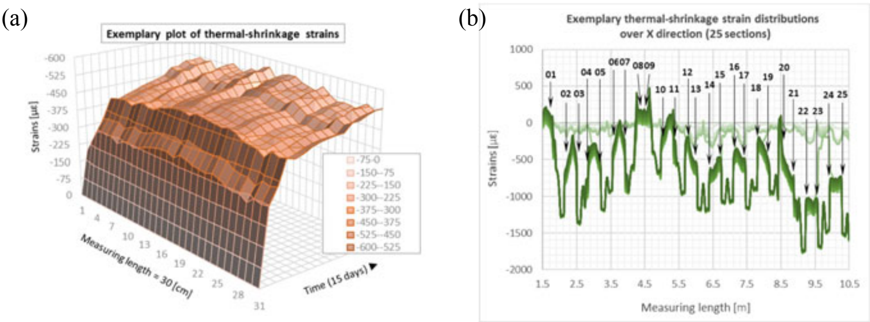


Fig. 4 **a** Exemplary plot of thermal-shrinkage strains of: **a** specimen made from fibre-reinforced concrete mixed with the ground, **b** concrete cube measured by the ‘tomograph’ fibre in X direction within 25 sections

3 In Situ Installations

3.1 Prestressed Truck Scale Platforms

Truck scales platforms are mainly used for weighting the car vehicles. Their main structural element is a slab which transfer the loads from vehicles into foundations through measuring devices. The crucial aspects during design phase are durability, bending stiffness and the dead weight. Thus, some platforms made from prestressed concrete were designed and implemented in Poland during last few years [15].

Platforms under consideration were prefabricated in the production hall in the technology of pre-tensioned concrete as fully prestressed, i.e. operating normally in a non-cracked condition. To reduce weight of the platforms, five oval Styrofoam inserts were placed along its length. Eight prestressing tendons were applied for the lower part of the cross section, and two for the upper. Moreover, reinforcing bars and stirrups were designed.

Several tests during different phases of the platform's lifecycle were performed, starting from hydration process (thermal-shrinkage strains), through tendons activation (strains regarding the transfer of compression forces from the tendons to the concrete) and finally during laboratory tests, when slabs were mechanically loaded in four-point bending test until destruction [14]. Distributed optical fibre measurement technology was used to record strain and temperature changes along selected measuring paths. For internal concrete strains, composite rods with integrated optical fibres were simply tied to the stirrups along the prestressing tendons—see Fig. 5a. The localization and numbering of all applied optical sensors are presented in Fig. 5b.

The measurements started immediately after concreting. Strains and temperatures were recorded every 30 min during first day of concrete hydration. During subsequent measuring sessions, the development of thermal-shrinkage strains was clearly observed. It is noteworthy that the distribution (shape) of strains along the member length is remarkably stable with respect to the shape from the beginning throughout all the following measurement sessions. Thus, the weakest points (those, where the local concentrations of strains occur) may be identified in the early stage, i.e. even then, when the concrete is not yet cracked or when only the micro-cracks invisible to the naked eye occur. The strain distribution plots with spatial resolution of 10 mm along the length of the platform under consideration during the first seven hour of hydration are presented in Fig. 6a for the lower (2) and Fig. 6b for upper (4) optical fibre rods.

During first hours of hydration the higher level of strains was observed for the lower optical fibre rod (2), because the concrete platforms were heated from below.

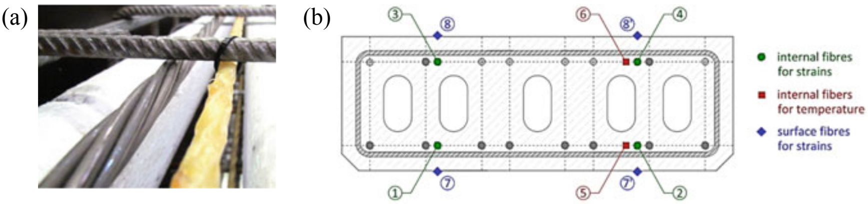


Fig. 5 **a** DFOS sensor tied to the stirrups before for concreting of the slab, **b** localization and numbering of all optical sensors

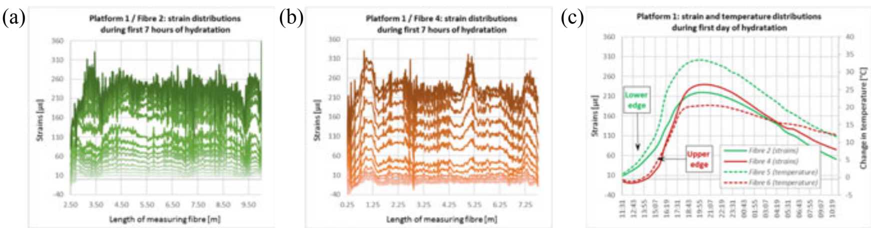


Fig. 6 Strains distributions: for fibre 2 (**a**) and 4 (**b**) over platform length during the first 7 h of hydration; averaged strains for fibre 2 & 4 over time during 23 h of hydration

Upper strains (4) at the very beginning were even slightly on the compressed side because of the external temperature domination before the start of concrete bonding end releasing hydration heat. The values of non-compensated strains (2, 4) and corresponding temperatures (5, 6) at lower and upper edges averaged over 1m base in the middle of the platform span are presented in Fig. 6c in time domain during first 23 h.

3.2 Slurry Wall

Other examples are a slurry walls made in technology of fibre-reinforced concrete mixed with the existing ground. These walls were executed within the research fields where their behaviour was monitored and analysed by composite optical fibre sensors (Fig. 7a) during the hydration process, but also during trenching the excavation (increasing the ground pressure—Fig. 7b), changing the thermal-moisture conditions, loading the surcharge with concrete slabs and loading the wall directly by the means of hydraulic jackets. Exemplary results of early-age concrete strains with simplified interpretation are presented below (Fig. 7c).

During the initial state, the shortening of the wall caused by the thermal contraction and shrinkage of the concrete-ground mixture was observed over entire length of the wall. However, due to the mechanical constraints (friction) between the wall and surrounding ground, the tensiled stress occurred causing the appearance of microcracks.

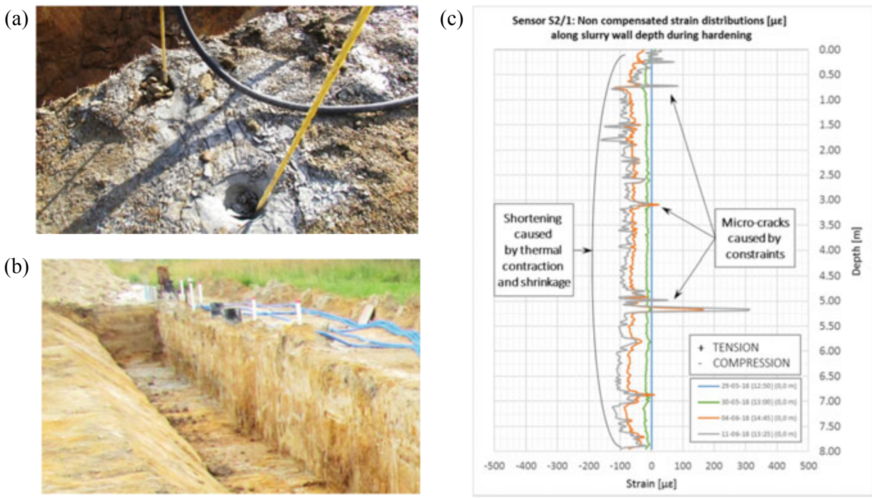


Fig. 7 **a** The view of optical fibre sensors installed in the slurry wall, **b** the view of slurry wall during trenching the excavation, **c** exemplary strain distributions of early-age concrete mixture

3.3 CFA Concrete Column

Continuous Flight Auger (CFA) columns are one of the most widely used ground improvement type because of their versatility, simplicity and efficiency. CFA concrete columns are formed by drilling the hollow to the required depth using special auger with inner tube, which is closed during driving and opened during extraction from the hole, allowing for down-up concreting in continuously way. This process is always monitored by an electronic system, but structural integrity of the columns is still affected by different factors such as concrete quality (low workability), cement consumptions, aggregate segregation or exudation. This is the reason why more and more effective and non-destructive ways of control the structural condition of the columns are developed.

One of the main advantages of installation internal optical fibre sensors is the possibility of measuring early-age concrete strains and temperature development. In research described further, distributed sensors were installed immediately after column execution. For this reason, special technology of installation (steel tubes with anchorages) was elaborated and implemented—see Fig. 8a.

In the first days of hardening, concrete reduced its volume (the length of the column was shorter and shorter) due to the phenomenon of thermal contraction as well as autogenous and drying shrinkage—see Fig. 8b. But, because the structural member under consideration is not totally free element (constraints through the friction within the shaft), tensile stress could be induced in the material. Depending on the level of constraints as well as the parameters of concrete mix used and conditions of hardening, this phenomenon can lead to the occurrence of microcracks and cracks.

(a) (b)

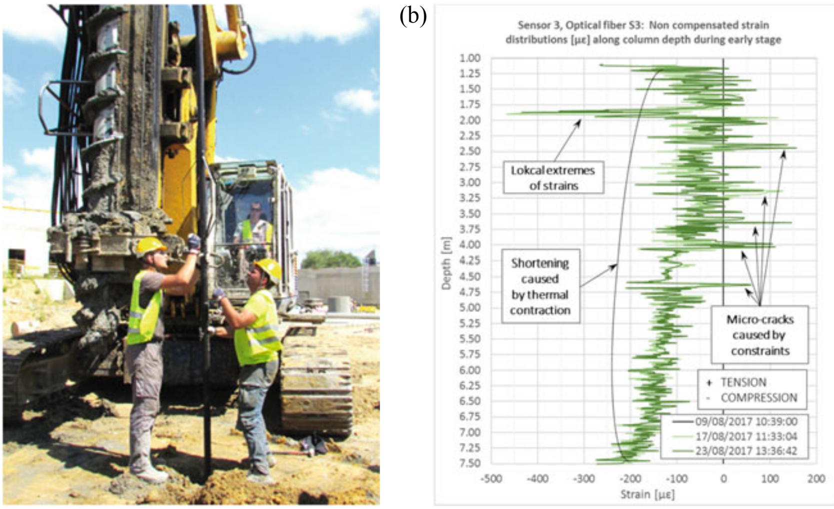


Fig. 8 **a** Installation of DFOS sensor inside CFA column, **b** exemplary strain distributions of early-age concrete

This is especially visible in the elements with reinforcement which is in fact additional internal constraint for the concrete. Thus, applying linear optical fibre sensor for early-concrete strain and temperature measurements along the whole column depth is very useful tool which allows for advanced structural condition assessment. With comparison with geological profiles, it is also possible to analyse cooperation of the column concrete with surrounding ground at selected depths. Optical fibres were also used for strain measurements during the load test of the CFA columns [13].

4 Conclusions

The pilot studies described in this article include comprehensive measurements of early-age concrete strains and temperatures on the examples of laboratory tests but also the pioneer in situ installations.

Strain and crack analysis of concrete structural members is crucial in the context of the assessment of their technical condition and safety [13] and this is especially challenging task for early-age concrete [10, 18], which behaviour depends on many factors and is not yet sufficiently investigated and described in the literature.

This is the reason why works and studies are ongoing to improve the methods used in this field. Based on the research carried out and presented in this article, it can be concluded that the distributed fibre optic sensor (DFOS) technology provides new opportunities in comparison with traditional spot measuring techniques (e.g. inductive, electrical resistance or vibrating wire spot sensors). It should be also emphasized that optical fibre sensors installed inside the structural members for early-age concrete strains measurements can be further used as a part of long-term structural health monitoring systems, significantly improving the possibility of structural condition assessment and thus safety of the structure and its performance.

Acknowledgements Authors would like to show gratitude to the SHM System company (Cracow, Poland, www.shmsystem.pl), which completed the project called "*Development of the new fibre optic sensor allowing for the determination of the vertical and horizontal displacements of the studied objects at the distances of up to 120 km*". This project was funded by the grant won at the National Centre for Research and Development within the framework of Intelligent Development Operational Program 2014–2020 (POIR.01.01.01–00-0550/15).

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