NDT-CE 2022 - The International Symposium
on Nondestructive Testing in Civil Engineering
Zurich, Switzerland, August 16-18, 2022

Distributed Fibre Optic Nerve-Sensors as Non-destructive Tool for Crack Detection and Widths Estimation

Rafał SIEŃKO[1], Łukasz BEDNARSKI[2], Tomasz HOWIACKI[3]*, Katarzyna ZDANOWICZ[4], Kamil BADURA[3]

[1] Faculty of Civil Engineering, Cracow University of Technology, Krakow, Poland
[2] Faculty of Mechanical Engineering and Robotics, AGH University of Science and Technology, Krakow,Poland
[3] Nerve-Sensors, Krakow, Poland, www.nerve-sensors.com
[4] Faculty of Geoengineering, University of Warmia and Mazury in Olsztyn, Poland
*Corresponding author, e-mail address: *tomasz.howiacki@nerve-sensors.com*

Abstract
In present times, due to the dynamic development of advanced technologies, the engineers are focused on designing smart infrastructure able for self-diagnostics. Distributed fibre optic sensing (DFOS) is one of the most promising techniques as it allows for direct local damage detection - for example, cracks in concrete structures. However, it is possible only when using appropriate monolithic sensors made of high-elastic composite. Such sensors create a system, which could be compared to the nervous system of the human body, informing about any threats at any point. Composite sensors resistant to corrosion, when integrated with the monitored structure, are a reliable solution for long-term monitoring and non-destructive testing, providing data from even thousands of measurement locations per one meter of the sensor.
The article describes the design of unique composite Nerve-Sensors dedicated to civil engineering and geotechnical applications. Non-destructive testing capabilities of these sensors were proven in hundreds of laboratory and in situ applications, including bridges, prestressed girders, roads, highways, collectors, pipelines, embankments, and many other smart structures. Selected case studies focused not only on crack detection but also on the estimation of their width, are described hereafter in the article.
Keywords: Strain measurements, distributed fibre optic sensing, DFOS, crack detection, structural health monitoring

1 Introduction

Distributed fibre optic sensing (DFOS) is nowadays becoming an optimal solution for many cases when structural health monitoring and non-destructive testing are needed [1, 2]. The DFOS technology enables to obtain measurement data from the whole length of the sensor instead of gaining information only in previously chosen points, as it is with conventional spot sensors used in civil engineering. Therefore a significant drawback of measurements with spot sensors, such as electrical strain gauges or vibrating wire strain sensors is being eliminated. Not only it is no longer necessary to define points where strain readings will be performed, but also the distributed measurements provide an opportunity to precisely detect cracks of concrete structures and to calculate and assess the crack widths. Both of these information are extremely important for long-term monitoring purposes. The aim of this article is to present the main principle of the composite fibre optic sensors and to describe selected laboratory and in situ applications in order to provide some insights about the possibilities of this technology.

2 Composite fibre optic sensors

2.1 Strain sensing with optical fibres

Strain sensing with optical fibres is feasible because of light scattering. Three main types of scatterings, namely Rayleigh, Brillouin and Raman scatterings are being utilised to obtain strain or temperature distribution over the length of the sensors [3]. Rayleigh scattering, which was used for all examples described in this article, is measured by an optical backscatter reflectometer as a function of length in a given optical fibre. Rayleigh backscatter is caused by random fluctuations in the refractive index along an optical fibre (Fig. 1). Spectral shifts in the reflected spectrum are a result of changes in the local period of the Rayleigh scatter. Because of these optical phenomena, local changes of mechanical and temperature strains can be recorded during subsequent measurements.

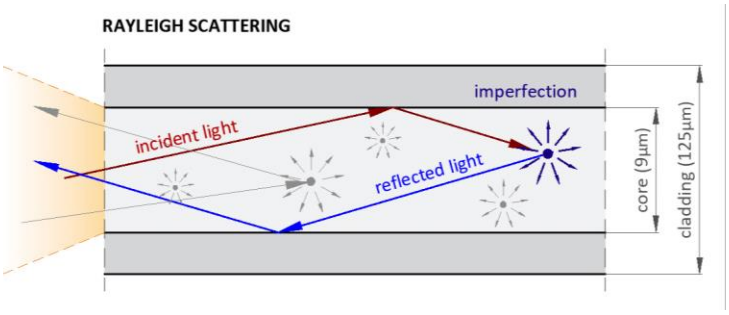

Figure 1: Schematic presentation of the Rayleigh scattering inside an optical fibre [4]

2.2 Crack detection and widths estimation

The main advantage of using distributed fibre optic sensing for strain measurements is its ability to detect cracks and estimate their widths. In such a way DFOS is an alternative method not only for conventional spot strain measurements, but also for crack detection methods such as digital image correlation (DIC) and photogrammetry [5]. During subsequent DFOS measurements, appearing cracks are visible as local increases of strain values, or strain peaks. If the crack is developing, strain peak values tend to increase, if the crack is closing it might be visible as a decrease in peak strain values. By analysing strain measurements it is possible to detect cracks which are not yet visible neither with an unarmed eye nor with a DIC method.

Another possibility is the estimation of crack widths. Assuming that reference measurements were performed before any cracks occurred and integrating the strain curve between two points at both sides of a crack, i.e. calculating the surface under the strain curve in the near proximity of a given crack (designated as $l_{eff,}$ in Fig. 2), crack width can be directly estimated. On structures which are already cracked it is still possible to calculate the changes in the widths of the existing cracks, so that information can be obtained if the cracks are developing further, remaining unchanged or closing.

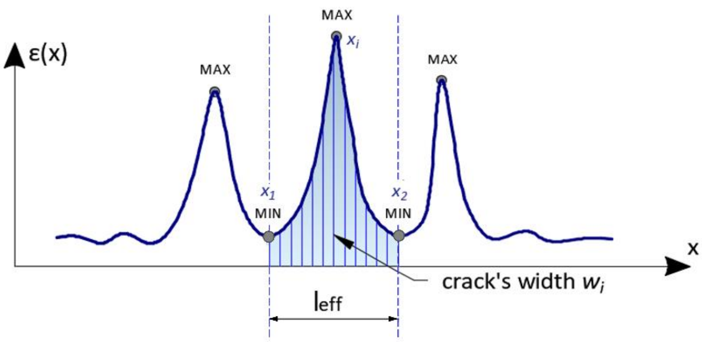

Figure 2: Estimating crack width by integration of the strain curve

Possibility of reliable crack detection and evaluation is of utmost importance in case of structural health monitoring and non-destructive testing of concrete structures and it needs to be highlighted that DFOS technology enables measurements and analyses which were not achievable before using a single technology – to measure strains and crack widths and spacing simultaneously.

2.3 Composite sensors

DFOS measurements can be performed with various types of optical fibres. In fact, the core of the fibre is usually the standard telecom single mode fibre with a glass core, while the coating and cladding layers differ. Among the most popular coatings acrylate, nylon, polyimide and Ormocer coatings can be mentioned. All of them have a diameter of max. 0.2 mm and are rather susceptible to mechanical damages. Therefore their application area is substantially limited for laboratory and precise purposes, not for typical civil engineering site conditions.

On the other hand, various strain sensing optical cables are available on the market, coming mainly from the aircraft and spaceship industries. They are robust, but most of them consist of multiple layers what makes it extremely difficult to ensure that strains from the measured structure were fully transferred to an optical fibre inside such cable. Another issue is the presence of steel protective elements inside some of the cables, which significantly reduces their sensing range. In such sensors, after reaching steel yielding strains at approximately 0.2% local plastic deformation occur and reliable strain measurements are not longer possible.

This is the reason why it was important to develop optical sensors suitable for the special needs of the civil engineering industry. First of all, they needed to be robust enough to sustain the site conditions, but also lightweight and easy to apply on various surfaces and in various mediums. Secondly, it was of utmost importance to avoid any layers and to obtain a monolithic cross-section of the sensors, in order to ensure reliable strain transfer without slippage between layers. Finally, also good bond conditions and durability in alkaline environment were necessary to achieve the possibility of placing these sensors inside concrete members. These conditions were fulfilled by developing and producing entirely composite sensors with a threaded external surface.

Two types of sensors for strain measurement and one for displacement measurements are available at this time point. Strain sensors, the so-called *EpsilonSensors* and *EpsilonRebars* are presented in Fig. 3, with their properties summarised in Table 1 [6, 7]. Both of them are suitable for strain measurements in broad range of applications, because of their high elastic strain range and mechanical parameters. *EpsilonSensor* has a negligible diameter of 3 mm and a low elasticity modulus of 3 GPa, which results in low stiffness and low impact on the measured structure. *EpsilonRebar* has higher diameter and a modulus of elasticity comparable with standard GFRP rebars, thus it can be used as a reinforcing bar and sensing element simultaneously.

The optical sensor for distributed displacement measurements is called a *3DSensor* and its principle is based on using several optical fibres located precisely inside a core of the sensor in a known distances. Basing on an algorithm described in [8], displacement profile in three dimensions can be calculated along the whole length of the sensor. This type of a distributed fibre optic sensor is a unique solution which finds multiple application cases in civil, structural and geotechnical applications.

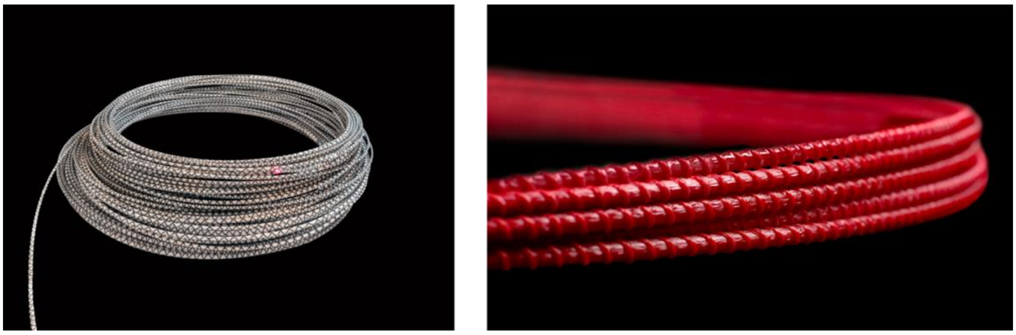

Figure 3: Composite DFOS sensors: EpsilonSensor (left), EpsilonRebar (right) [6, 7]

Table 1: Composite DFOS sensors – technical data [6, 7]

Property	**EpsilonSensor**	**EpsilonRebar**
Strain measurement resolution	1,0 μm	1,0 μm
Strain measurement range	± 4%	± 2%
Operating temperature	-20°C to +100°C	-20°C to +100°
Sensor dimensions	3 mm	5-20 mm
Modulus of elasticity	3 GPa	50 GPa

2.4 Comparison with layered sensing cables

With an aim to better visualise the differences between monolithic, composite DFOS sensors and layered sensing cables an extensive experimental research programme has been carried out [9], some of its findings are summarised hereafter. The experimental investigations were carried out on 4-meter-long, simply supported, beams subjected to flexural loading, equipped with both EpsilonSensors (ES), EpsilonRebars (ER) and two types of commercially available sensors (designated C1, C2). The visualisation and arrangement of the sensors is shown together with a photo in Fig. 4.

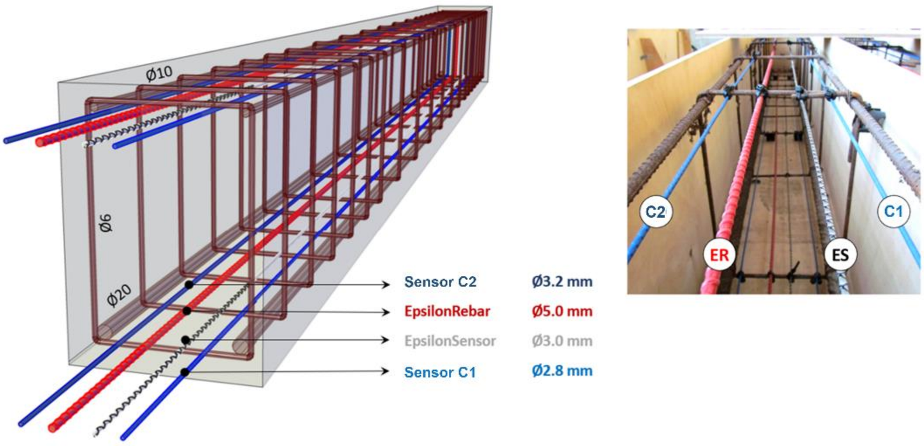

Figure 4: Visualization and arrangement of the sensors (left) together with a photo before concreting (right) [9]

After flexural loading of the beams, it was found that the ability to detect cracks in reinforced concrete beams was significantly dependent on the type of DFOS sensors used. With ES and C1 it was possible to determine the cracks with a high accuracy. The ER sensors have too high stiffness for such a small member size, cracks are detected yet the results are better with ES sensors at this scale. The C2 sensors could not detect any cracks at all (Fig. 5). Fig. 6 shows a direct comparison of C1, C2 and ES sensors in a beam in the last loading phase, where relatively high strains are induced. The left side shows the entire beam length, while the right side shows an enlargement of a chosen crack. It was observed that the C1 sensor works properly up to a certain strain level, after which slippage and detachment occur, and the area of the detected crack becomes wider. It is noteworthy that all these cracks developed under static loading. Therefore, the open question remains about the possible differences under cyclic or dynamic loading with higher frequency.

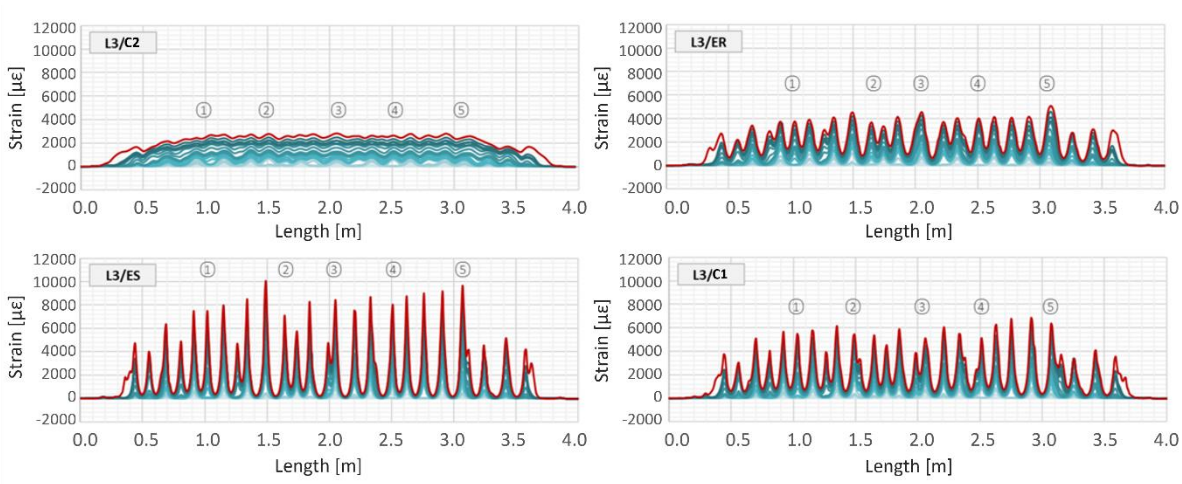

Figure 5: Comparison of measured strains along the beam and crack detection with various DFOS sensors [9]

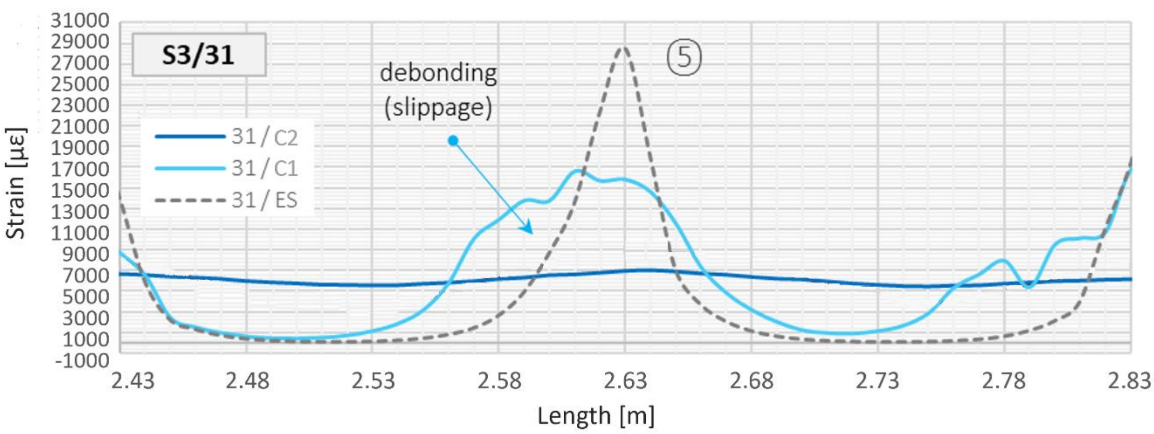

Figure 6: Comparison of strains measured with various sensors: a) total length of the beam, b) close up view to one of the cracks where slippage occurs [9]

3 Non-destructive testing capabilities

3.1 Laboratory testing of truck scale platforms

The first example presented describes truck scale platforms used for weighing of the trucks and car vehicles. Their main structural element is a platform (slab), which transfers the load from the trucks via measuring devices to the foundations. Between 2012 and 2014, truck scales made of partially prestressed concrete were manufactured and used in Poland as an alternative solution to conventional corrosion-prone steel structures or non-prestressed concrete structures [10]. In these prestressed slabs, fibre optic sensors were installed in the concrete near the prestressing strands and also glued to the surface of the slabs. The aim was to investigate the strains in the initial phase of the manufacturing of the platforms as well as the development of the strains during the activation of the tendons and during load tests under laboratory conditions.

Figure 7 shows the geometry of the platforms and the positions of the sensors in the cross-section. Eight prestressing tendons were installed in the lower part of the cross-section and two prestressing tendons in the upper part. In addition to the strain sensors, additional optical fibres for temperature measurement (5, 6) were freely installed in polyamide sleeves so that they were decoupled from mechanical stress.

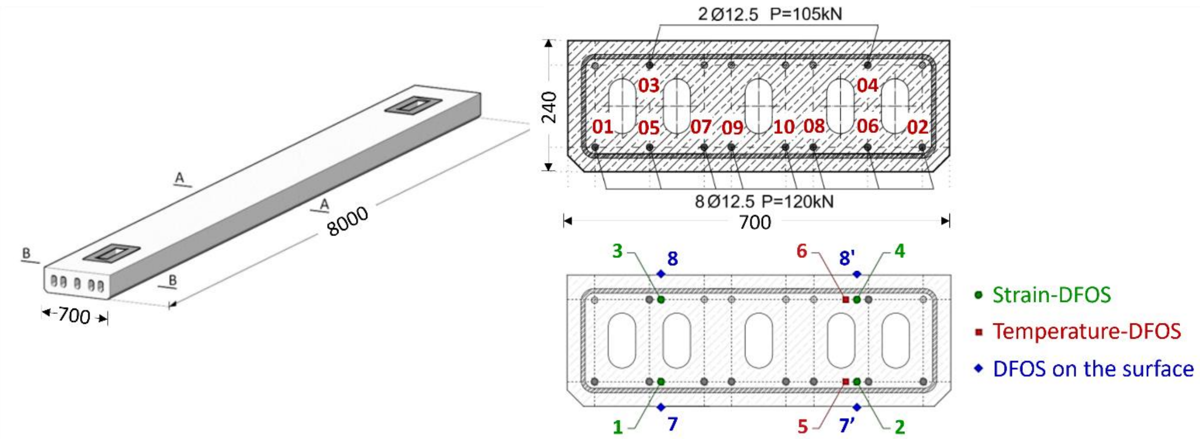

Figure 7: Geometry of the slab and the locations of the sensors in the cross-section [10]

Measurements were started immediately after the platforms had been concreted. In the first phase, strains and temperature were recorded every 30 minutes during the first day of the concrete hydration. In the next phase, all prestressing strands were activated to generate compressive stress in the slabs. The tendons were cut following their numbering and the measured strain distribution along the slabs is shown for the successive activation of tendons T01 to T10 in Fig. 8 (for the fibre optic sensors located near lower (2) and upper (4) tendons). Lastly, platforms were transported to the laboratory and subjected to four-point bending tests, for which additional optical fibres were attached to the surface of the platforms (Fig. 9). Furthermore, vibrating wire strain sensors were installed on the lower and upper surface of the platforms as reference measurement methods, which locally confirmed the values measured by DFOS.

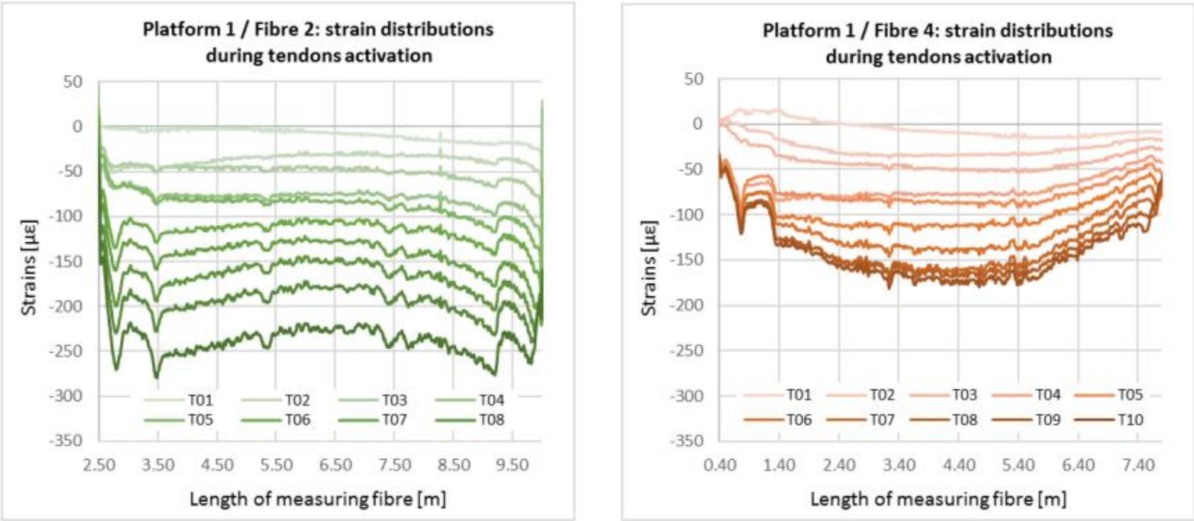

Figure 8: Strain distribution along slab 1 during consecutive activation of tendons T01 - T10, for the fibre optic sensors located near the bottom (left, fibre 2) and top (right, fibre 4) tendons [10]

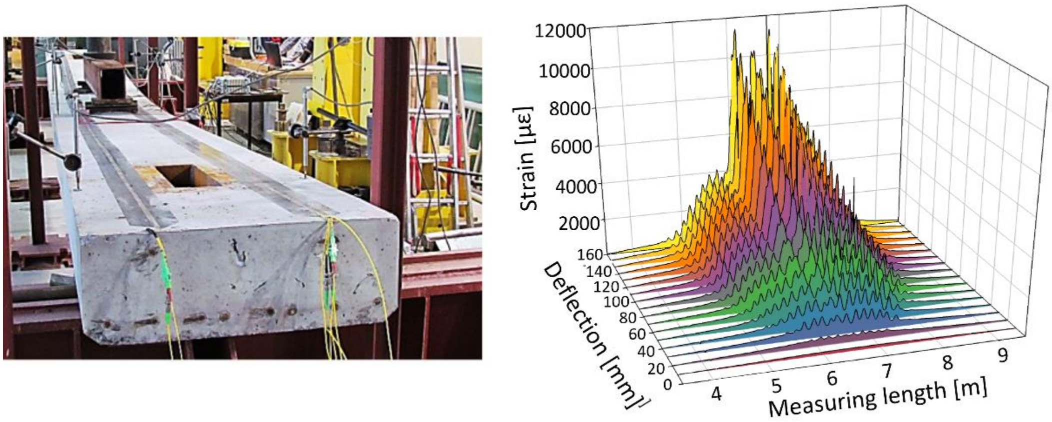

Figure 9: Slab under 4-point bending tests (left) and the strain profile for a selected load level measured with DFOS at the bottom surface of the slab (right) [10]

3.2 The Redzinski Bridge

The Redzinski Bridge in Wroclaw is a bridge with the highest pylon in Poland (reaching 122 m) [11]. Figure 10 shows the prestressed girder supporting two independent deck slabs of the bridge. The slabs are suspended from the main pylon of the bridge. To assess the existing cracks of the prestressed girder, the girder was equipped with four EpsilonRebar DFOS sensors on both sides of its cross-section near the top and bottom surfaces of the girder [12]. The length of the sensors ranged from 35.5 m to 38.5 m and had a diameter of 6 mm. The EpsilonRebars were chosen because of adequate stiffness (E = 50 GPa) and ease of installation. All sensors were installed in grooves (approximately 8 mm × 10 mm) that were cut along the girder, cleaned of any dust, and grouted with injection mortar after the sensors were in place. In such a way, the EpsilonRebars were well integrated into the girder, as well as well protected from external impacts and environmental influences. An EpsilonRebar sensor and its installation procedure are shown in Fig. 10. In addition, temperature sensors were installed to compensate for the temperature effects during strain measurements.

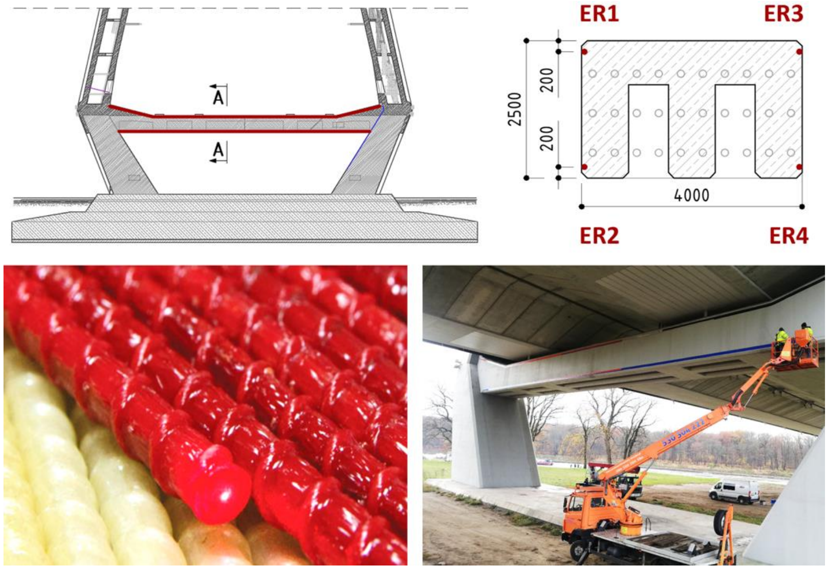

Figure 10: Geometry and location of the sensors on the investigated girder (top), EpsilonRebar close-up (bottom left) and installation process (bottom right) [12]

First of all, multiple measurements were taken subsequently while the bridge was under continuous traffic, what allowed for identification of the locations of existing cracks. Although the measurements were made within a few minutes only, the local peaks of the strains are clearly visible and it can be observed how the existing cracks work: closing (positive strain values) and opening (negative values), Figure 11. By integrating the area under the curves, the changes of the crack widths under random traffic load can be calculated, exemplary results for a selected area between 9.5 and 15.5 m are also presented in Figure 11. Further measurements and investigations of cracking of this bridge are planned for the near future.

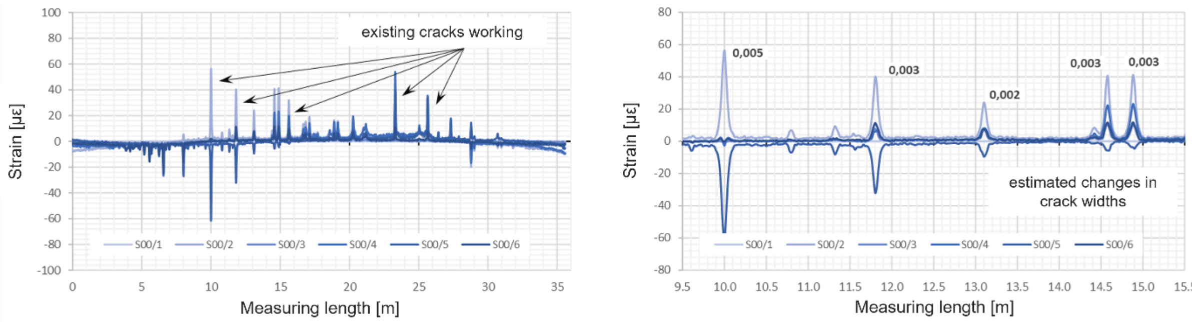

Figure 11: The strains of ER2 sensor measured in 6 subsequent measurements, within few minutes: total length of the girder (left) and a close up to area between 9.5-15.5 m (right) [12]

3.3 The steel truss bridge with concrete slab over the Notec river

A 90 m long steel truss bridge with a concrete slab was built for the crossing of the Notec river in Poland. During construction of the concrete slab, EpsilonRebars were embedded in the slabs over their entire length. They were delivered on-site in coils and fixed to the existing passive reinforcement near the main prestressing tendons. The location of the fibre optic sensors and the cross-section and view of the bridge are presented in Figure 12. Such system was implemented for two purposes – as a reliable measuring solution for short-term load tests on the bridge and also as a structural health monitoring system for long-term purposes.

Figure 12: Photo (left) and cross-section (right) of the steel truss bridge with designated location of the DFOS sensors

Strain results were obtained with EpsilonRebars with extremely high spatial resolution, therefore they allowed for a detailed structural performance analysis. The strain curve in Figure 13 shows the results from the load tests performed on the 90 m long bridge. Strain profiles exactly correspond to the geometry of the truss superstructure, influence of each of the spans and truss nodes can be visible on the strain distribution profiles.

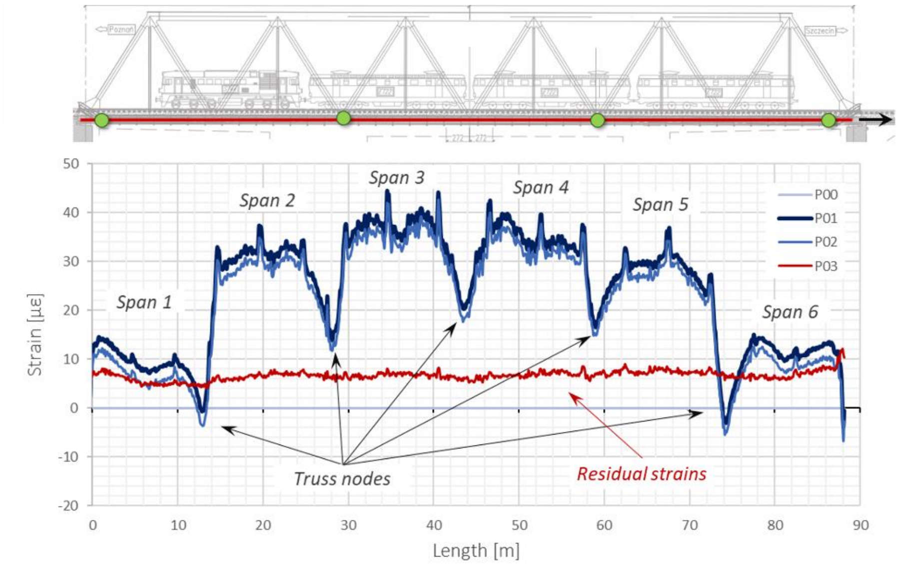

Figure 13: Strain distribution along the bridge during load test

4 Summary

The aim of this article was to highlight the possibilities of distributed fibre optic sensing in civil engineering and geotechnical applications and non-destructive testing. The design and idea behind composite DFOS sensors was described and this type of sensors were compared with other commercially available fibre optic solutions. The possibilities of crack detection and estimation of crack widths which are offered by DFOS sensors allow to obtain much more information about the structural behaviour of a structure than it was possible ever before. Although only several chosen projects have been briefly presented, the composite sensors have already been proven in numerous laboratory and in-situ applications, including bridges, prestressed girders, roads, highways, collectors, pipelines, embankments, and many other structures. Composite sensors are a reliable solution for short-term measurements, long-term monitoring and non-destructive testing, providing data from up to thousands of measurement locations per one meter of the sensor in a distributed way.

References

[1] F Sakiyama, F Lehmann, H Garrecht 'Structural health monitoring of concrete structures using fibre-optic-based sensors: a review', Magazine of Concrete Research 73, Nr. 4, pp 174–194, 2021, DOI: 10.1680/jmacr.19.00185

[2] A Barrias, J R Casas, S Villalba, 'A review of distributed optical fiber sensors for civil engineering applications', Sensors 16, Nr. 5, 748, 2016, DOI: 10.3390/ s16050748

[3] A H Hartog, 'An introduction to distributed optical fibre sensors', CRC press, London, United Kingdom, 2017

[4] T Siwowski, M Rajchel, T Howiacki, R Sieńko, Ł Bednarski, 'Distributed fibre optic sensors in FRP composite bridge monitoring: Validation through proof load tests', Engineering Structures, Vol. 246, 113057, 2021, DOI: 10.1016/j.engstruct.2021.113057

[5] J Mata-Falcón, S Haefliger, M Lee, T Galkovski, N Gehri, 'Combined application of distributed fibre optical and digital image correlation measurements to structural concrete experiments', Engineering Structures 225, 111309, 2020 DOI: 10.1016/j.engstruct.2020. 111309

[6] Nerve-Sensors [eds.] 'EpsilonSensor Technical Data' [online], https://nerve-sensors.com/product/epsilonsensor [Accessed on: 30.06.2022]

[7] Nerve-Sensors [eds.] 'EpsilonRebar Technical Data' [online], https://nerve-sensors.com/product/epsilonrebar [Accessed on: 30.06.2022]

[8] Ł Bednarski, R Sieńko, M Grygierek, T Howiacki, 'New Distributed Fibre Optic 3DSensor with Thermal Self-Compensation System: Design, Research and Field Proof Application Inside Geotechnical Structure', Sensors 21, Nr. 15, 5089, 2021, DOI: 10.3390/s21155089

[9] T Howiacki, 'Analysis of cracks in concrete structures with the use of distributed optical fibre measurements', PhD Thesis, Faculty of Civil Engineering, Cracow University of Technology, Poland (in press), 2022

[10] R Sieńko, Ł Bednarski, T Howiacki, 'About Distributed Internal and Surface Strain Measurements within Prestressed Concrete Truck Scale Platforms', IOP Conf. Series: Materials Science and Engineering 471, 052074, IOP Publishing, 2019, DOI: 10.1088/1757-899X/471/ 5/052074

[11] J Biliszczuk, W Barcik, J Onysyk et al., 'Redzinski Bridge in Wrocław – the largest concrete cable-stayed bridge in Poland', Structural Engineering International 24, Nr. 2, pp 285–292, 2014

[12] T Howiacki, R Sieńko, 'Report on deformation and crack measurement of the prestressed beam of the pylon of the Redzinski Bridge in Wrocław using DFOS measurement technology' (in Polish), pp 1–29, Internal report, not published, 2020