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Smart prestressed concrete girders with integrated composite distributed fibre optic sensors (DFOS): monitoring through all construction stages

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ABSTRACT: Distributed fibre optic sensing (DFOS) is a promising technology for many industries, mainly due to its ability to measure selected physical quantities continuously over entire fibre's length. This feature is directly responsible for the possibility of local damage detection, what is one of the main requirements for structural health monitoring (SHM) systems. Thus, in recent years, more and more practical examples of DFOS-based systems can be observed in civil engineering and geotechnical applications. However, to utilize all benefits coming from such an approach, several technical aspects should be carefully taken into account, including the sensor construction (its type) or way of installation (bonding properties). The paper discusses a real case study of prestressed concrete girders with the length of 24 meters, equipped with composite DFOS strain sensors during production stage. Composite sensors with monolithic cross section (unlike commonly used layered sensing cables) were embedded into the concrete. Bonding properties responsible for accurate strain transfer mechanism were ensured by external spiral braid, analogously like for composite reinforcing bars. Strain and temperature measurements were performed during the most important stages of construction lifetime, including hydration process (thermal-shrinkage strains), prestressing (tendons activation in order to transfer the compressing force to the concrete), activation of structural dead-weight (as a direct consequence of prestressing phase), installation within the structure (mounting stresses) as well as during the proof load tests. Thanks to the large number of distributed sensors located at selected heights of the girders, detailed analysis of strain profiles was performed during each construction stage. What is more, it was possible to identify all local cracks and analyze their behaviour over time (development during hydration process and closing during prestressing phase). The construction and parameters of applied DFOS sensors, way of their installation, specifications of data acquisition system, strain measurement results from selected construction stages and finally the most important findings are presented hereafter.

KEY WORDS: DFOS, distributed measurements, composite sensors, prestressed girders, strains, crack detection, temperature.

1 INTRODUCTION

1.1 *Structural health monitoring*

Structural health monitoring (SHM) is a process of gaining knowledge about the changes in safety-critical structural parameters over time [1, 2], aimed at making optimal decisions [3, 4] – Fig. 1. Having objective information on the current state of the structure (for example stress level, crack state, deflection etc.), it is possible to rationally plan the renovation strategy and maintenance procedures.

What is very important, this process is not a one-off as in the case of periodic inspections, but it applies to the entire life cycle of the structure [5, 6], bringing engineering and economic benefits over the long term.

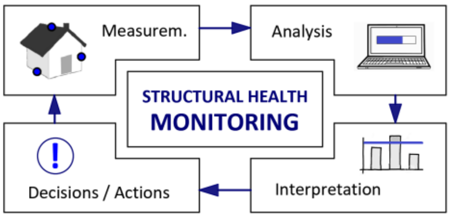

Figure 1. Structural health monitoring process.

Structural monitoring provides much more comprehensive information in comparison to laboratory researches under strictly controlled conditions. In situ measurements includes all factors like temperature and humidity changes, foundation settlements, random actions and many others. Thus, data interpretation must always be performed with a special care. Nowadays, monitoring process is usually supported by numerical (FEA) calculations and probabilistic theory [7], but still one of the most important aspects is the efficiency of both the sensors themselves and measuring techniques.

1.2 *Distributed fibre optic sensing DFOS*

One of the most promising measurement technologies, which could be successfully applied within civil engineering [8] and geotechnical applications [9], is distributed fibre optic sensing (DFOS) [10, 11]. The main advantage of DFOS over conventional spot measurements performed in selected structural points, is the possibility of performing measurements continuously over entire length of optical fibre sensor – Fig. 2.

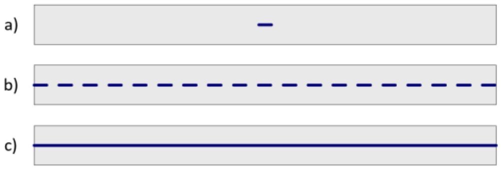

Figure 2. a) Spot, b) quasi-distributed and c) distributed sensing approach.

Modern optical dataloggers (reflectometers, interrogators) are able to provide extremely high spatial resolution [12] – what means even 1,000 measuring points per one meter of DFOS sensor. Thanks to this feature, finally it is possible to meet one of the main demands [13] made on SHM systems – local damage detecting, e.g. cracks [14, 15] in concrete structures.

It is worth mentioning that nowadays many advanced measurement techniques are being developed to obtain a full-picture of structural behaviour over entire length. They include methods based on image processing [16], characterized in many advantages like two-dimensional (surface) analysis. However, they cannot be yet successfully applied in the frame of structural health monitoring in real in situ conditions over long term.

1.3 *Prestressed concrete girders*

Reinforced concrete structures are one of the most commonly used in civil engineering structures due to the wide list of their advantages, including high resistance to corrosion, high durability, low operational costs or possibility of any geometry design. One of their main disadvantages is high dead weight, which could be, however, overcome by prestressing approach [17]. Providing compressing force to tensile areas allows for designing structural members which are much more slender, lightweight, stiff and durable. Therefore, such structures are very often operated under high loads and harsh environmental conditions [18].

On the other hand, to utilize all benefits coming from prestressing technology, it is necessary to provide a special production requirements and technology regime [19]. Control of this process is of the great importance, especially taking into account that final concrete parameters strongly depends on its early-age behaviour [20] (hydration, thermal-shrinkage strains, microcracks, curing).

A real case study of prestressed 24m length concrete girders equipped with DFOS measurement system is discussed hereafter. The drawings and the view of analyzed girders are shown in Fig. 3 (side view) and 4 (front views).

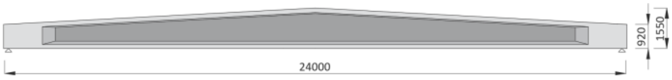

Figure 3. Side view of monitored prestressed-concrete girder.

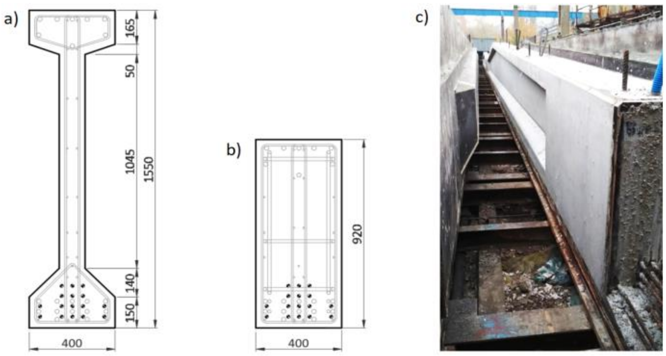

Figure 4. a) Midspan, b) front cross section and c) side view of monitored prestressed-concrete girder.

DFOS technique seems to be very promising tool for controlling the behaviour of prestressed concrete structures starting from a real zero state. This is because sensors can be installed before concreting (embedded into concrete). Usually, sensors in frame of long-term structural health monitoring systems are installed on the surface of existing structures. As a result, there is no possibility to include into analysis early-age concrete strains and microcracks, prestressing forces, dead weight or mounting stresses. All these aspects are crucial in the context of concrete component strength and durability.

The smart prestressed concrete girders described in the paper are currently under operation in one of the polish production halls – Fig. 5. Their technical assessment is performed taking into account phenomena measured with distributed fibre optic sensors during production stages.

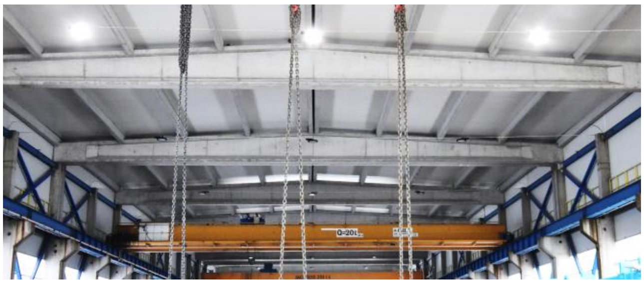

Figure 5. The view of analyzed smart girders under operation within production hall.

2 DFOS SENSING SYSTEM

2.1 *Rayleigh scattering*

There are a few DFOS-based techniques characterized in their own advantages and limitations, which should be individually selected depending on requirements of a given project. For example, Rayleigh-based systems [21] are adequate for short distances where high spatial resolution and damage detection are the most important aspects. On the other hand, Brillouin-based systems [22] are more suitable for km-distance projects, while Raman-based system are dedicated just for temperature measurements.

DFOS system integrated with analyzed girders was read using Rayleigh-based system ensuring 100 measuring points per one meter of the sensor and thus local cracks detection. Rayleigh scattering occurs in each section of the fibre [24] as a result of local fluctuations in the refractive index [25]. This is accompanied by light scattering in all directions, also including the backscattering (Fig. 6).

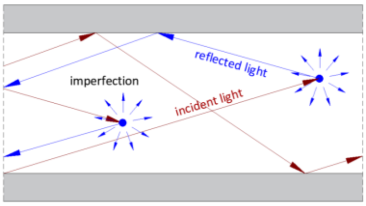

Figure 6. The simplified idea of Rayleigh scattering phenomena in the measuring optical fibre.

The dispersion amplitude is a random but constant property for a given fibre and it could be compared to its unique fingerprint [26]. Nowadays, the recording and analysis of this phenomena is performed using advanced optical reflectometers or interrogators, which then convert raw data to engineering units (strain and/or temperature).

2.2 *Optical reflectometer*

In all measurements described hereafter, optical backscatter reflectometer OBR4600 by Luna Innovations was applied – Fig. 7a. Selected measuring parameters important for data analysis are summarized in Table 1. Due to the application of multiple fibre optic sensors inside the smart girders, an optical switch was used to facilitate and accelerate the measurements – Fig. 7b.

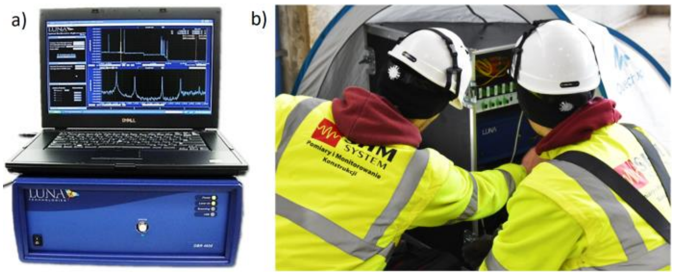

Figure 7. Optical backscatter reflectometer OBR4600:
a) general view [27], b) the view during measurements.

Table 1. Luna OBR4600 optical backscatter reflectometer – selected technical specifications.

Parameter	Value	Unit
Distance range (standard mode)	up to 70	m
Spatial resolution (gauge spacing)	10	mm
Gauge length	10	mm
Strain measurement resolution	±1.0	mm

2.3 *DFOS strain sensors – EpsilonRebars*

The most important aspect for final measurement accuracy and reliability, besides the DFOS technique itself, is appropriate selection of measuring tool. This tool should ensure accurate strain transfer from the monitored structure to the glass measuring optical fibre.

For laboratory researches, optical fibres in different types of their primary coatings are usually applied [28], but due to their negligible dimensions and brittleness, they cannot be applied in real operating conditions.

Thus, for in situ projects other solutions need to be applied, including layered sensing cables or monolithic sensors. Sensing cables are usually made of plastic and steel layers arranged around the central optical fibre. Such materials have very limited elastic range and are susceptible to debonding and slippage phenomena between particular layers. Thus, advanced mathematical models should be applied for data analysis [29] what significantly increases the total measurement uncertainty. Especially within the cracked areas with extreme high strain values. In practice, sensing cables could be applied for long distance projects with m-order spatial resolution, which allow to average all local disturbances.

For analysis of very localized events (such as cracks), monolithic, composite sensors should be used [30]. They ensure very large elastic strain range providing proper operation of the sensor even within the cracked area. What is more, the optical fibre is integrated with composite core during pultrusion process creating fully monolithic cross section. No layers mean no debonding (slippage) effect and thus accurate strain transfer mechanism [31].

To manufacture smart prestressed concrete girders, optical sensors called EpsilonRebars (ER) by SHM System was selected and applied – Fig. 8a. These sensors (from Composite-DFOS series) have a form of composite reinforcing bars with external spiral braid (Fig. 8b) ensuring appropriate integration (bonding) with the concrete.

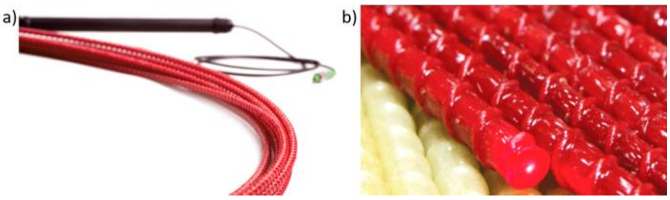

Figure 8. Composite-DFOS strain sensor EpsilonRebar:
a) general view; b) close up for external surface [32]

Selected parameters of applied EpsilonRebars are summarized in Table 2.

Table 2. EpsilonRebar – selected technical specifications [33].

Parameter	Value	Unit
Strain resolution	1	με
Strain range	±20 000	με
Operating temperature	-20 to +60	°C
Nominal diameter	6	mm
Attenuation	≤0.5	dB/km
Material	GFRP	
Cross section	Monolithic (no layers)	
Length	Any as ordered	
Delivery	Coils, straight sections	
Scattering	Rayleigh, Brillouin, Raman	

2.4 *Sensors arrangement and installation*

Sensors were delivered to the manufacturing hall in form of coils cut to the appropriate length. The installation only required the DFOS sensors to be tied to the existing reinforcement using zip ties – Fig. 8. It was very important to ensure compliance of sensors' positions with the designed traces, because this directly influences the final accuracy and data interpretation. Thanks to the low self-weight and appropriate stiffness of EpsilonRebars, the installation process could be carried out efficiently and quickly.

A total of 8 EpsilonRebars were installed, whose arrangement in the girder cross section is shown in Fig. 9. Each sensor has a length of 24 meters and assuming the 10mm spatial resolution, it means that during one measurement session a total number of 19,200 strain measuring points is obtained. What is more, 3 additional DFOS-temperature sensors were installed (see also section 2.5) over entire length to provide thermal compensation during long-term girders operation in real conditions.

Figure 8. Installation of EpsilonRebars to the existing reinforcement of smart prestressed-concrete girder – side view

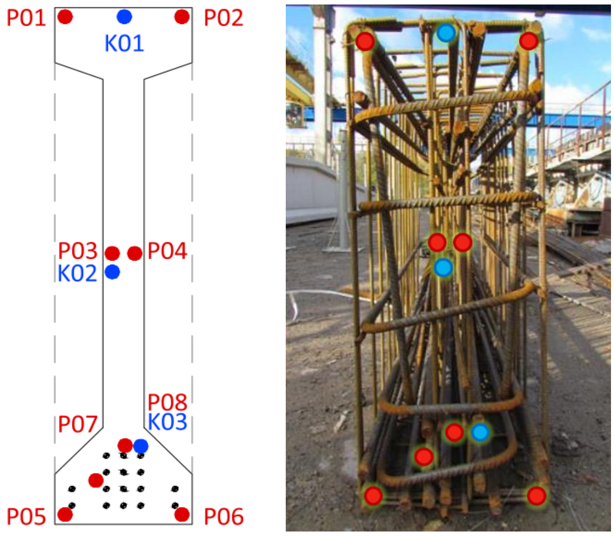

Figure 9. Arrangement of EpsilonRebars (P) and temperature sensors (K) within smart girder: cross section and front view

2.5 *Thermal compensation*

Influence of temperature changes on strain measurements is very often ignored during laboratory or short-term measurements under stable external conditions. However, this is very important factor in long-term structural monitoring of real engineering structures [34].

Also, temperature field is changing rapidly during hydration process of early-age concrete and thus the knowledge about temperature changes is necessary for correct interpretation of measured strains, which are the sum of thermal expansion effect and mechanical actions [35].

In smart prestressed concrete girders, 3 temperature DFOS-sensors were installed. Their basic operation principle is based on isolating the measuring fibre from mechanical effects through its free placement inside the plastic tube.

It is also worth mentioning that there are also other known methods for thermal compensation involving Raman-based devices, hybrid Rayleigh-Brillouin systems [26] or conventional spot thermistors.

3 MEASUREMENTS

A total of 3 smart girders with DFOS systems were manufactured, but in the further part of this paper only example results are presented for girder no. 3 and selected EpsilonRebars. However, results obtained for other girders and sensors are analogous in nature.

3.1 *Ealy-age concrete*

The first stage of research involved analysis of early-age concrete behaviour during its hardening. Zero readings were taken just after concreting – Fig. 10.

Figure 10. The view of smart girder just after concreting

Hydration process is accompanied by both shrinkage phenomena and thermal shortenings. Concrete mixture is transformed into solid concrete at high temperatures and then there is a gradual decrease in temperature. In case of simply supported beam, uniform temperature decrease will cause just the shortening of the element without generating any stress. However, due to the internal (reinforcement) and external (formworks) constraints, concrete free strains in the analyzed girders are limited, generating tensile stress and then microcracks – Fig. 11.

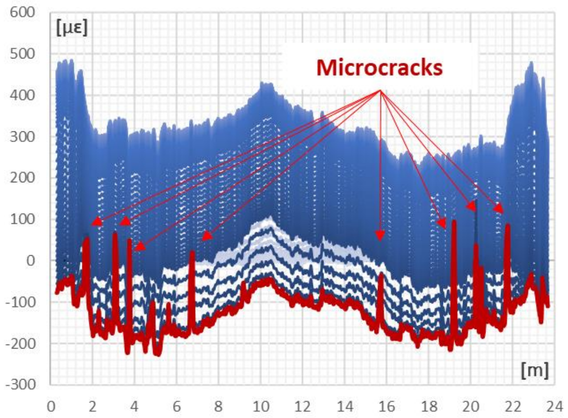

Figure 11. Strain distributions over length during first 2 days of concrete hardening – sensor no. P03

The widths of generated microcracks were estimated to be less than 0.01mm, which is very low value. However, these cracks could increase their width under higher mechanical loads and thus they directly influence the final durability of structural member. This is especially important for reinforced concrete structures, where there is no chance to close the cracks through prestressing (compression) force.

Effect of microcracks appearance in analyzed girders was especially visible for sensors P03 and P04 located within the web close to the neutral axis, while for other sensors (see example in Fig. 12) no cracks were observed.

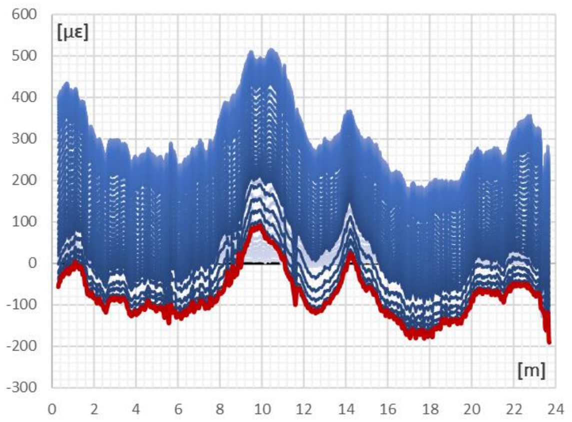

Figure 12. Strain distributions over length during first 2 days of concrete hardening – sensor no. P05

3.2 *Prestressing phase and mounting stress*

The second very important construction stage of the analyzed girders was prestressing (steel tendons activation). Because most of the tendons are located in the lower flange (Fig. 4, Fig. 9), their activation will bend the girder up and then activate its dead weight at the same time.

The zero measurement for this stage was taken just before cutting the first tendon off. Later, measurements were performed step by step after cutting each subsequent tendon. Strain distributions corresponding to this phase of research are presented by blue lines in Fig. 13 and 14.

Prestressing process cause the transfer of compressing force from steel tendons to the concrete within whole cross section, but this effect was stronger in the lower part due to the presence of a larger number of tendons (Fig. 13).

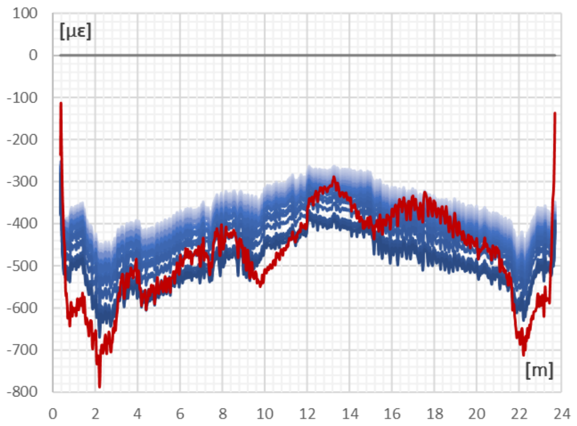

Figure 13. Strain distributions over length during tendons activation (blue lines) and after installation within the structure (red line) – sensor no. P05

Compressing force transferred during prestressing caused that all early-age microcracks were closed – Fig. 14. This is very favorable phenomenon in the context of the final durability of structural member. Such detailed information about crack state of analyzed member and its changes over time is extremely valuable for designers and inspectors.

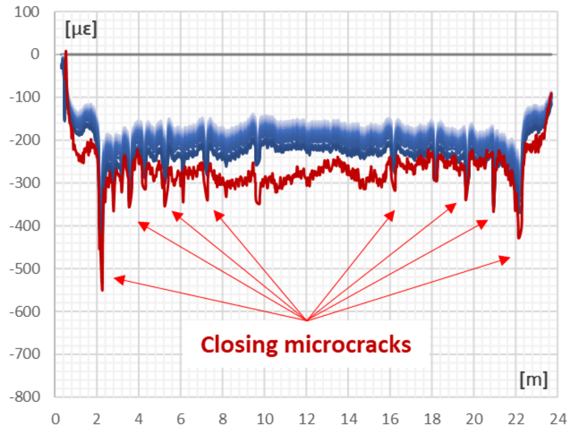

Figure 14. Strain distributions over length during tendons activation (blue lines) and after installation within the structure (red line) – sensor no. P03

It is worth mentioning, that closing the cracks will not happen in case of conventional reinforced concrete structures. Thus, it is advisable to equip also such members with DFOS-composite strain sensors, which can significantly support their technical condition assessment.

After prestressing, girders were transported to the construction site and built into the structure – Fig. 15. Measurements done after installation (see red lines in Fig. 13 and 14) allow for answering the question about the mounting stresses, which are very often omitted in structural analysis. It could be seen that there were no significant changes in strain state after girders installation, mainly because their deadweight was activated earlier during prestressing phase.

Figure 15. The view of smart girders during construction stage

3.3 *Proof load tests*

The last analyzed stage was proof load tests before commissioning the production hall. Smart girders behaviour was investigated under known mechanical loading. Three concrete blocks, each of 3,200kg, were suspended to the girders using steel chains – see Fig. 16. Zero measurement for this stage was done just before loading. Subsequent readings were taken after suspension of each block. Obtained strain distributions corresponds to the results of standard strength-static calculations done analyticity or numerically (with finite element analysis FEA). Thus, this data could be successfully used to validate and calibrate theoretical simulations.

Figure 16. The view of smart girder during proof load test

Fig. 17 shows extreme tensile strain values measured by sensor located at lower surface of the girder. However, strains are still very low and not exceed tensile strength of concrete itself (this strength is very often neglected during design stage). Thus, it could be concluded, that analyzed girders work safely and there are still load-bearing capacities reserves, which can be optimized during future designs.

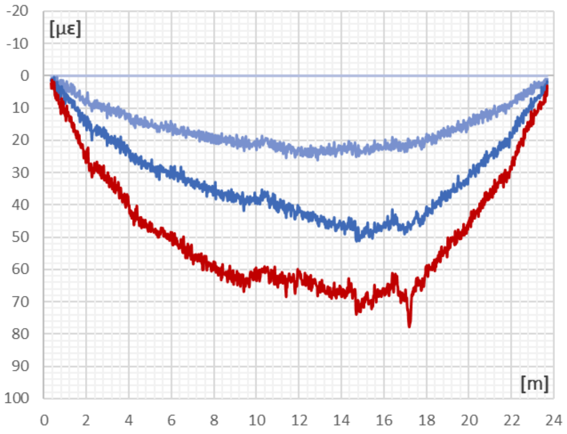

Figure 17. Strain distributions over length during mechanical proof load test – sensor no. P05

Assuming the static scheme of simple supported beam, girder work in linear range and presence only of bending effects, the strain distributions measured by sensors located near to the structural neutral axis (P03 and P04) should be approximately equal to 0. This is confirmed by data presented in Fig. 18, where no effect on strain distributions was visible during increasing the mechanical load.

What is very important, mechanical load did not activate the microcracks, which behaviour was clearly visible in previous stages (please compare Fig. 11 and 14). Girders are now operating under uncracked state and this is very favorable information. Such state will significantly prolongate their durability, especially taking into account harsh environmental conditions within the production hall. DFOS system embedded into smart prestressed girders can be read at any time in the future, supporting assessment of girders technical condition and thus improving decisions on further operation and maintenance.

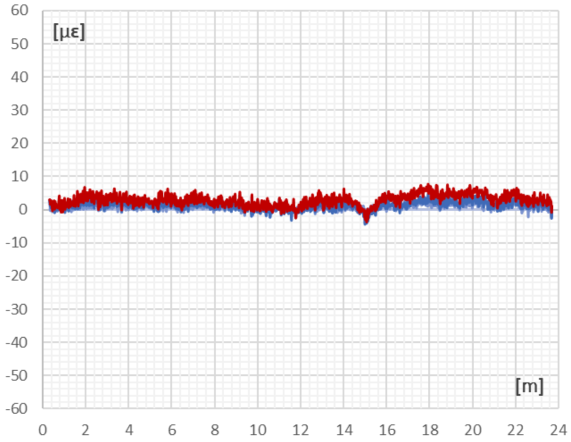

Figure 18. Strain distributions over length during mechanical proof load test – sensor no. P03

4 SUMMARY

The advantages of distributed fibre optic sensing (DFOS) are well known and used successfully in many civil engineering and geotechnical projects. However, the potential benefits of this technology are still very often not fully utilized. Mainly due to the lack of use of appropriate monolithic sensors, improper time and way of installation or poor data managing, processing and engineering interpretation.

The concept of smart precast, prestressed concrete girders dedicated for industrial engineering, integrated with advanced distributed fibre optic system for strain and temperature monitoring is very promising in the context of the performance, reliability, maintenance and durability of such infrastructure. Works, measurements and analysis described in this paper will hopefully contribute to the development of smart concrete structures, solving some technological, production and measurement issues.

What is extremely important, proposed solution allows for analyzing concrete structural behaviour from its real zero state i.e. including thermal-shrinkage strains of early-age concrete, prestressing process, activation of dead-weight or mounting stresses. These aspects are usually omitted with conventional approach to structural monitoring, when spot sensors are installed to the surface of existing structures.

During one measurement session, proposed embedded DFOS system provides information about the strain (stress) state in 19,200 structural points and about temperature changes in 7,200 points. Therefore, such sensors could be treated as nervous system of the structure [36] informing about any threats and abnormalities. All local damages, including cracks and microcracks, can be identify and assess directly based on strain measurements.

Currently, 3 smart girders are under operation in one of the production halls in Poland. Measurements performed periodically will assist experts in the assessment of girders technical condition, and in particular in the assessment of the crack state directly affecting the structural performance and durability.

What is more, obtained data from thousands of measuring points and tens of measuring sessions will be used to solve optimization problem and modify technology of prestressed concrete girders. During mass production of concrete structural members in a production plant, even a small change supported by reliable data can generate significant financial savings while maintaining the required level of safety.

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- *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* (POIR. 01.01.01-00-0550/15) - completed.
- *Innovative fibre optic sensor for measuring strain and temperature* (POIR. 01.01.01-00-1154/19) - pending.

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