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Smart Composite Rebars Based on DFOS Technology as Nervous System of Hybrid Footbridge Deck: A Case Study

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Abstract. The paper presents the concept and application of the smart pedestrian footbridge, equipped with DFOS strain sensors called EpsilonRebars. These sensors, in the form of composite rods being simultaneously the structural reinforcement for the concrete deck, were placed along the entire span of nearly 80 m. Thanks to the application of distributed optical fibre sensing technique DFOS, it is possible to perform measurements of strains, displacements (deflections) and temperature changes in a geometrically continuous manner along the entire length of the footbridge. The sensors integrated with the deck were used to measure selected physical quantities during the hydration of early-age concrete (thermal-shrinkage strains) as well as during the load tests. Sensor readings can be performed at any time of the structure operations in order to assess its technical condition (e.g. crack appearing) and to analyze the impact of environmental conditions and other factors, e.g. rheological phenomena.

Keywords: EpsilonRebar · DFOS strain sensors · Composite rods · Concrete strains · Footbridge

1 Introduction

1.1 Distributed Fibre Optics Sensing in Measurements of Engineering Structures

In recent years, there has been observed a significant interest in acquiring knowledge related to the operation of real engineering structures, not only specimens or components prepared in laboratory conditions. Structural health monitoring (SHM), understood as continuous measurements of selected physical quantities over time (e.g. strains or displacements), can provide engineering benefits related not only to increased awareness and improved safety of the object by early damage detection [1], but also to significant financial savings. Therefore, the most important tasks for SHM include:

– enabling immediate reaction (decision making [2]) to occurring events, e.g. snow removal from the roof, increasing the tension of prestressing tendons, replacing or

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adjusting the load-bearings, conducting an on-site visit, decommissioning of a facility, application additional assembly struts, etc. This approach results not only in clear improved safety, but also generates benefits resulting from the fact that the costs of preventing failures are always much smaller than the negative effects of such events,
– planning the optimal renovation strategy,
– optimization of technological and construction solutions, as well as designing algorithms,
– obtaining reliable data needed to calibrate numerical models and verify theoretical assumptions,
– compliance with construction law requirements and standard provisions.

In order for the above tasks to be carried out optimally, measurement solutions that provide comprehensive and reliable information being at the same time cost-effective are sought. Distributed fibre optics sensing (DFOS) raises great hopes in this context [3, 4], which, unlike conventional point measuring techniques, enables measurements of selected physical quantities in a geometrically continuous way along the entire length of fibre: from several millimeters [5] to even hundreds of kilometers [6]. The application of DFOS solutions (Fig. 1) allows to replace thousands of conventional spot sensors with one fibre, providing unique tool for structural condition assessment.

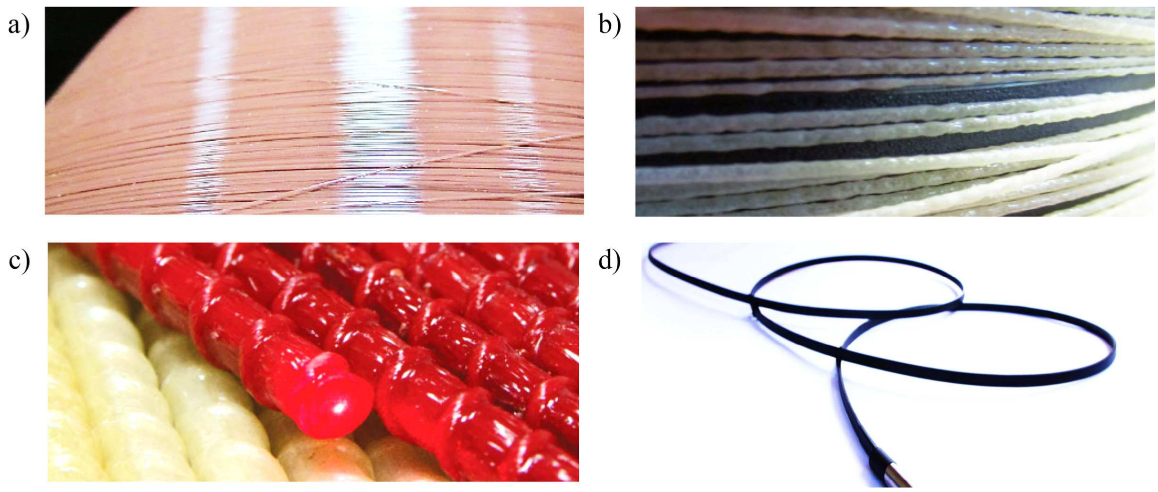

Fig. 1. Examples of distributed fibre optic sensors: a) SM9/125 telecom fibre in acrylic coating (lab), b) fibre in a special rough silica coating (lab), c) composite EpsilonRebar strain sensor in the form of reinforcement bars (in-situ), d) composite 3DSensor for measuring displacements in 3D space (lab/in-situ) [14].

Depending on the material of the structure or its component, monitored physical quantities, the method of assembly and the final destination (laboratory or in-situ), the sensor design should be chosen respectively. For laboratory purposes optical fibres in their primary coatings can be used (Fig. 1a, 1b), however, due to their brittleness they cannot be managed in in-situ conditions. For real applications special sensors should be applied, which guarantee high accuracy and are able to withstand hard installation and operation conditions. Examples of such sensors are shown in Fig. 1c (for strain & crack measurements [7, 8]) and Fig. 1d (for displacement measurements in 3D space).

1.2 DFOS in Bridge Monitoring

Due to the dynamic development of bridge structure in the last several years, more and more unique objects are created, characterized by unusual geometry, high slenderness, advanced construction solutions or the use of modern materials, e.g. FRP composites [9]. Hence, many bridge structures in the world, as well as in Poland [10, 11] are equipped with automatic systems for continuous monitoring of changes in selected physical quantities (e.g. strain, displacement, vibration, etc.) important from the structural safety point of view. This also applies to engineering objects, which have been in use for decades, particularly exposed to the negative effects of progressive degradation. Their technical condition often leaves much to be desired, and periodic inspections may not be sufficient to ensure safe operation. An example could be the bridge collapse in Genoa (Italy) of August 2018, which killed 43 people.

The application of distributed fibre optic sensing in monitoring of bridge structures is still a relatively young solution. An example would be the Musmeci bridge (Potenza, Italy), where measurements of strains and temperature changes were carried out using single-mode optical fibres attached to the surface of one of the concrete arches (Fig. 2). Despite the relatively high spatial resolution of the measurements, it was possible to identify the cracked fragment of the structure [12]. Another example was the application of optical fibres on a steel, I-section girder of a road bridge (Naples, Italy) with a span of 44 m [13]. Tests carried out during the load tests under the control of the reference measuring techniques, showed the effectiveness of proposed solution for monitoring the deformation state of the bridge structure along the entire length of the span.

Fig. 2. View of the reinforced concrete bridge erected in 1969 (Potenza, Italy), monitored using distributed fibre optics [8].

In Poland, fibre optic sensors using DFOS measurement technology have already been installed on four bridge structures:

– "Brama Przemyska" steel suspension bridge in Przemyśl (Fig. 3a),
– the Tadeusz Mazowiecki steel suspension bridge in Rzeszów (Fig. 3b),
– the first fully-composite bridge in Poland in Nowa Wieś near Rzeszów [10],
– footbridge in Nowy Sącz, which will be discussed in detail hereafter.

It is worth to notice that within the Mazowiecki bridge, the span of 150 m is equipped with four optical lines installed at selected heights of a steel box girder, with a total measuring length of 600 m. This makes this project the largest of its kind in Poland. The measurements are performed periodically using two optical dataloggers based on various physical phenomena (Brillouin and Rayleigh scattering) allowed for detailed structural analysis over time and bridge length.

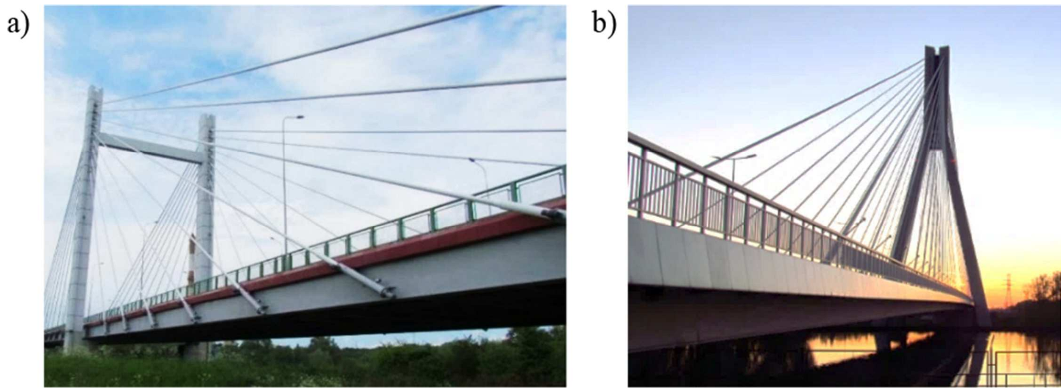

Fig. 3. Examples of Polish bridge structures with DFOS systems: a) "Brama Przemyska" in Przemyśl, b) The Tadeusz Mazowiecki bridge in Rzeszów [own materials].

It is also worth noticing the first road bridge in Poland made entirely of FRP composites, developed as part of the ComBridge project [10]. The girders and deck slabs have been equipped with optical fibres already at the production stage. Unlike the all previously presented examples, where the fibres were installed on existing structures, in this case it was possible to analyze the structural behaviour starting from the actual "0" state, taking into account residual strains from production process, dead load, weight of all equipment elements, impact of rheological phenomena, etc. This approach will be particularly important for concrete members, where the first months are crucial for their final performance and durability (thermal-shrinkage strains during the concrete hydration, formation of micro-cracks, transmission of prestressing force, high creep).

The paper presents another example of smart pedestrian footbridge, equipped with DFOS strain sensors called EpsilonRebars. These sensors, in the form of composite rods being simultaneously the structural reinforcement for the concrete deck, were placed along the entire span of nearly 80 m. The sensors integrated with the deck were used to measure selected physical quantities during the hydration of early-age concrete (thermal-shrinkage strains) as well as during the load tests.

2 Brief Description of the Analyzed Footbridge

The pedestrian-cyclist footbridge in Nowy Sącz across the Kamienica river was built as part of the European network of EuroVelo cycle routes. This is a project of the European Cyclists' Federation, whose goal is to build fourteen long-distance bicycle routes that run all over Europe. The total length of the routes is going to be around 70,000 km.

The main load-bearing members of the footbridge are two steel arches with a pipe cross-section of Ø508 mm, inclined symmetrically towards the interior of the structure (Fig. 4). In the upper part, the connection of both arches was made using ten pipe bracings with the diameter of Ø244.5. Deck slab is supported by perpendicular beams (traverses) with the spacing of 5,2 m fixed to two longitudinal I-beams IPE500. This system is additionally stiffened by X-type bracings. I-beams are suspended by the tendon system to the steel arches (Fig. 4, 5, 6). The footbridge is based on massive concrete abutments by neoprene bearings (there is a fixed support on the one side and movable on the second). The maximum height of the structure is 10 m, usable width 2.5 m and the span length equal to 78 m.

The footbridge was designed with a hybrid concrete-composite deck (see also Fig. 8). The FRP (fibre reinforced polymer) composite panels were used as lost formworks, where composite reinforcement was installed (including smart EpsilonRebar strain sensors). Finally, the slab was concreted continuously along the entire span (nearly 80 m).

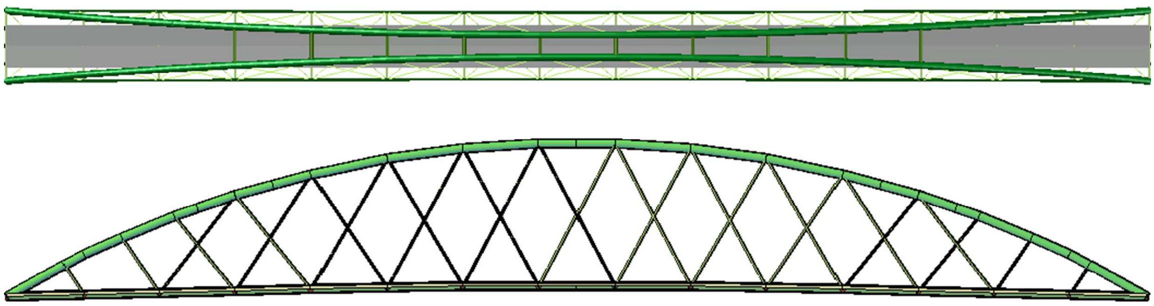

Fig. 4. Plane and side view of the analyzed footbridge FEM model in Nowy Sącz [own work].

a) b)

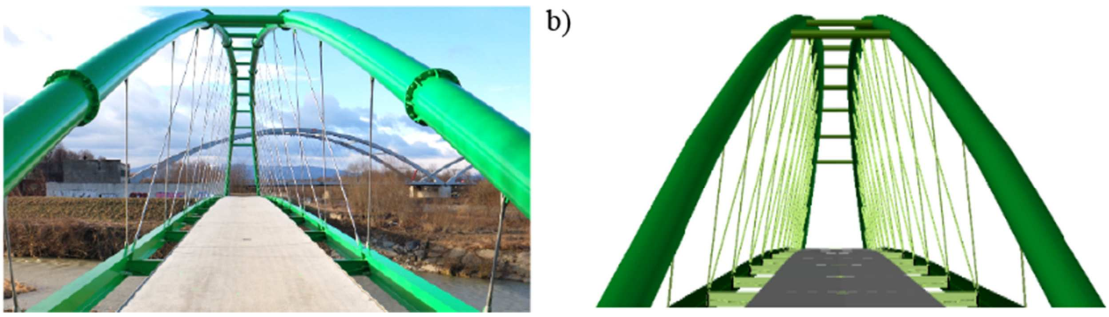

Fig. 5. Footbridge in Nowy Sącz: a) front view, b) front view from FEM model [own work].

The general contractor of the bridge was *Przedsiębiorstwo Usługowo-Inżynieryjne Budmost Rafał Jędrzejek*. *Mostostal Warszawa S.A.* developed a hybrid FRP composite bridge with equipment elements. *ComRebars Sp. z o.o.* supplied composite rebars, and *SHM System Sp. z o.o. Sp. Kom.* Smart EpsilonRebar strain sensors. *Rzeszów University of Technology* was responsible for the design of the composite-concrete hybrid deck slab reinforced with GFRP bars, performing the laboratory tests of formwork panels as well as the design and implementation of the footbridge load tests.

Fig. 6. View of the finished pedestrian-cyclist footbridge in Nowy Sącz.

3 DFOS Monitoring System

The integrated structural monitoring system was built primarily on the composite EpsilonRebar strains sensors manufactured by SHM System [14]. They are made in the form of GFRP reinforcing bars, where measuring optical fibres are integrated during production (pultrusion process) within the monolithic cross-section of the bar.

Such bars are characterized by excellent strength and adhesion parameters (an additional braid is used to rough the external surface – see Fig. 1c). Thanks to this, EpsilonRebar sensors perform not only a measuring function, but as a structural reinforcement included in the static-strength calculations, became an integral part of the structure. EpsilonRebars of a given length (equal to the span length) were delivered to the construction site in the form of coils (Fig. 7a) and then tied to the existing composite reinforcement mesh (Fig. 7b). At the conceptual level, this solution can be compared to the human nervous system, which is responsible for detecting specific, worrying changes occurring at each point of the human body and thus, triggering an appropriate defense response.

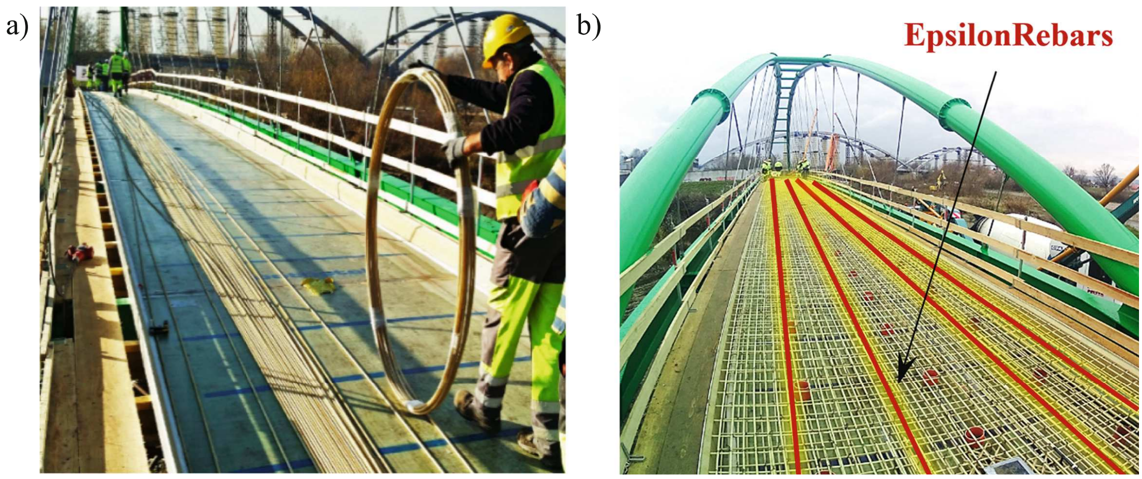

Fig. 7. a) Installation of DFOS composite EpsilonRebar sensors within composite deck panels, b) view of the composite reinforcement and EpsilonRebars just before concreting.

Depending on the way of installation (see details in Fig. 8), EpsilonRebars return information about different phenomena:

– strains in the reinforcement mesh, both the upper and lower level,
– strains of the composite formworks (adhesion to the FRP material),
– strains in concrete (adhesion to the concrete).

Thanks to this, detailed analysis of e.g. cracks, concrete stress, slippage between concrete and composite panels or calculation of deflections can be performed. What is more, DFOS temperature sensor were installed to compensate strain results due to temperature changes during hydration process of concrete as well as during further exploitation.

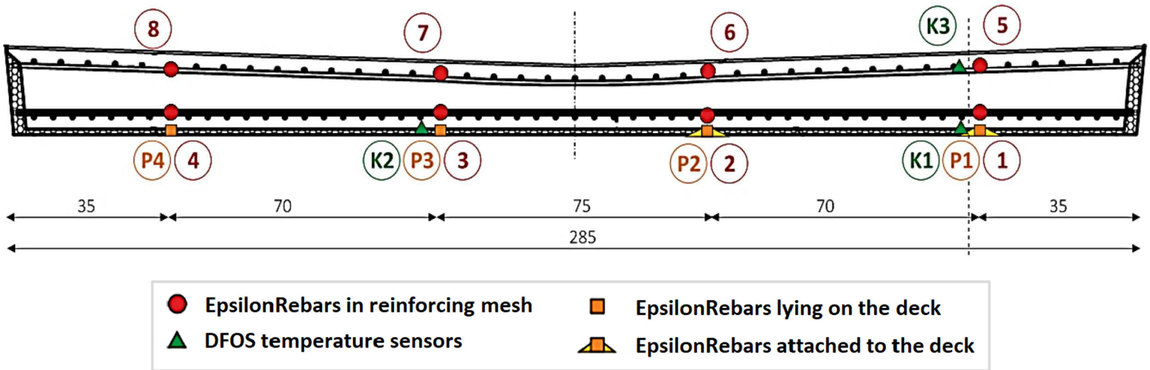

Fig. 8. Cross section of the hybrid deck slab with location and numbering of EpsilonRebar strain sensors and compensation sensors for measuring temperature changes.

Optical fibre measurement sessions were carried out according to the planned schedule during the hydration process of the concrete mixture, dead weight activation as well as during the load tests. The hybrid slab was additionally equipped with reference vibrating wire sensors, which were installed in three cross-sections inside the deck slab. Measurements with VW strain sensors were performed automatically with a frequency of 15 min during the first two weeks of the concrete mix hydration. The sensors are averaging strain values from the base of 151 mm.

4 Exemplary Strain Results

Reference reading both for DFOS and VW sensors were adopted immediately after concreting the deck slab (November 16, 2018). Then measurement sessions were performed according the planed schedule. Base lengths and spacing of virtual fibre optic sensors (arranged in series along EpsilonRebars) can be defined in data post-processing (the spatial resolution can start even from 5 mm). For further analysis base and a spacing were assumed equal to 100 mm. It means that one single EpsilonRebar replaces 780 traditional strain gauges arranged in series (on one measuring line). Considering the fact that a total number of EpsilonRebars and DFOS temperature sensors within this project is 15, information from 11,700 measurement points is received during single measurement session.

The Fig. 9 presents the exemplary strain distribution along the entire length of the slab for the EpsilonRebar No. 5 (located in the upper reinforcement mesh), compensated due to the temperature effect. This means that strain values correspond to the mechanical stress in the concrete slab coming from its dead load and occurred during hydration process (free thermal strains are not taken into account in this case). To make this plot more readable, only data from measuring session P02 (December 3, 2018) are presented.

DFOS strain data were compared with reference VW strain sensors (VW_P02, VW_P03, VW_P04) installed in three cross sections on the longitudinal direction in the near area of EpsilonRebars. Very good agreement between these two independent techniques was obtained. However, the above graph clearly shows the basic limitation of all conventional spot methods, consisting of a significant dependence of the results obtained (and thus their interpretation) on the selected installation site. Information about phenomena occurring between measuring points is lost and theoretical approximation, even using advanced numerical models, may very often be insufficient. This is especially visible in the case of heterogeneous materials such as concrete, where the result of the measurement averaged from a short measurement base, may be affected by the random presence of stiff aggregate grains or the occurrence of the cracks. Measurements using distributed fibre optic sensors completely eliminate this limitation.

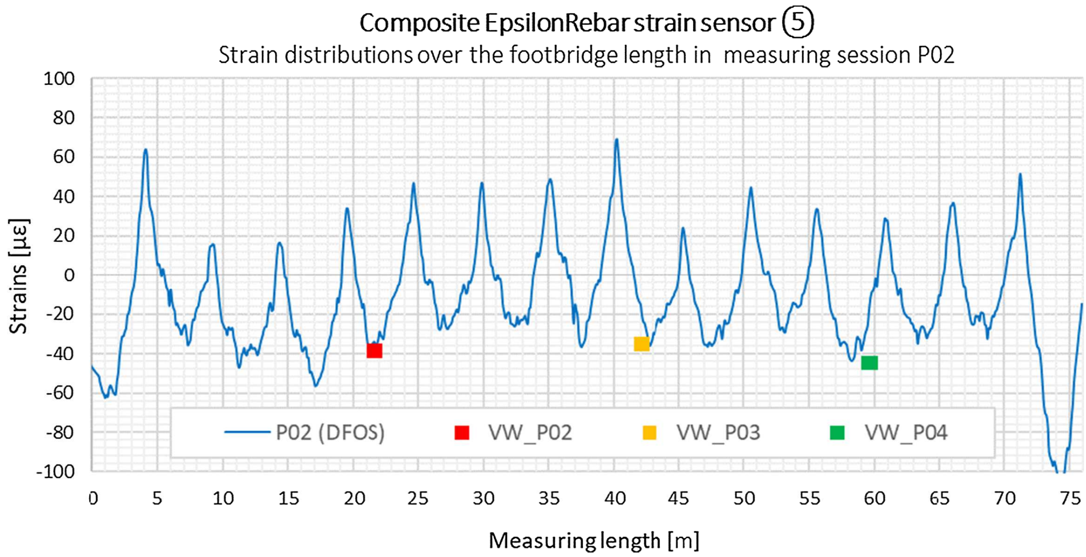

Fig. 9. Exemplary results of DFOS strain measurements with EpsilonRebar No. 5 along the entire length of the slab against the reference VW measurements after activation the slab dead weight (measuring session P02).

The static of the slab, represented by strain distributions along its entire length, was clearly influenced by the presence of steel traverses constituting flexible supports (possibility of imitated displacements in vertical direction).

A large amount of data obtained from one measurement session can be used for thorough verification of the theoretical assumptions made at the design stage as well as for calibration the numerical model, e.g. in the context of material parameters (modulus of elasticity, coefficient of thermal expansion) or stiffness of structural joints and supports. For the purposes of this article, a simplified numerical model of the pedestrian-cyclist footbridge in Nowy Sącz was prepared in the SOFiSTiK software including beam (load bearing system), cable (tendons and bracings) and surface (hybrid deck slab) FEM elements.

Exemplary results of numerical calculations against the measurement data obtained from one of the EpsilonRebar strain sensors were compared qualitatively in Fig. 10 for the loads combination: slab dead weight + thermal-shrinkage strains after the first two weeks of hydration.

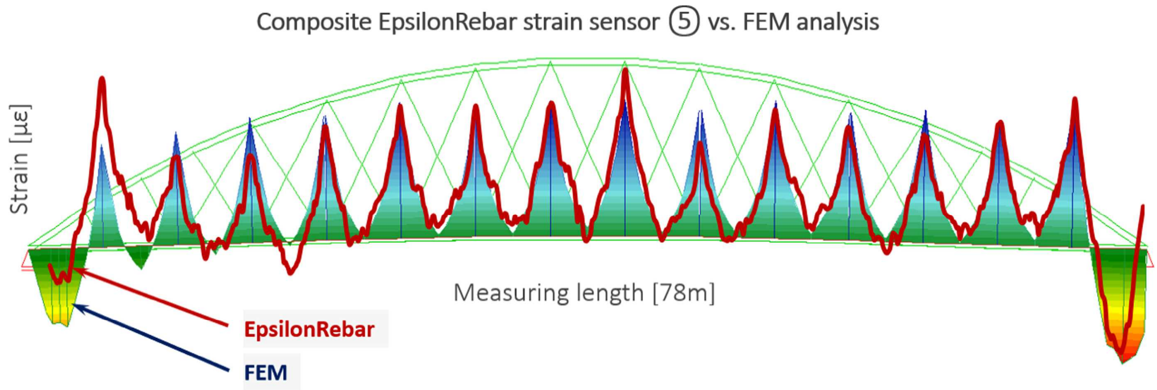

Fig. 10. Qualitative comparison of strain distributions obtained from FE model and measurements with EpsilonRebar no. 5 (dead weight + thermal-shrinkage strains).

It is worth to emphasize that in well-designed SHM system, frequency of measurements must appropriately adapt to the phenomena occurring in the structure and the environment (daily or annual cycles, rainfall, atmospheric conditions, temperature changes, exceptional loads).

The combination of the advantages of techniques enabling automated measurements over time (e.g. vibrating wire) together with the DFOS technique used for continuous measurements in the geometric sense leads to the creation of hybrid structural health monitoring systems. In such cases, automatic sensors, except from measuring physical quantities in selected places of the structure, also fulfill an activation function for fibre optic measuring sessions (performed in addition to the standard schedule) – giving an opportunity to optimize their number.

5 Conclusions

The hybrid structural health monitoring system presented in this article, based on composite DFOS EpsilonRebar strain sensors supported by automatic vibrating wire technology, is consider to be unique on a global scale. This type of solution and measurement results have not been published in the world literature so far. DFOS sensors were integrated with the concrete deck during construction stage, while the structure was yet supported on temporary supports. Thanks to this, all effects (e.g. thermal-shrinkage strains of early-age concrete, dead load, permanent loads, initial rheology) can be taken into account, what is impossible for conventional sensors installed to the surface of existing structures.

In the coming years fibre optic sensors have a chance to become a breakthrough in the widespread monitoring of engineering and geotechnical structures, primarily due to their ability to detecting local damages, measuring strains, displacements and temperatures over km-range distances and due to very low costs of fibre optic sensors themselves, negligible in the scale of the entire investment.

Considering the number of advantages and benefits demonstrated on a specific example of the implementation within a pedestrian-cyclist footbridge in Nowy Sącz, as well as other field and laboratory experiments, it is recommended to equip all newly designed concrete bridges with DFOS fibre optic sensors enabling measurements of strains along their entire length. Measurement sessions should be carried out at least as part of periodic technical inspections (in this case, measurement data can be used to support the expert in assessing the technical condition of the structure). However, what is even more important, such measurements can be performed in emergency situations (e.g. activated by automated sensors or after hitting the bridge by a vehicle), enabling immediate reaction based on objective data about structural condition (e.g. distribution of cracks along entire length), not available either for conventional measuring techniques or during visual assessment by people. This approach. Thanks to the appropriate arrangement of the sensors within cross-section of the structure, allows for determination deflections without the need for additional equipment.

References

1. Farrar, C.R., Worden, K.: An introduction to structural health monitoring. Philos. Trans. R. Soc. A **365**, 303–315 (2007)
2. Faber, M.H.: Statistics and Probability Theory in Pursuit of Engineering Decision Support. Springer, Heidelberg (2012). ISBN 978-94-007-4055-6
3. Barrias, A., Casas, J.R., Villalba, S.: A review of distributed optical fiber sensors for civil engineering applications. Sensors **16**(5), 748 (2016)
4. Glišić, B., Inaudi, D.: Fibre Optic Methods for Structural Health Monitoring. Wiley, Hoboken (2007)
5. Samiec, D.: Distributed fibre-optic temperature and strain measurement with extremely high spatial resolution. Photonic Int. **1**, 1–13 (2012)
6. Inaudi, D., Glišić, B.: Long-range pipeline monitoring by distributed fiber optic sensing. J. Press. Vessel Technol. **132**(1), 9 (2010)
7. Sieńko, R., Bednarski, Ł., Howiacki, T.: About distributed internal and surface strain measurements within prestressed concrete truck scale platforms. In: 3rd World Multidisciplinary Civil Engineering - Architecture - Urban Planning Symposium WMCAUS, Prague, Czech Republic (2018)
8. Sieńko, R., Bednarski, Ł., Kanty, P., Howiacki, T.: Application of distributed optical fibre sensor for strain and temperature monitoring within continuous flight auger columns. In: 4th World Multidisciplinary Earth Sciences Symposium WMESS, Prague, Czech Republic (2018)
9. Bai, J.: Advanced fibre-reinforced polymer (FRP) composites for structural applications. Woodhead Publishing, Cambridge (2013)
10. Siwowski, T., Rajchel, M., Sieńko, R., Bednarski, Ł.: Smart monitoring of the FRP composite bridge with distributed fibre optics sensors. In: 9th International Conference on Fibre-Reinforced Polymer (FRP) Composites in Civil Engineering, CICE 2018, Paris (2018)

11. Bednarski, Ł, Sieńko, R., Howiacki, T.: Analysis of rheological phenomena in reinforced concrete cross-section of Rędziński bridge pylon based on in situ measurements. Proc. Eng. **108**, 536–543 (2015)
12. Minardo, A., Persichetti, G., Testa, G., Zeni, L., Bernini, R.: Long term structural health monitoring by Brillouin fibre-optic sensing: a real case. J. Geophys. Eng. **9**, S64–S69 (2012)
13. Minardo, A., Bernin, R., Amato, L., Zeni, L.: Bridge monitoring using Brillouin fiber-optic sensors. IEEE Sens. J. **12**(1), 145–150 (2012)
14. dfos.shmsystem.pl/en