Composite and Monolithic DFOS Sensors for Load Tests and Long-Term Structural Monitoring of Road Infrastructure

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Abstract. Distributed fibre optic sensing (DFOS) is a versatile measurement technology, especially useful to monitor linear structures including road infrastructure. It allows measuring strains, displacements or temperatures continuously in a geometrical sense, so all local events (e.g. cracks or sinkholes) can be detected directly. The article summarises the newest achievements related to composite and monolithic DFOS sensors created especially for civil engineering and geotechnical applications. The design of the sensors supported by theoretical background and practical applications are discussed in relation to road embankments and asphalt layers. These successful applications of composite and monolithic DFOS sensors are the first of such types in the world.

Keywords: Distributed sensing · DFOS · Road infrastructure · Measurements · Monitoring · Monolithic sensors · Composite sensors · Strains · Displacements

1 Introduction

1.1 Distributed Fibre Optic Sensing (DFOS)

Distributed fibre optic sensing (DFOS) is a measurement technology being a real breakthrough in structural health monitoring (SHM). In contrast to conventional spot methods, it allows for direct local events (damages) detection. Application of different optical phenomena, like Rayleigh [1], Brillouin [2], or Raman scattering allows the measurements to be done continuously over a long distance, which is particularly useful for linear structures like roads, highways or embankments.

However, to utilise all the benefits coming from this approach, appropriate DFOS sensors must be applied [3]. The essential requirements include an undisturbed strain transfer mechanism, complete bonding with the surrounding material (ground, concrete, asphalt) and resistance to harsh installation conditions.

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1.2 Measuring Fibres and Layered Cables

There are a few DFOS tools dedicated to strain measurements. The simplest approach involves optical fibres in their primary coatings: acrylate or polyimide. However, they are very fragile because of negligible dimensions (Ø ≈ 250 μm) and thus cannot be used in field conditions. Acrylate coatings have a few times wider strain range and are resistant to concrete alkaline environments in contrast to polyimide coatings. Such fibres can be successfully applied under laboratory conditions, i.e. with controlled installation procedures and constant environmental parameters.

Popular DFOS tools used in actual operating conditions are layered cables. Unfortunately, because of their telecom origin, they often do not meet the high requirements of engineering projects. They are built from many intermediate layers (Fig. 1), and the internal slippages can disturb the correct mechanism of strain transfer from the material to the measuring fibre. There are many works [4, 5] dealing with this problem. However, because of the randomness of these nonlinear effects, the application of mathematical correction to strain results is not possible in practice.

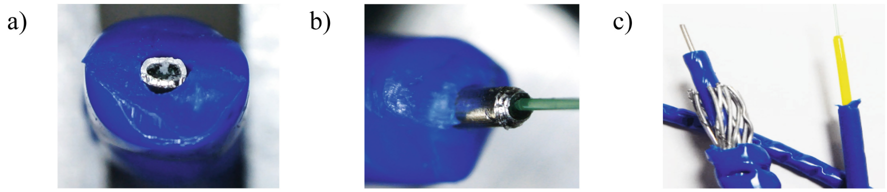

Fig. 1. Example multilayered cables: a) cross-section; b) c) side views.

Other limitations of layered cables include steel and plastic components (very low elastic range), smooth external surfaces (poor bonding properties) or no axial stiffness (waving and need for pre-tensioning).

2 Composite and Monolithic DFOS Sensors

2.1 Design and Theoretical Background

Layered cables were used in many projects mainly because of the lack of reasonable alternatives. However, the new quality of DFOS measurements is provided by composite and monolithic sensors, which overcame the existing limitations. That was confirmed by extensive laboratory research [6]. Composite sensors are produced in the pultrusion process, in which optical fibre is fully integrated inside the monolithic core (without any layers). Moreover, composite allows obtaining extremely high strain level (up to ±40 000 με). So, the sensors can be used to monitor cracking in the concrete or yielding in the steel. They are also durable and fully resistant to corrosion. Outer braid (Fig. 2) provides perfect bonding properties with the surrounding material. That is why DFOS sensors can create an auto-diagnostic system inside the structure, similar to the nervous system in the human body [7], able to detect the minor changes in the measurand with extremely high precision and accuracy.

Fig. 2. Example composite and monolithic DFOS sensors [8]: a) cross-section; b) c) side views.

Composite DFOS sensors can also be successfully used for temperature monitoring. Thanks to their monolithic cross-section, they are characterised by the linear thermal coefficient for strain results compensation in form of a single multiplier.

2.2 Not Only Strains (and Temperatures) but also Displacements

Another essential capability introduced by composite and monolithic sensors is measuring not only axial strains but also displacements (shape changes) in the planes perpendicular to the sensor axis [9, 10]. There are no alternatives for engineering applications available in the market. Thanks to displacement measurements, all local sinkholes can be identified at the very early stage, before the initiation and development of the higher movements. This is particularly important for road infrastructure.

2.3 Installation

The important stage during the entire SHM process is installation because it directly influences the final results and the possibility of their correct physical interpretation. Attention must be paid to the exact positioning of the sensors in accordance with the design. In the case of the layered cables with no axial stiffness, this task is complicated due to their extensive waving.

On the other hand, monolithic sensors tend to hold their shape. It is also possible to modify their standard geometrical and mechanical parameters (e.g. increase the diameter and elastic modulus). In some cases, they can be even treated as structural reinforcement taken into account during strength calculations [7].

Sensors are delivered to the site on drums (Fig. 3a) or in coils cut at the appropriate length (Fig. 3b) and unrolled on place by hand (Fig. 3c).

There are a few installation methods depending on the specific requirements of a given project. The simplest approach is to stabilise the sensors directly on the ground using special pins. Figures 4a, 4b and 4c show the examples at the base of the road embankment, below the asphalt layer and below the large-aggregate layer, respectively. In the case of the reinforced components, the thing is also very comfortable and easy as the sensors can be tightened to the existing bars by cable ties (Fig. 4d). The more challenging task is to install the sensors in the middle of the liquid layer (e.g. concrete mixture) with no reinforcement. Then, special mounting brackets must be applied (Fig. 4e) in a spacing adequate to the sensor's stiffness. Figure 4f shows the installation under (at the base) of the existing embankment using the drilled holes filled with the injection after installation.

Fig. 3. Sensors delivery to site: a) on a drum [11]; b) c) in coils cut at desired lengths [8].

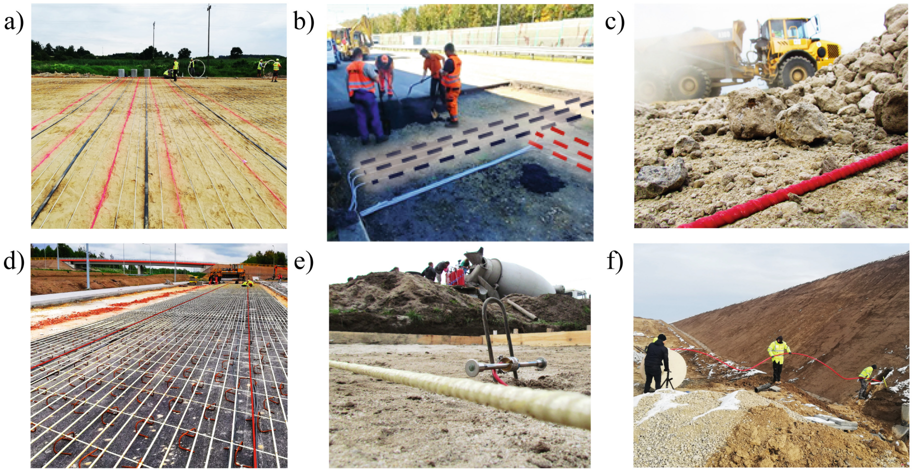

Fig. 4. Example installation methods of composite DFOS sensors: laying on the ground (a), below asphalt layer (B) and aggregate layer (c); d) tightening to the existing reinforcement; e) positioning above ground (inside non-reinforced concrete layer); e) insertion under the existing earth embankment;

2.4 Laboratory Verification

Before the composite DFOS sensors were deployed on actual road structures, they underwent dozens of tests under laboratory conditions. Example research on sensors performance inside the substrate (aggregate) and asphalt layers is presented in Fig. 5a and 5b. Several sensors were installed in small-size laboratory casings, but thanks to their negligible stiffness, they were no reinforcement disturbing the actual structural response to mechanical loads.

Both axial strains and vertical displacements (sinkholes, settlements) were investigated under the control of reference measurement techniques. Thanks to that comprehensive approach, complete knowledge about the deformation state is obtained, unreachable when measuring only strains or only displacements [12].

Figure 6 shows the example results obtained during mechanical load tests of the substrate (aggregate) layers presented in Fig. 5a. Strains measured by *EpsilonSensor* [8] and displacements measured by parallel *3DSensor* [8] are presented in Fig. 6a and 6b,

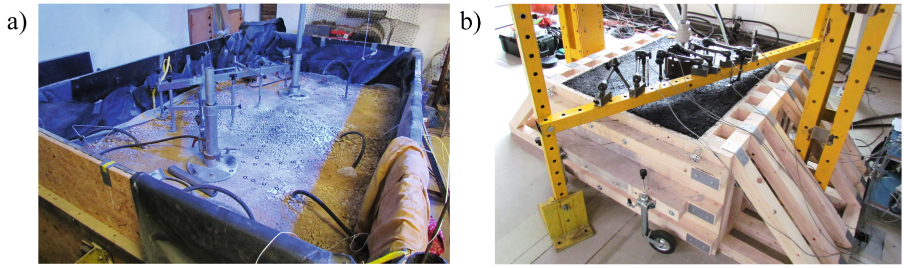

Fig. 5. Research on DFOS sensors' performance in the aggregate (a) and asphalt (b) layer.

showing the differences between these two engineering quantities. Generally, the tension strains (positive values) are observed in the lower layers under the force, but because of heterogeneity of the aggregate, they are locally disturbed by grains which even generate local compression zones (negative values). On the other hand, vertical displacements are expressed directly in millimetres and they have a much more intuitive engineering interpretation, showing the real changes in the shape of the sensor.

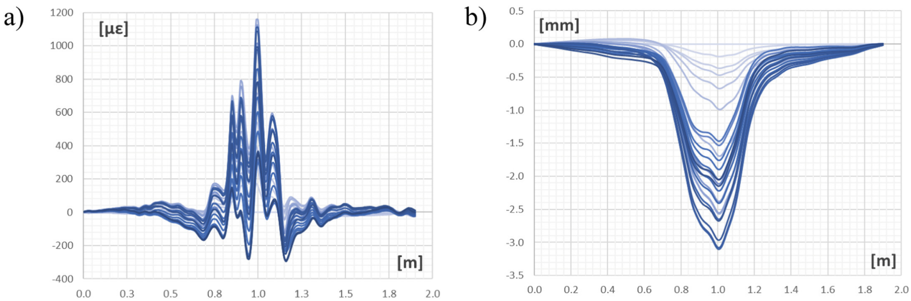

Fig. 6. Example axial strains (b) and vertical displacements (b) profiles over length.

3 Road Embankments – Case Studies

By 2021, there are five road embankments in Poland equipped with DFOS sensors from the *Nerve-Sensors* family [8]. Depending on the project requirements, strain, displacements or temperatures are monitored. Detailed descriptions of two projects are presented in [9] and [11]. This section briefly summarises the other examples.

3.1 Strains - Embankment Reinforced with Composite Rebars

The base layer of the embankment in question was reinforced with composite rebars. This innovative solution is very favourable in terms of durability and resistance to corrosion. Some of the bars were replaced with *EpsilonRebars* – composite strain sensors [8] with double function: sensing and reinforcing at the same time (Fig. 7a). The sensors were capable of operating correctly even under the most difficult installation conditions, where the layer of the large-grain aggregate was placed directly above the sensors – see Fig. 4c.

Example strain profiles registered during subsequent construction stages are presented in Fig. 7c. Both negative (compression) and positive (tension) values along the length confirm the highly variable operation of this layer, caused primarily by uneven substrate (local cavities and rises at the time of sensor installation) and irregular loading of the soil layers during construction. Comprehensive knowledge gained from thousands of measurement points integrated with structure will be used for optimizing design procedures of similar structures in the future.

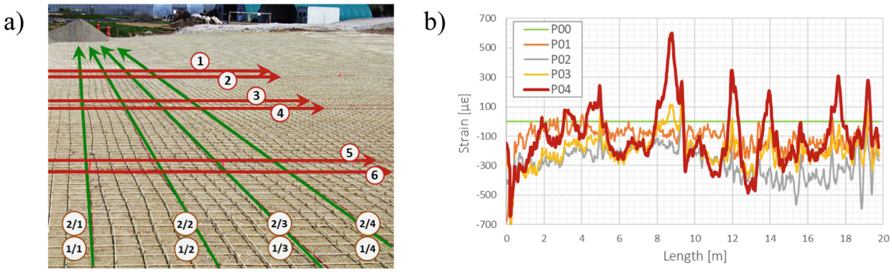

Fig. 7. a) The view of composite reinforcement at the base of the embankment; b) example strain profiles over length registered during subsequent construction stages.

3.2 Displacements - Embankment Above Concrete Columns

Another embankment was equipped with both *EpsilonRebars* for strain measurements and *3DSensors* for displacement measurements (Fig. 8a). Sensors were installed within the transmission layer above the substrate strengthened with CFA concrete columns, both in the longitudinal and transverse directions (see also Fig. 4a). Transverse sensors are situated in such a way that they pass between the columns on the left and directly above the columns range on the right. The embedded DFOS-based nervous system allows analysing the actual deformation state in the subsequent constructions stages as well as during operation.

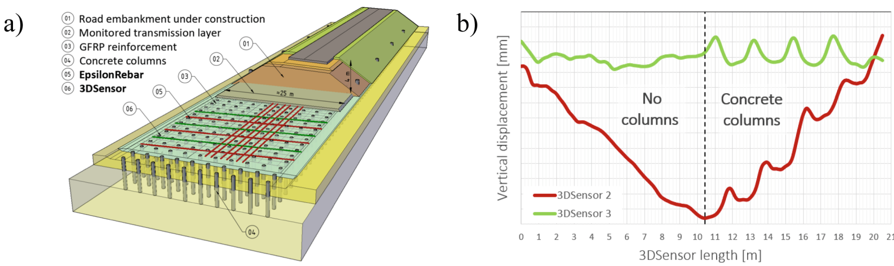

Fig. 8. a) Spatial visualization of the embankment; b) example displacements over length.

Figure 8b shows an example displacement (shape changes) profiles in the selected construction stage for two 3DSensors. A clear difference between the left and right areas is observed, showing local disturbances caused by the stiff concrete columns. Data obtained from thousands of measurement points inside the structure were the first of such type in the world and will be used for validation of advanced spatial numerical models to improve standards and calculation procedures.

3.3 Temperatures – The Highest Road Embankments in Poland

The last example concerns the highest road embankments in Poland with a height of more than 30 m (Fig. 9a). This time *EpsilonRebars* were used parallel with other measurement techniques, including horizontal inclinometers and hydraulic *SHMProfiler* [11]. Installation was done within the existing structure (see Fig. 4f). DFOS measurements were done based on Raman scattering which is insensitive to mechanical strains and thus allows for monitoring temperatures only. Data were used for thermal compensation of the results provided by reference techniques. This was a very important aspect, as temperature gradients over length exceeded 10 °C due to the slope geometry, sun exposition and actual weather conditions on site. Example data are presented in Fig. 9b for subsequent readings.

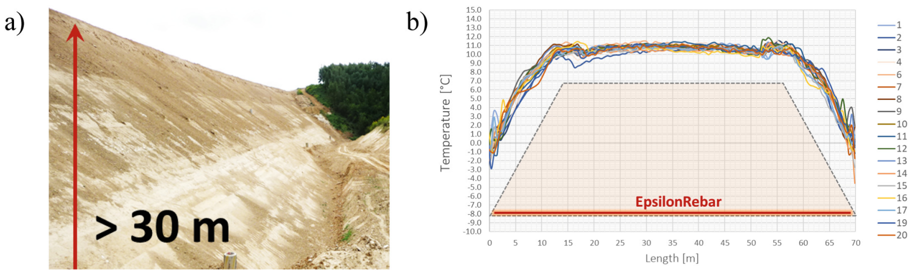

Fig. 9. a) The highest road embankment in Poland; b) example temperatures over length.

4 Road Layers – Case Studies

Earth road embankments are among the strategic infrastructures whose construction time is of crucial importance. What is more, very large deformations (settlements) during construction are expected due to the compaction of a number of ground layers. However, another important group of construction stages and structural components are road surface layers, including both substructures and asphalt. This section gives a few examples of their DFOS-based measurements and monitoring.

4.1 Foam-Concrete Substructure Layer

This project involves the experimental field, where a new type o road with a foam-concrete substructure was examined. *EpsilonRebars* were used to monitor structural response during mechanical load tests. Sensors were installed not only along the horizontal sections but also along with the vertical ones – Fig. 10a. It's worth noticing that there was no reinforcement facilitating the installation within the entire structure, so special mounting brackets had to be applied (see also Fig. 4e) for horizontal sensors. Some example results from selected sensors are presented in Fig. 10b in relation to the geometry of the loading truck.

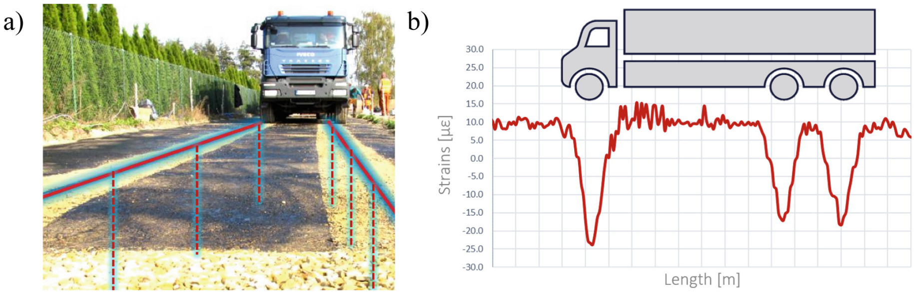

Fig. 10. a) Arrangement of vertical and horizontal DFOS strain sensors; b) example longitudinal strain profiles registered by horizontal sensor due to the truck loading.

4.2 Static and Dynamic Tests of Asphalt Layers

EpsilonRebars were installed inside the asphalt layers of the road located in the mining areas where very large deformations are expected. The research field was equipped with both longitudinal and transverse sections and measurements were done both in a static and dynamic (real-time) way during the truck runs (Fig. 11a).

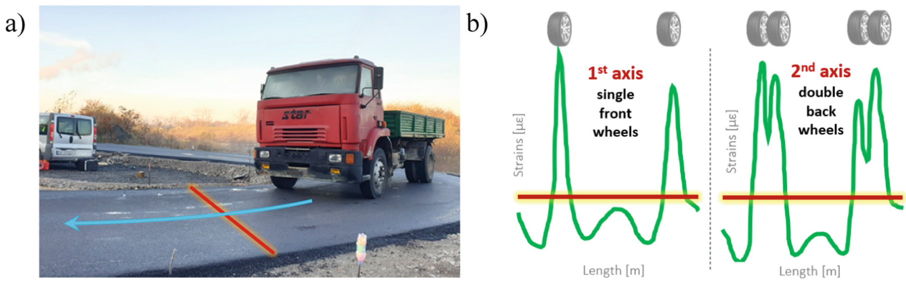

Fig. 11. a) The view of the loading truck during dynamic tests; b) example transverse strains profiles caused by the first (single) and the second (double) axes of the truck.

Thanks to the perfect bonding of composite sensors with surrounding asphalt and no internal slippages, the smallest changes of strains could be registered with high frequency (even those caused only by the engine operation). Figure 11b shows example strain profiles from the transverse sensor measured at selected time steps, corresponding to the loading by the first (single) and second (double) axes of the truck. The influence of the weight and wheel geometry was analyzed with 5 mm spatial resolution, which means 1000 measurement points for only one transverse sensor. This diagnostic system will be also used in terms of long-term structural health monitoring.

4.3 Concrete Highway

The last example involves innovative and experimental 100 m long section of the highway reinforced only with composite bars. The concreting was done without any dilatations (Fig. 12a), so the knowledge about the crack morphology over time was extremely important for designers. That is why *EpsilonRebars* with increased diameter (18 mm) was used to monitor strains over the entire length. They were also the structural reinforcement simultaneously.

The DFOS-based system was designed not only for short term measurements in a daily cycle but also for long term measurements annually. That is why it was possible to analyse the influence of temperature on strains and cracks development. The crack morphology over the entire length, but also changes of their widths over time were carefully investigated. Thanks to the perfect bonding properties and no slippages inside the monolithic sensor, it was possible to distinguish between the cracks located very close to each other (Fig. 12b). It is not achievable when using loose cables.

a) b)

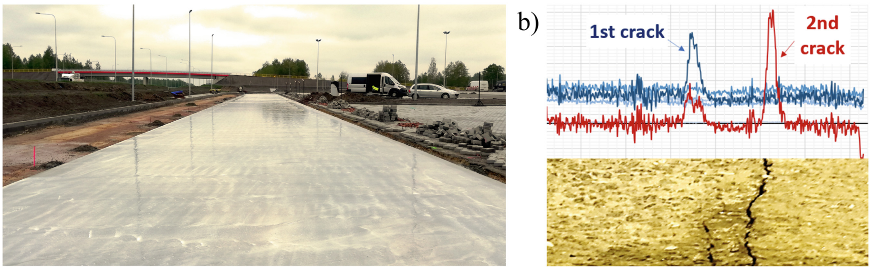

Fig. 12. a) The view of the innovative section of the concrete highway; b) example strain results showing the development of the cracks over time.

5 Summary

The article summarises the newest achievements related to composite and monolithic DFOS sensors designed especially for civil engineering and geotechnical applications. The attention was paid to present their possibilities in relation to road engineering including earth embankments, substructures and asphalt layers. Laboratory and field examples were briefly discussed showing practical capabilities and advantages of this versatile technique in terms of strain, displacement and temperature measurements.

Geometrical and mechanical parameters of monolithic sensors can be adjusted to meet the requirements of a specific project. That is why their high-quality performance was proved not only in controlled laboratory conditions but also within hundreds of field applications including road, highways, embankments, pipelines, collectors, bridges, concrete and prestressed concrete structures, industrial structures, piles and geotechnical structures and many others. Using monolithic sensors it is possible to create an auto-diagnostic system inside the structure itself, similar to the nervous system of the human body. It will be capable to inform about any threats at any point in terms of long-term structural health monitoring.

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