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Hybrid monitoring systems: synergising distributed fibre optic sensing with spot measurements

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ABSTRACT: The diagnosis and maintenance of both new and ageing infrastructure are among the main challenges facing the civil engineering and geotechnical industries today. The effectiveness of monitoring systems depends on several factors, including the choice of measurement techniques. Conventional point-based methods (e.g., vibrating wire sensors, electrical strain gauges, or accelerometers) are inherently limited by their locality, as they cannot directly capture what occurs between discrete measurement points. In contrast, distributed fibre optic sensing (DFOS) introduces new capabilities for structural condition assessment by enabling continuous measurement of various physical quantities along the entire length of the sensor. This eliminates the risk of missing localized extreme events or damages, such as cracks, leakages, or stress concentrations. However, the widespread adoption of DFOS is hindered by the high costs of optical interrogators, which often restrict its use to periodic measurements rather than fully automated monitoring. A practical solution to this challenge is the synergistic combination of point-based and distributed technologies within hybrid monitoring systems. Such systems leverage the strengths of both approaches, offering a more comprehensive understanding of structural behavior. This paper explores the concept of hybrid systems, illustrating their potential and real-world applications through selected case studies.

KEY WORDS: hybrid system, DFOS, distributed sensing, optical sensors, bridges.

1 INTRODUCTION

Diagnostics and maintenance in an appropriate technical condition of existing, ageing infrastructure (including bridges, tunnels, pipelines and other safety-critical facilities) is one of the key challenges currently faced by both Polish and global civil engineering. Today, experts conducting periodic inspections have significantly broader responsibilities than in the past [1], along with an increased scope of accountability for the decisions they make. Therefore, the decision-making process [2] related to the operational safety of structures, particularly those with large spans [3] or unconventional structural solutions, should be supported by objective, effective, and cost-efficient diagnostic methods. As a result, integrated structural health monitoring (SHM) systems [4] are increasingly being used, enabling the measurement of selected physical and mechanical parameters of structures during their normal operation.

Beyond the growing awareness within the engineering community, the development of monitoring systems is also, unfortunately, driven by the recurring occurrence of structural failures and collapses [5][6]. These incidents often stem from errors made during the design, construction, and maintenance of bridge structures. From a statistical standpoint, it is impossible to completely eliminate such errors. However, it is essential to take measures aimed at minimising the risk of structural failures. SHM systems contribute to this objective by providing early warnings of potential hazards, detecting trends that enable forecasting of structural behaviour over time, and supplying objective data for the calibration of theoretical and numerical models.

The effectiveness of monitoring systems, however, depends on numerous factors, including the choice of measurement techniques, data acquisition methods, installation quality, selection of measurement locations, accuracy of applied data processing algorithms, thermal compensation, and the adopted diagnostic procedures. Developing an effective system requires interdisciplinary knowledge that often extends beyond the expertise of civil engineers and even mechanical specialists. Another challenge is the wide range of measurement techniques available on the market, each with its own advantages and limitations. There is no universal solution. Monitoring systems should therefore be designed individually, tailored to the specific characteristics and operational conditions of a given structure.

Analysing the rapidly evolving market for structural diagnostics and monitoring, certain trends shaping the general approach to monitoring systems design can be observed. One of the most promising directions is the development of hybrid monitoring systems, which aim to synergistically combine selected measurement techniques to optimise the information obtained about the structural safety while simultaneously reducing overall system costs. The following sections of this article explain the concept of hybrid systems and present their operational principles using the selected case studies, with the main focus on bridge structures.

2 SPOT MEASUREMENTS CONTINOUS IN TIME

The fundamental requirement for implementing an early warning system is to carry out measurements automatically and continuously over time. The vast majority of such systems are built using spot sensors, installed at selected locations within the structure – Fig. 1.

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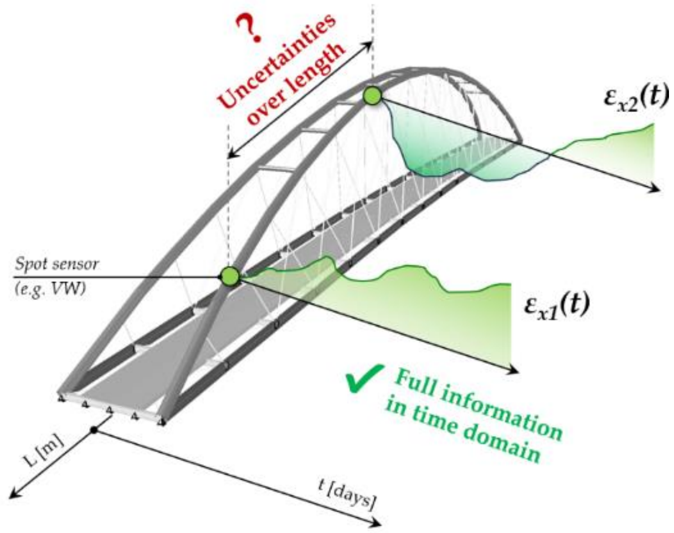

Figure 1. The scheme of the monitoring based on automatic spot sensors, performing continuous measurements over time at selected locations of the structure.

Thanks to their long-term stability, high accuracy, and resistance to environmental conditions, vibrating wire gauges [7] have found widespread use in such systems. The most commonly measured physical quantities are strains [8], based on which local stress in the monitored material can be estimated. Nowadays, all vibrating wire gauges are equipped with integrated thermistors, allowing for appropriate corrections to the measured strain values due to temperature changes over time, as well as enabling an assessment of the global structural performance due to the thermal loading [9]. This approach allows for the analysis of time-dependent phenomena, including trend identification, forecasting the behaviour of the structure, and identifying potential threats that become apparent in changes in locally measured parameters.

Depending on the design of the vibrating wire gauge, in addition to strains, it is possible to measure other physical quantities such as stress, displacements, rotations or forces. Other spot measurement technologies are also used, such as piezoelectric accelerometers for vibration monitoring, MEMS inclinometers for measuring rotations, inductive sensors, and many others. A typical scheme of a spot-based monitoring system for a bridge structure is shown in Figure 2.

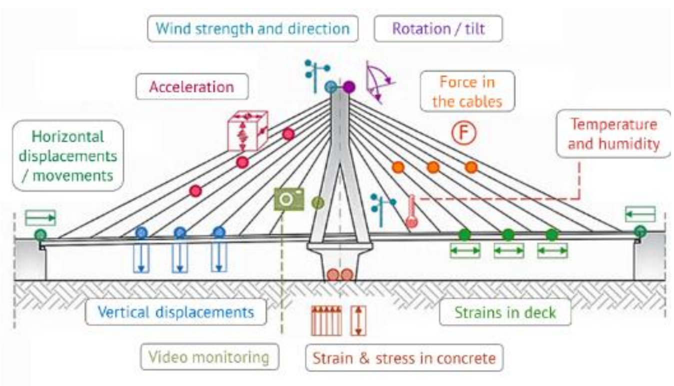

Figure 2. A typical monitoring system for a bridge structure designed with spot gauges.

The gauges are connected to local dataloggers that send measurement data to a remote server, where further analysis and interpretation are carried out. The cost of such loggers is typically negligible in the context of the entire investment. However, despite the many advantages of this approach, it also has several limitations. First, measurements are only taken at selected spots. Aside from the need to choose optimal measurement locations, which is often not a trivial task, there is a lack of information during operation about what is happening with the structure between the measurement points. In other words, this system does not allow for the direct detection of local threats, such as cracks, damage, or stress concentrations. Furthermore, the unit cost of a single gauge is relatively high due to the justified necessity of using high-quality sensors. Another issue is often the need to install long and complex cable routes, as each sensor must be connected to the logger using dedicated signal cables.

3 DISTRIBUTED FIBRE OPTIC SENSING (MEASUREMENTS CONTINOUS OVER LENGTH)

Distributed fibre optic sensing (DFOS) [10] features a number of advantages such as high accuracy, measurement stability over time, and immunity to electromagnetic interference. However, its primary characteristic and advantage, distinguishing it from traditional discrete methods, is the ability to perform measurements of strain, temperature, displacement, and vibration not only at selected points of the structure but along its entire length (Fig. 3), ranging from a few centimetres to several hundred kilometres. Therefore, the analysis of the structure's performance can be carried out not only in the time domain $\varepsilon(t)$ but also in the length domain $\varepsilon(l)$, providing entirely new insights and diagnostic possibilities.

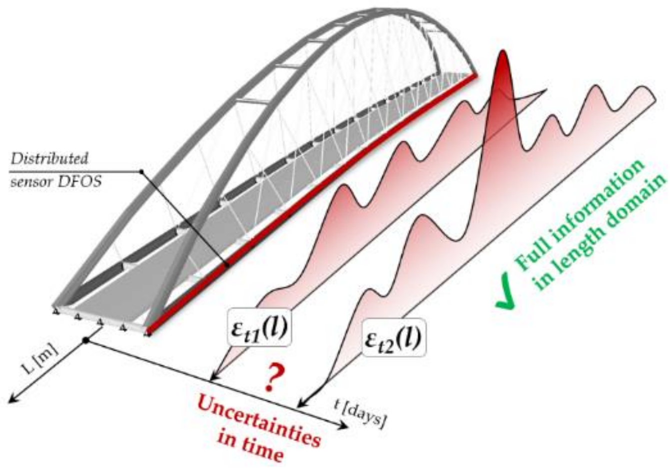

Figure 3. The scheme of the monitoring based on fibre optic sensors (DFOS), performing continuous measurements along the entire length of the structure.

Thanks to the use of linear sensors, there is no need to select optimal locations for measurement locations, the number of which is often limited by budget constraints. DFOS sensors are installed along the entire length of the monitored elements or entire structures [11], such as bridges [12][13], roads [14], tunnels [15], railways [16][17], collectors and pipelines [18], or linear concrete elements like girders [19]. A significant

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consequence of performing geometrically continuous measurements is the ability to directly detect local damage or threats, such as concrete cracking [20][21], local stress concentrations, sinkholes, leaks, and others. As a result, the effectiveness of the measurement system in early risk identification is very high – there is no possibility of missing extreme values of the measured physical quantities. This is one of the main reasons for the dynamic growth and development of DFOS technology in construction and civil engineering, which translates into a noticeable increase in its practical applications. Figure 4 shows selected examples of implementations within Polish bridges only [22, 23, 24, 25, 26, 27]. The full list of bridges and various types of structures is much longer.

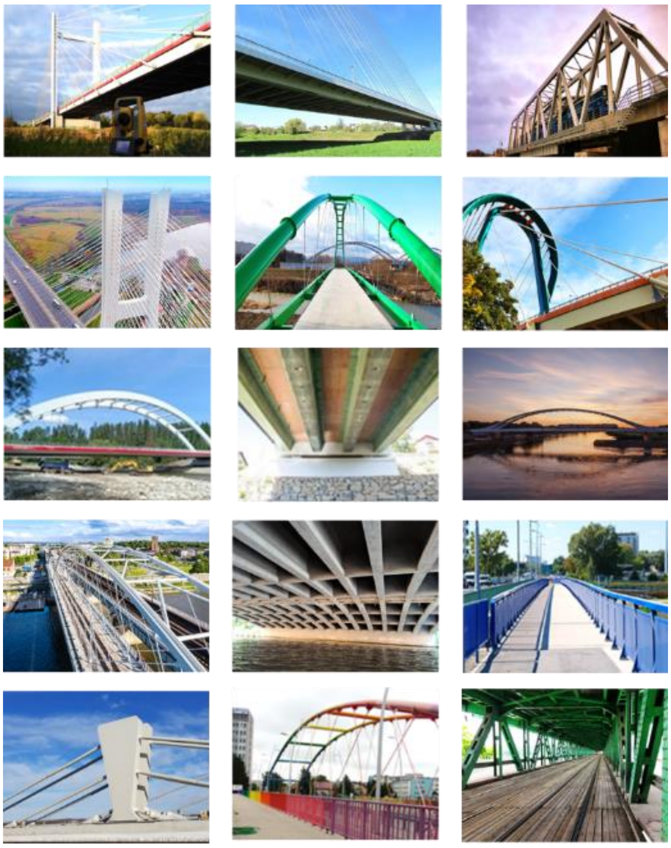

Figure 4. Example bridge structures in Poland equipped with distributed fibre optic sensing DFOS systems.

It is worth emphasising that depending on the type of chosen interrogator (optical datalogger), sensors, and installation approaches, the DFOS technique allows for the measurement of various physical quantities. The most commonly measured parameters include mechanical-thermal strains [28], but also shape changes (displacements) [29][30] and vibrations. Interestingly, there is the possibility of connecting the same sensors to different optical interrogators for simultaneous measurements of various quantities, such as strain and temperature. It should also be noted that, although the DFOS technique can represent a breakthrough in monitoring and diagnosing structures, there is no one universal solution for optimal sensor and interrogator properties. In other words, a wide range of optical fibres, cables, and sensors is available on the market [31][32][33], each characterised by its own advantages and limitations. When selecting a specific sensor, attention should be given to aspects such as:

- size and shape of the cross-section (round, rectangular),
- internal construction (layered, monolithic),
- core material parameters such as elasticity modulus or maximum elongation,
- type of outer surface (smooth, ribbed, with a braid),
- mechanical, chemical, and environmental resistance,
- minimum bending radius.

It is important to emphasise that both the parameters of the interrogators and sensors should be selected individually based on the needs of a given project. For example, in the case of embedding sensors in concrete, round cross-sections and an external braid to improve adhesion are preferred. On the other hand, for gluing to flat surfaces, a flat rectangular cross-section without a braid is better. Sensors are a key component of the entire system. Once integrated into the monitored structure, they should provide reliable information about its performance throughout the entire service life. In telecommunications applications, optical fibres are used with various protective coatings, as well as layered cables, where the fibre is protected by additional protective layers. However, these layers usually do not adequately transmit strain to the sensing fibre inside the cable, creating the risk of data misinterpretation [20]. Therefore, in engineering applications, sensors designed as composite elements with fibres fully integrated with the single-material core during production are more often applied. Fig. 5 shows the family of various monolithic sensors. The EpsilonSensor has a low modulus of elasticity (3 GPa), making it particularly sensitive to detecting cracks in concrete. The EpsilonRebar, with a modulus of 50 GPa, can, in addition to its sensing function, also serve as reinforcement with parameters similar to typical GFRP (glass fibre reinforced polymer) bars. The EpsilonFlat is suitable for bonding to the surface of structures, while the EpsilonGraph is ideal for projects where rapidly changing temperature is a key parameter.

Figure 5. Typical monolithic sensors for mechanical-thermal strains [courtesy of SHM System / Nerve-Sensors].

There is no doubt that a well-designed DFOS system can provide unique information, allowing reliable inferences about the technical condition of a structure. However, a key limitation of this technology in practice, slowing down its widespread

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adoption, is the high cost of optical interrogators. Therefore, a common practice is to use a single device for periodic readings from sensors installed on multiple structures. Of course, the cost efficiency of the system will also depend on the scale of the investment and the responsibility (failure consequences) of the monitored structure.

While DFOS measurements are most commonly performed periodically today, it is worth noting the rapid development of optical equipment. In recent years, new devices have appeared on the market, and existing ones have been improved in terms of selected parameters, such as spatial resolution or maximum measurement range. The high cost is partly due to the patents in place, which, in some cases, will expire in a few to several years. Therefore, it is expected that the cost of such devices will decrease in the future, while their diagnostic capabilities will increase. Creating intelligent infrastructure today, equipped with relatively not expansive DFOS sensors, will not only allow precise periodic measurements but also prepare for the use of future, yet unknown capabilities.

It is also worth noting that DFOS sensors are, at the same time, signal cables (transmitting information from thousands of measurement points directly to the interrogator). In spot measurements, a signal cable must be routed (and secured) from each sensor to the local datalogger, which in many cases can be problematic. This applies especially to structures such as bridges, large-scale buildings (halls and stadiums), and linear infrastructure such as pipelines, collectors, or railways. A comparison in cross-section volume of 20 typical signal cables with a single optical fibre is shown in Figure 6.

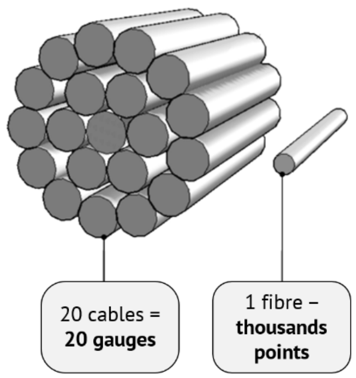

Figure 6. Comparison of 20 typical signal cables with a single optical fibre, capable of handling tens of thousands of measurement points.

4 HYBRID SYSTEMS

To summarise the above considerations, it should be stated that the primary limitation of classical spot techniques is their locality, while the limitation of DFOS methods is their periodicity (resulting from economic, rather than technical, factors). Therefore, a natural consequence of attempting to solve this problem is the synergistic combination of spot technology with geometrically continuous sensing through the design of a hybrid system – Figure 7. In this approach, automatic spot measurements (continuous in time) are supported by periodic DFOS measurements (continuous in length) to optimise the obtained information, while maintaining economic feasibility. Hybrid systems have the following advantages:

- low cost of distributed fibre optic sensors,
- possibility of limiting the number of relatively expensive spot gauges and cabling,
- no need to purchase expensive DFOS interrogators,
- ability to install distributed sensors during the construction phase, with measurements taken at later times (a "time-delayed investment"),
- increased system reliability through comparative analysis of data from at least two independent measurement techniques,
- direct detection of local damage, cracks, or stress concentrations (using DFOS sensors),
- possibility of analysing and identifying long-term trends in the operation of the structure (forecasting with spot gauges).

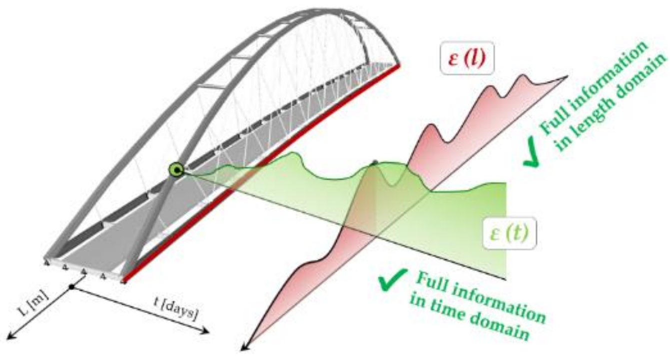

Figure 7. Concept of a hybrid system providing information about the technical condition of the structure both as a function of time and as a function of length.

Hybrid systems are not just a theoretical concept, but an increasingly common solution used in practice. According to the authors, it is one of the main directions that the structural health monitoring market will follow in the coming years. The further part of this article discusses the examples of the use of a hybrid approach for the diagnostics of one of the polish bridge and gas pipeline.

5 EXAMPLE APPLICATION – THE CONCRETE BRIDGE IN NOWE MIESTO LUBAWSKIE

The analysed system concerns the road bridge over the Wel River, which is the longest and most technologically complex structure on the Polish national road DK15. This five-span bridge, with a total length exceeding 267 m, was built as part of the bypass around the city "Nowe Miasto Lubawskie". The load-bearing structure of the bridge is a prestressed concrete box girder (Figure 8) with a structural height of 3.5 m. The installation of the box girder system using longitudinal launching technology was divided into 9 segments, each of which was cast in two stages. Due to certain concerns regarding the durability of the structure, it was decided to equip the existing bridge with a hybrid monitoring system, consisting of: 1) distributed fibre optic sensors for strain measurements and crack detection, and 2) automatic vibrating wire gauges for strain and temperature measurements continuous in time.

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Figure 8. General view of the analysed bridge from the outside (top) and inside of the prestressed box (bottom).

Distributed strain sensors (EpsilonSensors) with an external braid were installed in four measurement lines (A, B, C, D) along the entire length of the bridge, achieving a total of 1040 meters of sensing path. Assuming a spatial resolution of the interrogator used at 5 mm, this results in a total of 208,000 measurement locations within a single session. Installing such a large number of spot gauges with cabling would be impossible both technically and economically. The sensors were installed inside the prestressed box in near-to-surface grooves using a dedicated mortar. Additionally, 4 sections were installed on the side wall of the box along the prestressing cables, with a total length of 44 m, by gluing the sensors without external braid directly to the surface (Figure 9).

Figure 9. Installation of the EpsilonSensors with braid in near-to-surface grooves (top) and without braid directly on the concrete surface (bottom).

For the automatic measurements, spot strain gauges in the form of vibrating wire transducers were chosen, installed in 3 cross-sections, with 4 gauges in each section. This resulted in a total of 12 measurement locations, additionally equipped with reference thermistors – Figure 10.

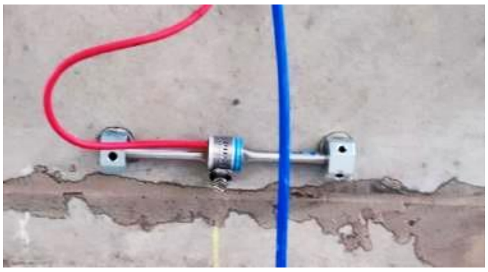

Figure 10. Example view of vibrating wire strain gauge (Geokon 4000) during installation.

The location of all the sensors (both spot gauges and distibued EpsilonSensors) within the hybrid system in question is shown in Figure 10.

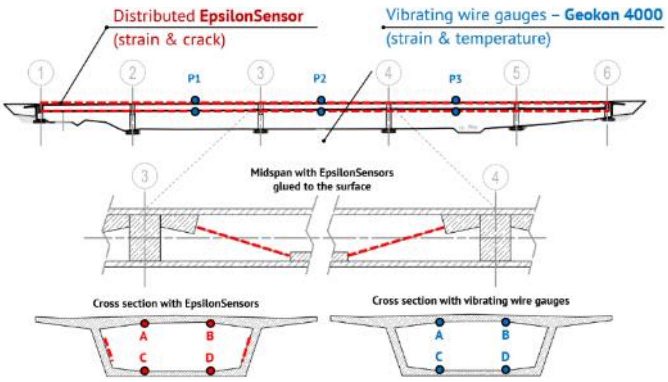

Figure 11. Location of distributed sensors (red) and vibrating wire gauges (blue) within the considered hybrid system.

An example of the strain and temperature plot as a function of time for a selected spot gauge is presented in Figure 12. The period under consideration is the first year of system operation, from July 2023 to July 2024. The obtained results indicate a complete dependency of strain on temperature changes on an annual basis, without any visible alarming trends. The graph shows three vertical blue lines marking the moments of periodic DFOS measurement sessions (S00, S01, and S02). The S00 session was the reference state (zero reading) for both independent techniques to enable their direct comparison.

On the other hand, the profile of the measured strains along the entire length of the central span (60 m) obtained during the periodic, but distributed measurements is presented in Figure 13. The DFOS-based strains profiles exhibit a smooth course, without distinct local extremes characteristic of cracking. Based on the measurements, no open cracks were found along the entire length of the bridge, which is a crucial piece of information for assessing the durability of the analysed structure. Local fluctuations are related to the typical behaviour of concrete as a heterogeneous material. During the first measurement session (S01), a temperature drop of approximately 30°C was recorded in reference to zero reading, which caused the bridge length to decrease due to thermal contraction (negative strain values). Measurements in session S02 were taken under similar thermal conditions to session S00, so the measured strain profile is close to the zero axis.

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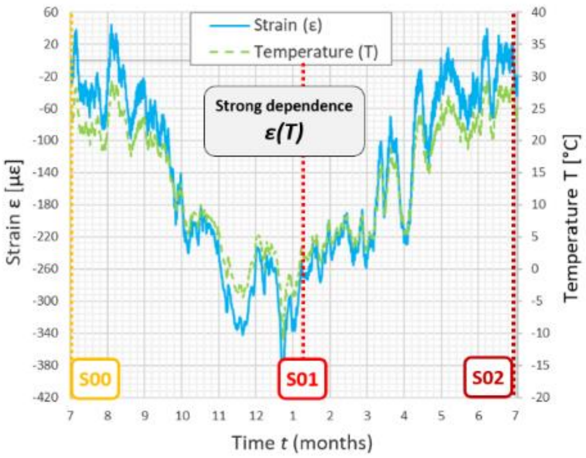

Figure 12. Example strain changes versus temperature changes over time at selected location.

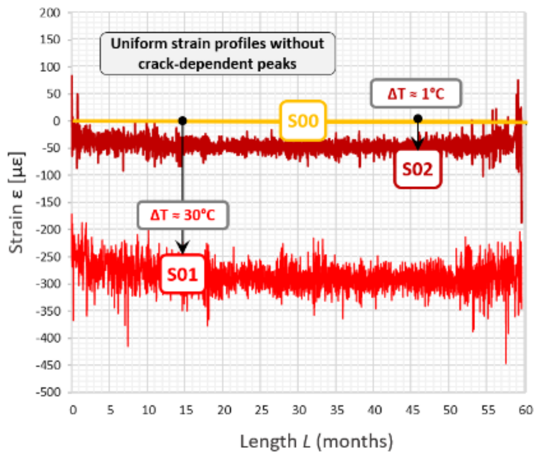

Figure 13. Example strain distribution along the central span in subsequent measurement sessions.

The data from the first year of system operation indicate the normal behaviour of the bridge (in accordance with theoretical predictions) under varying thermal conditions. No hazardous trends were identified through continuous measurements, nor were any local damages detected by distributed sensing.

6 EXAMPLE APPLICATION - PIPELINE

The second example concerns the high-pressure pipeline monitored with a hybrid approach. The general concept of the system is visualised in Figure 14. The installation included 12 vibrating wire strain transducers (Geokon 4150) arranged within four cross-sections (Figure 15). On the other hand, the entire 180 m long segment of the pipeline was equipped with distributed strain sensors (EpsilonRebas) and distributed shape sensors (3DSensors).

There were two types of installation approaches. The first one (and more challenging) included the gluing the strain sensors directly to the pipeline surface (Figure 16). On the other hand, both strain and displacements sensors were embedded in surrounding ground (Figure 17), which is relatively simple procedure. The goal of that was to analyse the quality and possible correlation of the data obtained with these two methods and thus to optimise the future installations.

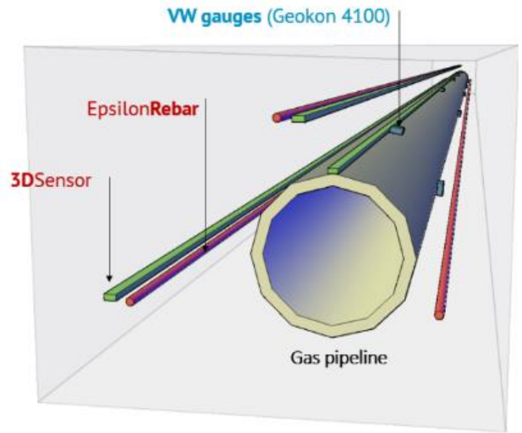

Figure 14. Visualisation of the hybrid monitoring system for the analysed gas pipeline segment

Figure 15. Vibrating wire gauges and their initial check during installation on the pipeline section.

Figure 16. Distributed strain sensors (EpsilonRebars) during the installation (just before glueing) directly on the pipeline.

Figure 17. Distributed displacement sensors (3DSensors) during the installation within the surrounding ground.

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Figure 18 shows the analysed segment of the pipeline equipped with all the sensors in the final installation stage, right before backfilling the entire section with soil.

Figure 18. The view of the monitored section during final stage of installation (just before its backfilling with the soil).

The example data provided by the system in the first year of its operation are discussed hereafter. Figure 19 shows the relationship between strain and thermal changes measured by one of the spot gauges at a selected location. As with the previously presented bridge, the data indicate the normal, cyclic behaviour of the pipeline with no alarming trends. There is a full correlation between these two quantities, indicating that other potentially hazardous mechanical actions (e.g. mass movements, settlements, or sinkholes) are not present.

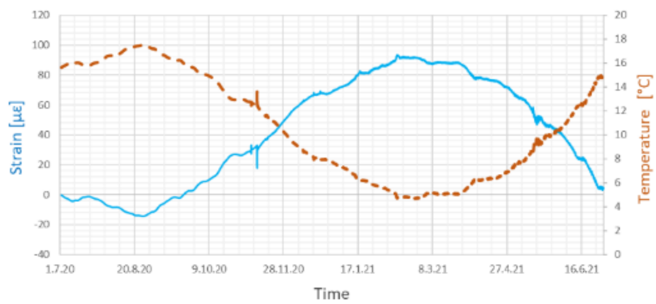

Figure 19. Example strain changes versus temperature changes over time at selected location.

Despite the importance of the above findings, it is not possible to determine the extreme strain (and stress) values or directly answer the question regarding the pipeline's state between measurement locations based on spot gauges. Since no significant deformations were identified throughout the entire year of operation, the results from the pressure test conducted before the pipeline was put into service were selected to demonstrate the capabilities of distributed measurements.

Figure 20 presents the influence of spiral welds, resulting in local distortions in strain profiles. These welds cause both tensile and compressive strains. In the theoretical analysis of a continuous pipeline section under the pressure test, only tensile strains are expected. A similar effect, but much stronger, was observed at the pipeline bends, as shown in Figure 21. Such effects are not always considered in engineering analysis during the design stage, nor are they detectable by conventional spot techniques. This is why the DFOS approach enhances the understanding of the structural performance of pipelines, enabling better (safer) designs in future applications, as well as effective monitoring for optimised maintenance.

The last, but not least, example of DFOS data shows strain distributions at the beginning of the analysed section (Figure 22). Based on this, it is possible to estimate the length of the transition zone along which the friction between the pipeline and surrounding ground is mobilised. After this length, the mean strains in the pipeline section oscillate around zero due to full constraint.

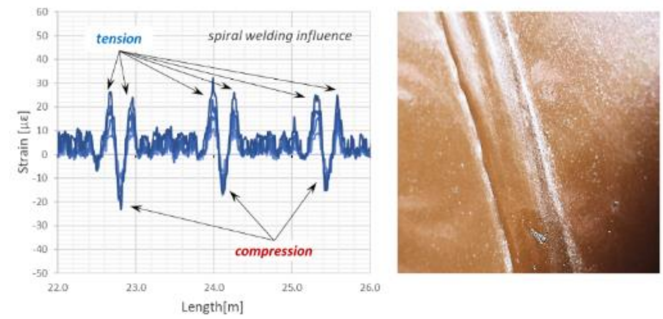

Figure 20. Distributed strain sensing results: the local influence of spiral weld along the length

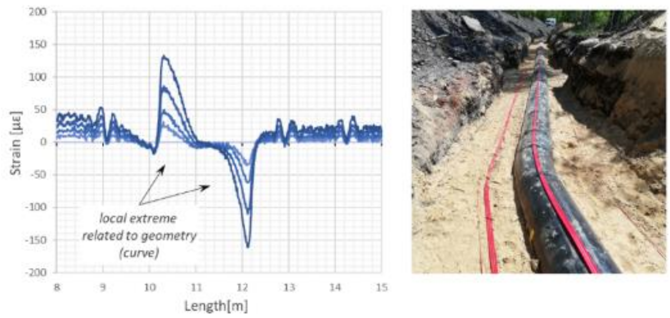

Figure 21. Distributed strain sensing results: the local influence of the turn (curve) along the length

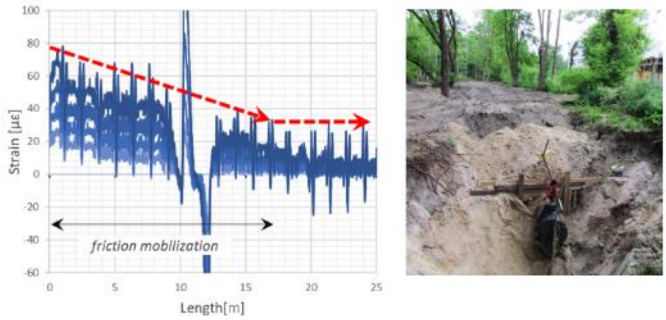

Figure 22. Distributed strain sensing results: the estimation of friction mobilisation at the beginning of the section

An important feature and, at the same time, an advantage of DFOS technology is its capability to measure various physical quantities using exactly the same sensors connected to different optical interrogators. In the present project, EpsilonRebars provided mechanical strain data, as shown above, but also enabled distributed temperature sensing (DTS) with a Raman-based interrogator. Example temperature profiles measured over three consecutive months along the entire length of the

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monitored pipeline section are presented in Figure 23, alongside results from reference spot thermistors. The data comparison shows very good agreement, demonstrating the required accuracy of DFOS technology in practical field applications.

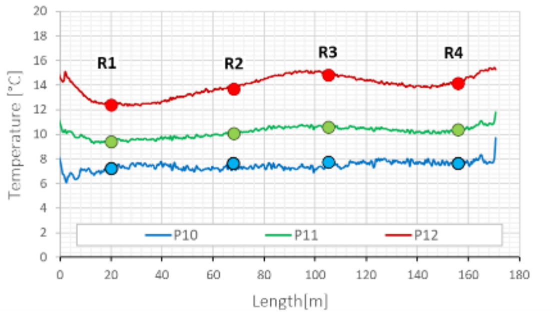

Figure 23. Example temperature distributions along the pipeline in three subsequent months versus results from reference spot thermistors (R1, R2, R3 and R4).

The temperature can be averaged over the entire length and presented in the time domain to observe changes on an annual basis and identify possible trends. Such data are presented in Figure 24 for three EpsilonRebars glued directly to the pipeline surface. The colours in the last three months correspond to the colours in the temperature distributions in Figure 24.

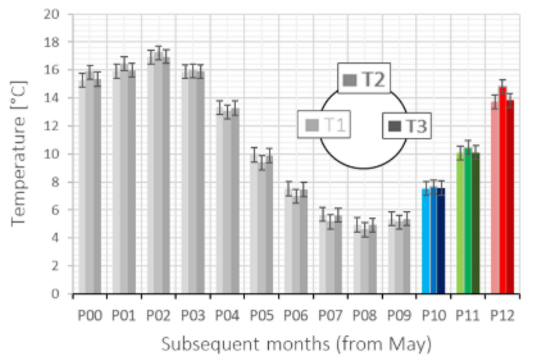

Figure 24. Mean temperature values from three EpsilonRebars in subsequent months over the entire year.

7 SUMMARY

The article discusses the concept and an example implementation of a hybrid monitoring system on a bridge and a gas pipeline. Thanks to the adopted approach, it was possible to obtain extensive information about the technical condition of these structures while maintaining economic feasibility.

In the first year of the systems' operation, the full correlation between strain and temperature over time was identified using automatic spot measurements. No concerning trends in the structures' performance (e.g., a monotonic increase in strains unrelated to temperature changes) were observed.

Meanwhile, periodic, geometrically continuous DFOS measurements enabled a detailed analysis in the length domain. In the case of the prestressed bridge structure, they confirmed that it remained in an uncracked state along its entire length - crucial information for assessing technical condition and structural safety. For the pipeline, DFOS provided deep insights into the local influence of welds and geometrical bends on strain distribution, an aspect that could not be captured by other spot sensing technologies.

The technical effectiveness and economic benefits of hybrid monitoring systems, along with lessons learned from previous applications, suggest that this approach will be increasingly adopted in the structural health monitoring market in the near future, particularly within safety-critical infrastructure.

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