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Using distributed fiber optic sensors to monitor underground infrastructure

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Abstract

The development of monitoring system technology enables more accurate measurement at regular intervals of many parameters affecting the safety and proper functioning of underground infrastructure. Means of monitoring underground infrastructure using distributed fiber optic sensors (DFOS) are presented in this paper. DFOS use is developing rapidly and investment is increasingly visible internationally – examples are given. The preliminary results are also presented of research on the application of DFOS for monitoring pipeline deformation and thin-walled GRP (FRP) panels used in the renovation of existing sewage networks.

Key words: DFOS, GRP, monitoring, sewage collectors

Highlights

- Modern method of monitoring collectors and pipelines.
- Significant improvement of measurement resolution compared to traditional monitoring methods.
- Lower installation costs compared to traditional monitoring systems.
- Low maintenance costs of monitoring.
- Increasingly used in underground construction.

Graphical Abstract

INTRODUCTION

Current city and metropolis development is aimed at providing the highest quality services to residents to meet their basic needs including, primarily, their safety and comfort. Urban development is connected to searching for compromises between functionality and the aesthetics of the surrounding city space. New urban development projects must be characterized by increasingly better use of

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urban areas, which leads to high-rise over-ground construction, and the development of more and denser sub-surface infrastructure (Madryas 2014).

Modernizing existing networks and constructing new ones increases their interactions, and makes direct access for maintenance and repair increasingly difficult. More and more advanced and automated monitoring is therefore needed. Early and precise identification of hazards enables effective prevention of failures, which limits their negative consequences, including primarily the scale of necessary repairs, and the level of user-functional limitations; for example, access to drinking or for heating water (Popielski 2019). Modern measurement technologies can help, at low cost in relation to the main investment, to achieve a monitoring network with high measurement resolution, and providing information continuously and automatically.

Distributed fiber optic sensors

One modern technology used increasingly in construction is distributed fiber optic sensors (DFOSs). They were used initially in the aerospace industry because of the high level of responsibility and need for innovative solutions. Among other things, they were used to measure aircraft wing and spacecraft hull plate deformation (Beard *et al.* 2005; Mckenzie & Karafolas 2005; Ma & Chen 2018). The use of fiber optic sensors is becoming increasingly important in engineering fields including infrastructure such as bridges, tunnels and deep foundations. Such sensors are characterized by very high measurement resolution at low purchase and installation cost. They replace the classic vibrating wire, electro-resistance and electro-mechanical sensors, and enable geometrically continuous measurements along the sensor's length, with a minimum resolution of 1 cm and a maximum measuring length of up to 100 km (depending on need). Classical sensors are point-based, so size, unit cost and mounting methods do not permit ranges and resolutions as high as those offered by DFOS (Sieńko *et al.* 2017) – Figure 1.

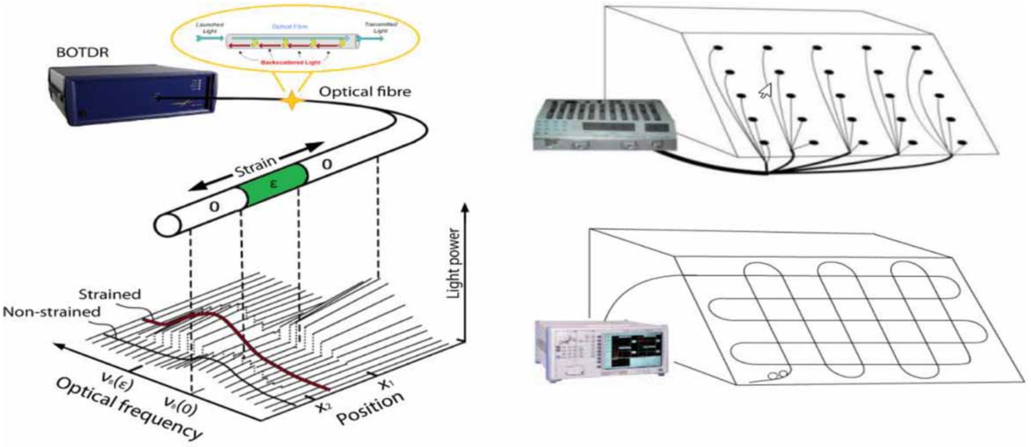

Figure 1 | DFOS principles of operation (left). The difference between point and DFOSs (right) (Guo & Zhao 2018).

The high sensitivity of DFOSs provides proper spatial resolution. It is possible to find out, for example, that a pipeline is suffering disturbing mechanical stress in real time, as well as exactly where the fault is – in some cases to centimeter accuracy – which is sufficient on the scale of large diameter linear objects. A service crew can be dispatched immediately to deal with the problem before severe damage occurs (Mitschke 2016).

Some fiber optic sensors can measure strain or temperature, depending mainly on the signal frequency analyzed, and the discreet Rayleigh, Raman and Brillouin peaks in the electromagnetic spectrum (Tanimola & Hill 2009). DFOSs use natural impurities in fibers that cause backscattering of specific wavelengths of light, which can be read by Brillouin optical time domain reflectometers (BOTDR).

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APPLICATION EXAMPLES

Fiber optic technology is used increasingly in many engineering disciplines. It is particularly popular in relation to sub-surface infrastructure – for example, deep foundations, tunnels and pipelines – where other methods are difficult or impossible to use, by their nature.

Tunnels

Fiber optic sensors play important roles in tunnels where significant stress concentrations can occur from rock masses. DFOS monitoring was implemented successfully in Semmering Base Tunnel, Austria, based on the new Austrian tunneling method (NATM). This method is based on choosing the right load capacity for the ground conditions during excavation, which is not possible during design. Tunnel construction is based on excavating the cross-section segment, then adding reinforcement and applying the external cladding using sprayed concrete. Initial deformations are then observed to determine the required cladding load capacity.

Previously, the evolution of the movements of flexible, sprayed-concrete floor coverings was measured manually with a total station every day, a time-consuming and costly process, so measurements were taken only in the early weeks of tunneling. DFOS enabled stress determination from the rock mass over a more extended period and without the need to stop traffic. DFOS allows automatic and non-invasive measurement of stress evolution over long periods, and is cheaper than other measuring techniques like laser scanning and total station (Lienhart *et al.* 2019). Fiber optic sensors were installed both circumferentially (perpendicular to the tunnel axis) and in loops (alternately perpendicular and parallel to the tunnel axis), to record stresses in the longitudinal direction – Figure 2 (Monsberger & Lienhart 2017).

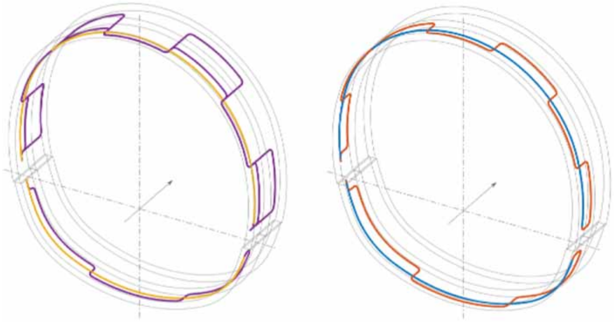

Figure 2 | Fiber optic sensor arrangement in Semmering Base Tunnel cavity side (left) and rock side (right) (Wagner *et al.* 2019).

Measurements were taken automatically for several weeks to capture the stress evolution inside the shotcrete layers from the moment of installation until deformation changes had ceased completely. After the successful initial installations in the Semmering Base Tunnel, further tunnel sections were made, enriched with additional measurement techniques such as laser scanning. The project authors assume that the fiber optic sensors installed will be able to perform their function for the entire expected 150-year operating period (Lienhart *et al.* 2019).

DFOS has also been used in a railway tunnel in the Southern Italian Apennines. The original tunnel, built in 1880, had to be renovated in 1992 as a new and massive structure, due to landslide movements. Unfortunately, the approximately 1 cm/a displacement along the two glide surfaces, (20 and 40 m deep), since about 2005, posed a growing threat to the tunnel's safety. At first, the tunnel was only monitored periodically and in places where changes were visible. In 2016, two fiber optic cables were glued along the tunnel's inner walls and used to measure changing

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displacement along it. The bi-annual measurements are based on a ‘zero’ (reference) reading, and deformation is read using BOTDR (Minardo *et al.* 2018).

Drilling tunnels close to existing infrastructure is a significant challenge because of the poor understanding of their impact on neighboring sub-surface sites. Fiber optic sensors have helped to monitor the existing Royal Mail, 3 m diameter, cast-iron tunnel in London during construction of two new platform tunnels underneath. One of them, Crossrail’s 11 m diameter east-bound Liverpool Street Station platform tunnel, was built about 2 m below the Royal Mail tunnel. DFOS sensors were placed along a 40 m section of the existing tunnel, perimeter spaced at 10 m intervals – Figure 3. While the tunnels were drilled tunnel underneath it, deformations of about 500 $\mu\varepsilon$ were observed in the Royal Mail tunnel, corresponding to 66 MPa of stress (Elshafie *et al.* 2015).

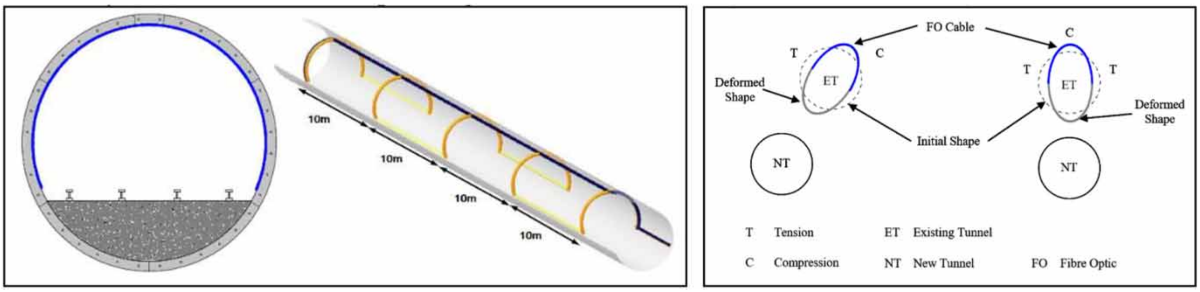

Figure 3 | Schematic diagram of DFOS deployment in the Royal Mail tunnel, London (left); changes in the tunnel’s shape in two cross-sections (right) (Elshafie *et al.* 2015).

Foundation structures

Fiber optic sensors can also play an important role in the deep foundations of roads, railways and skyscrapers. They are not directly related to sub-surface infrastructure, but their increasingly frequent occurrence in densely populated urban areas has an impact on nearby structures. Monitoring can also provide better understanding of the interaction of sub-surface structures.

DFOSs were used in London, where Cambridge University’s Centre for Smart Infrastructure and Construction (CSIC) installed fiber optic sensors on eight 0.9 m diameter and 25 to 37.7 m long reinforced concrete test piles in three different facilities. The fiber optic cables were fixed to the reinforcement baskets with cable ties at approximately 1 m centers. The instrumentation at each point was a single DFOS circuit consisting of temperature and stress wires that could be interrogated simultaneously from a single BOTDR channel. In addition to DFOS, all eight piles carried conventional instruments comprising built-in vibrating wire strain gauge (VWSG) pairs and recoverable extensometers at several points. Temperature sensors are also integrated into the reinforcement baskets at 30 cm intervals to measure the concrete hydration temperature. These three instrumentation systems were used to assess the accuracy of the DFOS data. Battista *et al.* (2016), who report on this work, note that DFOSs not only provide continuous measurement but also data sets that would require three different traditional measurement systems.

Pipelines

There are few examples of practical DFOS for pipeline monitoring applications in the literature. Research has been carried out since the early 2000s, however, and many reports indicate that the technique is suitable for detecting the full strain profile along a pipeline. Even local effects such as loss of rotational and/or axial resistance at the joints can be detected. It enables the condition of the pipeline to be determined below ground, taking into account the complexities of the joint

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behavior, pipe-to-soil interactions, and the interactions between individual pipe sections when the pipeline is displaced by soil deformation (Vorster *et al.* 2006).

The first applications of fiber optic sensors in practice were to detect leaks – for example, in the 500 m gas pipeline described by Inaudi & Glisic (2006), where fiber optic sensors were used to detect gas leaks by observing temperature changes over short distances.

Another example is in a pipeline built in 2002 near Berlin to transport brine from underground natural gas storage. Fiber optic sensors for temperature monitoring were installed along the route to avoid environmental pollution arising from leaks. The fiber optic sensor was buried 10 cm below the pipe in the trench bottom, this position in relation to the pipeline being essential to ensure that all leaks are detected (Inaudi & Glisic 2010).

The 55 km pipeline was divided into four measurement sections, with measurement devices between the 2nd and 3rd sections, to transmit data to the central station. After a year, the system detected its first leak and indicated the location precisely. This enabled rapid repair and the minimization of soil contamination (Nikles *et al.* 2004).

TESTING OF STRENGTH DEFORMATION OF LARGE DIAMETER GRP PIPES

In the Department of Hydraulic Engineering at Warsaw University of Technology, the possibility has been investigated of using helical filament winding DFOS to measure deformation in composite GRP pipes – both circular and non-circular cross-section (Figure 4). Pipelines of any shape and variable wall thickness – longitudinally and transversely – can be made using this technology, which enables the renovation of existing sewers by relining (Walczak 2008). For relining, a new pipe in the form of a liner is inserted into the existing pipeline, and grout injected into the annular space between the elements. This produces a layered structure consisting of the liner, the injected grout and the mother pipe (Nienartowicz 2015). Accurate determination of stress concentration zones and values allows both data verification against design assumptions and wall thickness optimization in pipe cross-sections, which can reduce pipe section production costs. A single fiber optic cable is glued to the outer and inner pipe sections in three loops – Figure 5.

Figure 4 | Pipes with DFOS mounted on outside and inside.

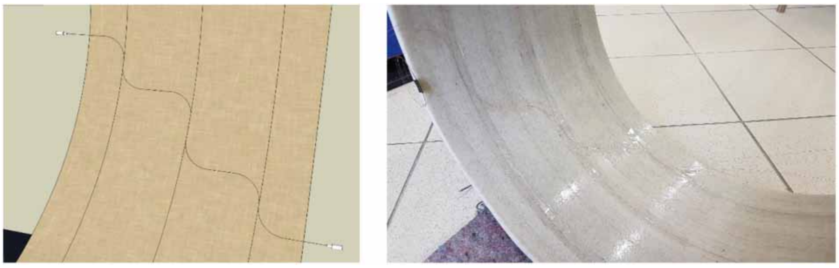

Figure 5 | Fiber optic spacing scheme inside a pipe.

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The strain tests were performed statically and, after the press arm reached the preset force, it was stopped and the deformation measured using a BOTDR (Figure 6). Measurements were made within the permissible force range for pipe deformation in steps of 0.5 kN. To compare the deformation results, the measurement was made using a clock sensor inside the pipe at the point where the force was applied. A 'zero' measurement was made for each pipe, followed by 10 to 15 measurements at the appropriate load and a final measurement without load.

Figure 6 | Test stands for GRP pipe measuring deformation using BOTDR.

Figure 7 shows the sensor deformation values for a circular cross-section, 700 mm diameter pipe, for the forces applied in the press. For each loop, the deformations correspond to the tension and compression zones, with their intensity depending on the force applied.

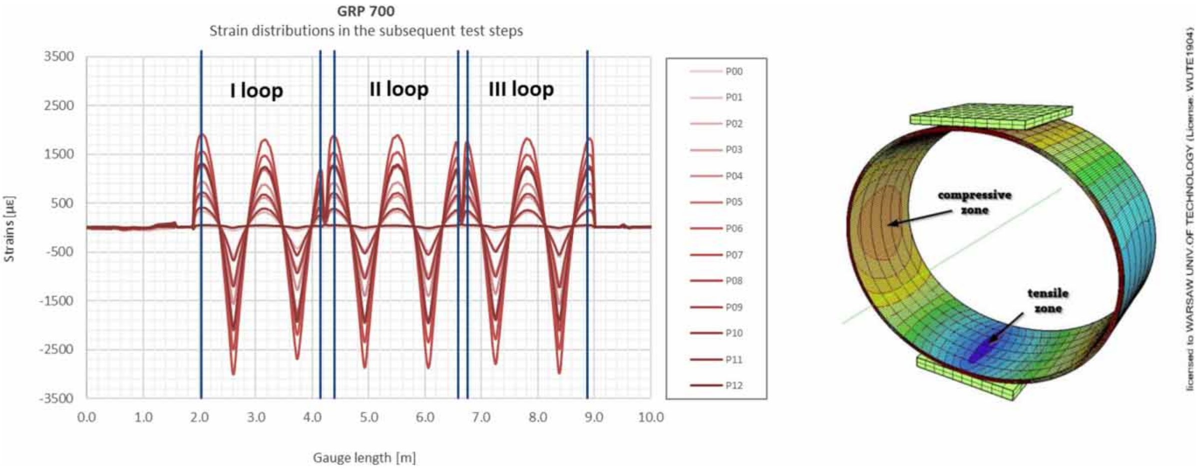

Figure 7 | Individual fiber optic sensor loop deformations, with visible tension and compression zones, and corresponding zones in the mathematical model.

The installation of fiber optic sensors in the test samples involved the fiber optics, resin adhesives, and a measuring device. The fiber optic cost was 0.15 EUR per linear meter, and resin adhesive worth approximately 5 EUR was used to glue 10 m of optical fiber. The highest cost arises from purchasing the BOTDR unit, whose cost exceeds EUR 100,000. In laboratory conditions, a cheaper solution seems to be reusable clock sensors, which cost about 200 EUR. However, the quality and quantity of data obtained, continuously, through fiber optic sensors gives a massive advantage over traditional methods, which can measure displacement only at one point.

For urban wastewater collector renovation and construction projects over large network lengths, the cost of installing DFOS monitoring will be small compared to the cost of potential failures during its operation, as the main cost driver will be the fiber optic cable. With the installation of

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optical fiber, as for the Royal Mail tunnel in London (Elshafie *et al.* 2015), collector sections several kilometers long can be monitored at 5 to 10 cm resolution, which is considerably better than other monitoring systems.

SUMMARY

Recently, interest in DFOS use for sub-surface infrastructure monitoring has increased significantly. Many sensor installations have shown that DFOSs increase the quality of sub-surface monitoring, and provide significantly more data on behavior during construction and operation. It is also clear that the technology's practical potential exceeds what has been done at this early stage. There are still many issues to be solved, however.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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