Distributed Fiber Optic Monitoring Systems in Tunneling: Implementation from research into practice

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ABSTRACT: Structural monitoring in combination with reliable data interpretation is essential to understand the deformation behavior of the lining and finally, to guarantee safe construction and operation. Conventional techniques may involve limitations, either in the spatial or the temporal resolution and do not deliver the overall deformation behavior along the entire lining. Distributed fiber optic sensing (DFOS) has significantly evolved in recent years to monitor large scale civil infrastructure, with scientific sensing designs being realized within various research projects. The technology can be advantageous for in-situ tunnel monitoring since the distributed strain and temperature sensing feature delivers a complete picture of the linings' structural deformation behavior without blind spots. This paper discusses numerous DFOS tunnel monitoring designs and realizations at different construction sites and demonstrates that fiber optic sensors have considerably developed and provide essential capabilities to extend the conventional, geotechnical monitoring toolkit.

Keywords: Distributed fiber optic sensing, tunnel lining, field applications, deformation behavior, structural integrity monitoring.

1 INTRODUCTION

Increasing road and railway traffic world-wide with respect to limited space, increased sustainability as well as longer service lifetimes entails modern tunnel constructions, often in complex environments. Civil structural health monitoring (CSHM) combined with reliable data analysis has therefore become significantly more important in tunneling within the last decades to ensure safe construction works, durable operation and maintenance at the right time.

Conventionally, geodetic targets along the inner surface of the tunnel lining are monitored during construction using total stations (Rabensteiner 1996 or Austrian Society for Geomechanics 2014), which however always require a direct line of sight to the tunnel surface. Automated measurements are often impossible due to several prism targets in the field of view of the automated aiming or regular visual obstructions due to construction traffic. Therefore, displacement readings are usually carried out manually by the surveyor once or twice a day, which is not only time consuming, but also implies safety hazards for the surveyor on-site. The measurement frequency itself may be sufficient to understand the system behavior, but critical events between the observations might be overlooked. Moreover, monitoring beyond the constructional phase during operation usually requires physical human access to the tunnel and limits the availability of the structure, which must be partially or even totally closed during the assessment. Electrical sensors like vibrating wire sensors (Radoncic et al. 2015) or extensometers (Barla 2009) may be additionally installed inside the lining to provide continuous information. The number of sensors inside the lining is however limited due to practical reasons as each electrical sensor needs its own connecting cable to the data logger and hence, information can only be obtained at particular locations.

Distributed fiber optic sensing (DFOS) enables continuous strain (and temperature) monitoring along the entire sensing cable without any visual line-of-sight to the structure. The sensing cable can be directly integrated into the structure, where only one lead-cable is utilized to realize hundreds or even thousands of measurement points inside the lining. This allows an overall assessment of the deformation behavior without blind spots between the sensing locations. The interrogation unit itself may be placed kilometers away from the measurement location (i.e. at the crossway nearby or even outside of the tunnel), which is why distributed monitoring can be performed without any interference with construction works or later operation.

In recent years, scientific DFOS concepts have been practically implemented at various tunnel construction sites, including shotcrete tunnel liners (Battista et al. 2015, Buchmayer et al. 2021 or Wagner et al. 2020), tunnel shaft linings (Lienhart et al. 2019), pre-cast tunnel lining segments (Kechavarzi et al. 2016 or Monsberger et al. 2018) as well as inner tunnel linings (Monsberger et al. 2022). This paper discusses general DFOS capabilities for tunnel monitoring and reviews selected DFOS realizations with focus on practical feasibility, demonstrating the implementation from research into practice.

2 DISTRIBUTED FIBER OPTIC SENSING SYSTEMS IN TUNNELING

Fiber optic sensors have been used in several scientific fields over the last decades. Common sensor types in civil engineering can be divided into pointwise sensors, quasi-distributed FBG (fiber Bragg grating) sensors and fully distributed sensors (DFOS). The latter one utilizes natural scattering effects, which occur when an optical pulse is propagating forward along the sensing glass fiber. Small parts of the scattered effects are reflected back to the interrogation unit and can be analyzed there for sensing purposes, where the backscatter carry distributed information about the strain and temperature behavior along the entire sensing fiber.

The achievable spatial resolution, characterizing the minimum distance between sensing events to separate them, is related to the sensing principle. Rayleigh backscattering systems based on the OFDR (Optical Frequency Domain Reflectometry) can provide high resolution measurements with a spatial sampling in the millimeter range and a measurement resolution of about 1 µm/m (Luna Inc. 2019), comparable to conventional strain gauges. Their sensing range is however limited to 100 m or lower, which is essentially disadvantageous for practical field applications. Interrogation units based on Brillouin scattering enable monitoring over tens of kilometers (fibrisTerre 2020). Despite limitations in the spatial resolution (between 0.1 and 10 m) and the strain repeatability (typically about 2 to 10 µm/m), the sensing technique provides significant benefits for tunneling as measurements can be performed automatically and monitoring is feasible without any interference with the construction and operation.

Distributed fiber optic sensing in harsh environmental conditions like tunnels implies essential mechanical impacts for optical glass fibers with a diameter of 250 µm/m only. The sensing fibers must therefore be reliably protected during installation and monitoring to ensure their integrity. Beside others, SOLIFOS AG (Switzerland) provides prefabricated sensing cables, which are specially designed for sensing in harsh geotechnical environment. It must be noted that DFOS signals are usually sensitive to both, strain and temperature changes. In order to cope with this cross-sensitivity, two individual sensing cables, one with a loose and one with a tightly coupled fiber, are typically installed in parallel to compensate arising temperature effects. An appropriate knowledge on the sensor characteristic curve with respect to strain and temperature changes is mandatory in this process to avoid systematic errors of several percent (Monsberger et al. 2018).

3 PRACTICAL IMPLEMENTATION AND MONITORING RESULTS

DFOS monitoring networks in civil engineering require an appropriate design depending on the structural characteristics. This chapter briefly reviews three different, already realized tunnel monitoring concepts with the intention to provide an overview on general DFOS capabilities in tunneling.

3.1 Conventional shotcrete linings

The installation of any sensors inside the shotcrete lining in conventional tunneling is challenging since the instrumentation has to be integrated in the regular excavation works. The installation procedure must therefore be reliable, but also quick to reduce the interruption to a minimum. Various sensing paths (e.g. in circumferential direction) may be realized by attaching the fiber optic sensing cables to the supporting wire meshes using cable ties or similar (see Figure 1, left). The rigid bond between the cable and the surrounding material is achieved later once the shotcrete is appropriately hardened. Alternatively, the sensing cables may also be installed to an already existing shotcrete lining (Monsberger et al. 2022).

The individual sensing cable layers are collected at a central point for each cross-section, e.g. at a connecting box. Subsequently, supply fibers (i.e. one single connecting cable) can be used to assemble the individual cross-sections to an enhanced sensing network (c.f. Monsberger et al. 2022), which is finally connected to the sensing unit kilometers away from the sensing location.

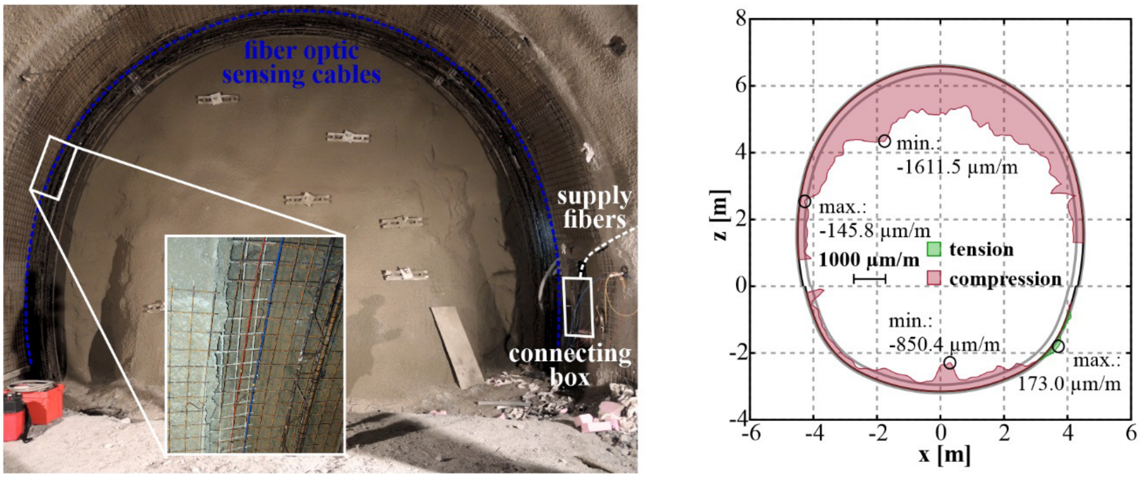

Figure 1. Monitoring of conventional shotcrete linings (Monsberger 2018):
DFOS installation procedure (left) and measured strain distribution along the entire cross-section (right).

The measured strain distribution allows an overall assessment of the deformation behavior in the circumferential direction, as exemplary shown in Figure 1 (right). Distributed information can therefore be captured along the invert, which is not feasible using conventional techniques. If two or more sensing layers are parallelly aligned along the structure (i.e. one layer closer to the cavity or to the rock mass, respectively), curvature profiles orthogonal to the DFOS sensing direction and the corresponding cutting force distribution (Radoncic et al. 2015) can also be derived. Furthermore, the distributed curvature information can be combined with geodetic displacement readings to analyze fully-distributed displacement profiles along the entire cross-section without modeling (Monsberger and Lienhart 2021).

3.2 *Pre-cast tunnel lining segments*

Pre-cast tunnel lining segments can be directly instrumented during manufacturing before the ring is installed inside the tunnel, which not only allows a more reliable sensor protection, but also reduces the excavation interruption. The patented approach (Lienhart and Galler 2016) intends one continuous sensing cable for each segment, which is individually guided along the reinforcement (or a supporting structure for fiber-reinforced concrete, alternatively) and hence, a complete coverage of the segment can be realized. The optical cable connectors are stored at a connection box for each segment during concreting. Later, when the ring is finally set up inside the tunnel, the individual segments are assembled to one continuous measurement loop for each cross-section, see Figure 2 (left). The designed system is arbitrarily expandable to numerous cross-sections within the same network, where all can be cost-effectively interrogated using one sensing unit only. Once the construction is completed, the system might also be integrated into the tunnel's fiber optic network to enable measurements during operation without physical access to the tunnel, e.g. from the operational building.

In addition to the overall assessment, the fully-distributed strain sensing feature also allows the detection of local distortion events like concrete cracks or similar. As an example, Figure 2 (right) shows the temporal progress of the strain distribution obtained along one selected tunnel lining segment. The waterfall chart depicts an immediate strain change at a specific point in time, which could be clearly related to a concrete spelling by visual inspection at the same location. Knowledge about local distortions could be particularly relevant for predictive maintenance measures in due time since newly constructed tunnels are often designed for lifetimes of 100 years or longer.

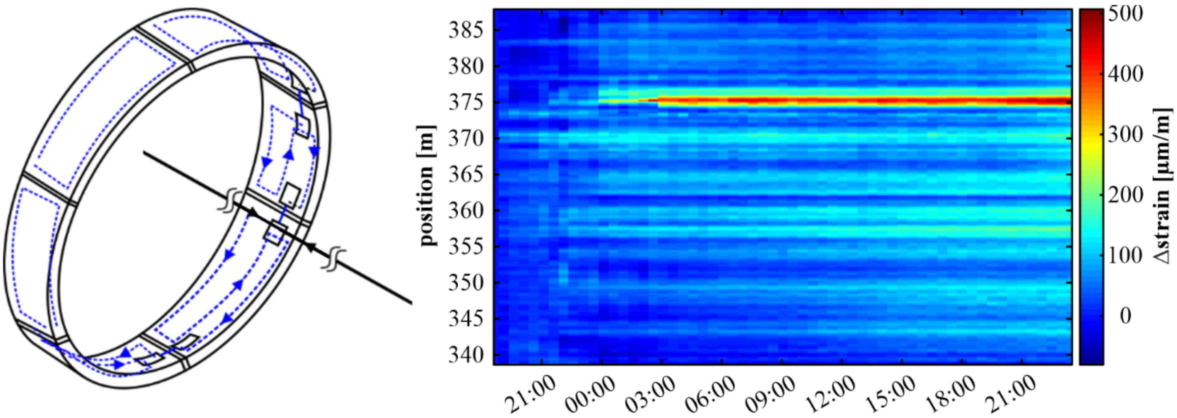

Figure 2. DFOS instrumentation of pre-cast tunnel segment:
Schematic representation of tunnel installation (left, based on Lienhart and Galler 2016) and temporal progress of strain distribution of one selected lining segment (right).

3.3 *Cast-in-place inner tunnel linings*

The monitoring instrumentation of inner tunnel linings enables an additional assessment of the long-term stability of modern tunnel constructions, especially in complex geological conditions or even in urban areas with minimum overburden and other constructions above or nearby. It is essentially beneficial that the locations of monitoring cross-sections can be defined with respect to geological boundary conditions, which are already well known from the excavation process. Monitoring is therefore established in zones of major geotechnical interest, where appropriate sensing systems are integrated at the earliest possible moment during manufacturing to detect and localize arising changes in the structural performance, to evaluate external loading impacts and finally, to plan and design condition-based maintenance works during operation.

The sensor application is usually performed along the reinforcement (Figure 3, left) or even along supporting structures for plain concrete linings. Subsequent installations along the surface of an already existing lining are also feasible (Vorwagner et al. 2020) to allow monitoring of additional zones of interests of ageing tunnels. The appropriate spatial allocation of the sensing cable guiding is important for in-situ DFOS installations to relate the cable position to the physical location inside the tunnel. Laser scanning in combination with total station measurement can not only capture the sensing cable paths, but also provide information of the surrounding area as shown in Figure 3 (right). Hence, the one-dimensional strain information can be seen in their right three-dimensional context for the correct interpretation of local effects as well as the documentation of the structural long-term behavior.

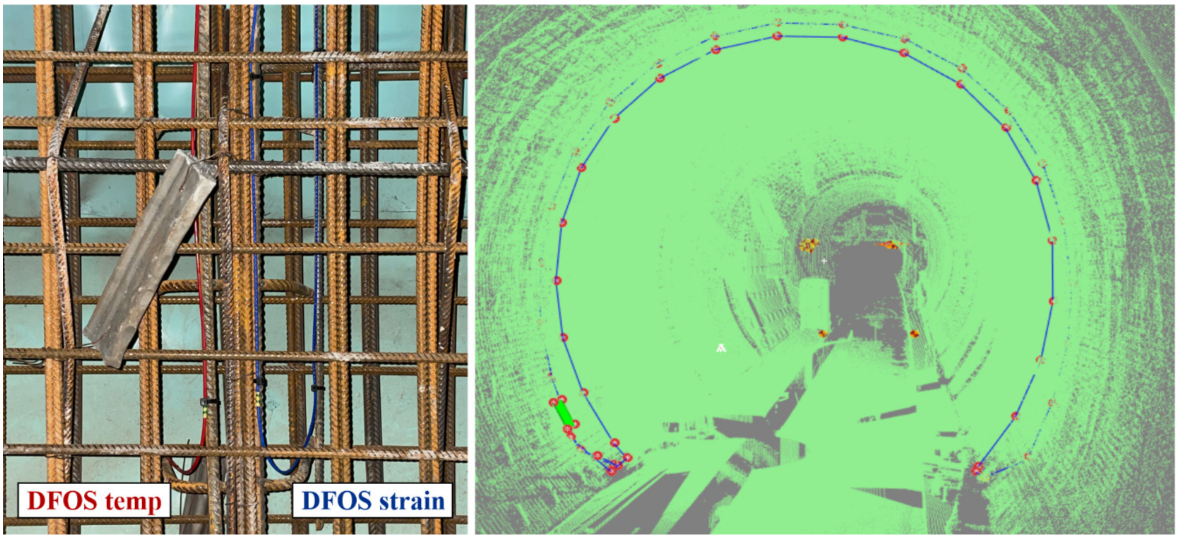

Figure 3. DFOS instrumentation of inner tunnel linings: Installation of strain (blue) and temperature (red) sensing cable along reinforcement (left) and laser scan of monitoring cross-sections after installation (right).

4 CONCLUSIONS

The range of DFOS applications presented in this paper demonstrate that the technology has essentially developed within in recent years and can provide an auspicious alternative to conventional geotechnical monitoring techniques. Suitable installation techniques with robust, reliable fiber optic components are however required to fit the sensor installation to the construction process and reduce any interruption to a minimum. The distributed DFOS strain sensing feature not only allows an assessment of the overall behavior of the tunnel lining, but also enables the detection of local distortions like cracks or concrete spellings. This is especially beneficial for long-term monitoring since arising changes in the structural performance can be detected at an early stage to plan and design predictive maintenance works during the operational lifetime. The DFOS monitoring system can be fully integrated into the tunnel's fiber optic network once the construction is completed, so that measurements can be carried out without physical access to the tunnel.

Current large-scale tunnel projects in Europe and Asia are already being tendered with enhanced DFOS monitoring solutions. However, it must be noted at this point that the expertise and corresponding project references are still limited to a handful of people world-wide. Experts should therefore be consulted and involved into the design and realization phase to ensure the appropriate implementation and finally, the overall quality of the DFOS monitoring results.

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