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Distributed fiber optic sensing in civil structural health monitoring at the next level – Realization of a comprehensive sensing network along the Brenner Base Tunnel

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ABSTRACT:

The Brenner Base Tunnel (BBT) is one of the key civil infrastructure projects currently under construction world-wide and will be the longest underground railway connection globally with a total length of about 64 km once completed. Its service lifetime of 200 years implies essential requirements on the tunnel design, with focus on reducing risks and enabling optimized maintenances works based on appropriate monitoring. The tunnel owner BBT SE has therefore initiated an enhanced distributed fiber optic sensing (DFOS) network inside concrete tunnel lining segments for structural monitoring without human access. This contribution introduces the designed DFOS network, consisting of more than 35 km sensing cable along numerous tunnel cross-sections, spread over more than 30 km tunnel drive and two different construction lots.

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ABSTRACT: The Brenner Base Tunnel (BBT) is one of the key infrastructure projects currently under construction and will be one of the longest underground railway connection with a total length of approximately 64 km once completed. Its service life of 200 years implies essential requirements on the tunnel design. One important focus is to increase the availability of the tunnel, e.g. by enabling optimized maintenance work based on appropriate monitoring. The tunnel owner BBT SE has therefore initiated an enhanced Distributed Fiber Optic Sensing (DFOS) network inside the segmental lining for structural health monitoring without human access. The technology has significantly evolved in recent years to monitor large scale infrastructure, especially for in-situ tunnel monitoring as the distributed sensing feature can provide a complete picture of the strain distribution without blind spots. This contribution introduces the designed DFOS network, consisting of more than 35 km sensing cable along numerous tunnel cross-sections, spread over more than 30 km tunnel drive and two different construction lots. The monitoring data is autonomously evaluated and transferred to the online dashboard in real time. Analysis of the strain distribution provides fundamental information about the actual loading state of the segmental lining. The results together with experiences gained from practical implementations demonstrate the technology's high potential for innovative civil structural health monitoring.

KEY WORDS: Distributed fiber optic sensing; segmental tunnel lining; structural integrity monitoring; deformation behavior; strain distribution

1 PROJECT CHARACTERISTCS AND MONITORING OBJECTIVES

The Brenner Base Tunnel (BBT), a flat rail link with high transport capacity, will connect the Tulfes portal (near Innsbruck, Austria) with the Franzensfeste portal (Italy) over a total length of approximately 64 km in the near future. The cross-alpine rail link is a key project of the 9,121 km long TEN-T Scan-Med (Scandinavian-Mediterranean) corridor and cuts the alpine crest in the base, with high overburdens of up to 1,720 m. It consists of two single-track railroad tunnels with a diameter of 8.1 m, spaced 70 m apart and accompanied by a continuous exploratory tunnel running 12 m below in-between (Figure 1). The exploratory tunnel improves the geological forecast for the rail tunnels, which are partially being advanced by tunnel boring machines afterwards.

Availability plays a decisive role for key infrastructures such as long cross-alpine rail tunnels. The tunnel design includes increased partial safety factors and concrete cover to reach a 200-year service life. Maintenance should be possible without interruption of the operation as far as technically feasible. Tunnel equipment has therefore been shifted to accessible areas or high-maintenance installation areas became accessible by horizontal shafts from the accompanying exploration tunnel.

In addition, the BBT-SE has incorporated an enhanced strategy for structural health monitoring (SHM) during construction and operation using Distributed Fiber Optic Sensing (DFOS). The technology is beneficial compared to conventional techniques as the fiber optic sensing cable can be directly embedded inside the structure to enable distributed strain (and temperature) assessment along hundreds of sensing points. The measurement results can be well compared to traditionally used vibrating wire sensors [1], but also allow an overall assessment of the strain and temperature without blind spots. The sensing unit itself may be placed even kilometers away from the measurement location, even outside of the tunnel and monitoring is possible without any interference with construction works or later operation. The sensor's durability and insensitivity against electromagnetic interferences are essential with respect to the use in rail operation.

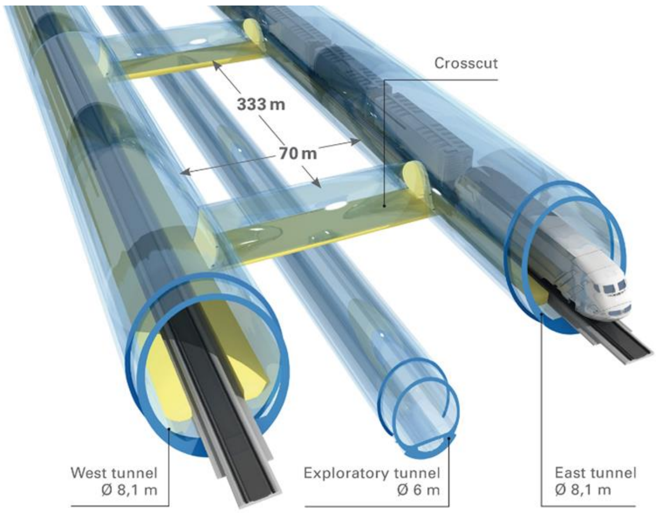

Figure 1. Schematic representation of the typical tunnel cross-sections at Brenner Base Tunnel project (based on [2])

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The DFOS implementation at the BBT focusses on structural health monitoring of the segmental lining, with the aim of optimizing maintenance works by monitoring during operation [3].

Machine-driven tunnel structures within the BBT are constructed efficiently as single shells. Various monitoring approaches have been initiated during construction including chord length measurements, geodetic displacement readings of discrete targets using total stations, laser scanning and fiber optic sensors in defined cross-sections. While the first three are used for accompanying the construction process. The DFOS measurement ring is installed only at structural cross sections of interest like the intersection of rail tunnel and cross-passage as well as in fault zones. The deep-lying machine-driven tunnel and the high stiffness of the segmental lining require a load monitoring with high accuracy. The DFOS strain sensing feature is deployed to analyze the loading condition at dedicated locations inside the segmental lining. Hence, decisions can be made based on these results by choosing the appropriate pre-designed supporting measure for the openings of the cross passages. Additionally, supporting measures like secondary linings are placed according to the load bearing capacity of the existing lining.

The DFOS approach is therefore designed to pursue three primary monitoring objectives:

1) **Construction phase monitoring:** Verification of segmental ring openings and cross-passage advancements.
2) **Load-bearing assessment:** Ensuring compliance with structural safety requirements.
3) **Operational Structural Health Monitoring:** Enabling long-term monitoring without interrupting rail operations.

2 DFOS DESIGN AND MONITORING NETWORK

The instrumentation of concrete tunnel lining segments can be performed outside of the tunnel apart from excavation. This procedure is advantageous in terms of installation as the sensing cables can be reliably attached without time-consuming and cost-intensive inferences with the excavation works, which have not to be interrupted due to the sensor installation.

For more information about the implemented DFOS sensing cables for strain and temperature monitoring as well as the sensor installation inside the individual tunnel lining segments, reference is given to [4].

Inside the tunnel, the fiber optic monitoring segments are built as a normal ring without restrictions after the excavation has been performed. Once the ring is set, the connection boxes for each segment can be opened and the individual segments can be connected to establish a continuous monitoring loop. Supply cables are used to connect the fiber optic sensing cables inside the ring to the reading unit, which is placed in a measurement equipment box approx. 150 m to 200 m behind the monitoring cross-section (see Figure 2). This location is advantageous as the space along the TBM's back-up system is limited and the reading unit shall be as accessible as possible during monitoring for potential maintenance. The equipment box itself is waterproof and does not only contain the reading unit, but also an uninterruptible power supply and an industrial PC with stable internet connection for reliable data transfer. The fiber optic installation works can be usually performed in about 90 to 120 minutes once the ring is constructed. Monitoring is started immediately after the installation, with the monitored segmental lining ring inside the shield, before the TBM continues its further excavation work.

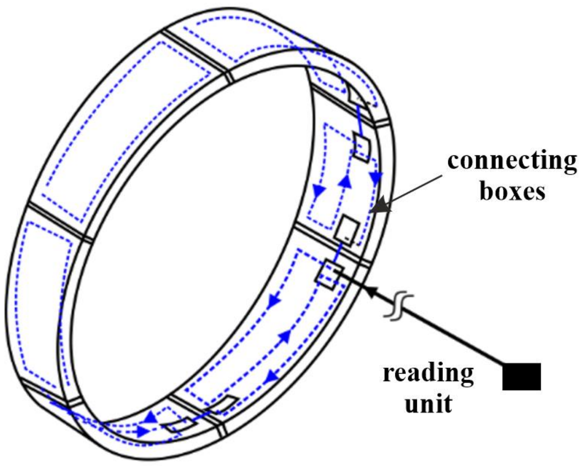

Figure 2. Schematic representation of tunnel installation (based on [5])

The DFOS system's long-term performance and its suitability must be well considered within the network design to provide reliable monitoring over decades. Each individual monitoring cross-section is therefore not only linked to their equipment box behind the TBM, but also connected to a continuous network, which allows monitoring of numerous cross-sections using only one reading unit per tube (Figure 3, top). The so-called active monitoring zone during construction can therefore include up to 7 cross-sections in the actual configuration, excluding additional cross-sections in geological interference zones, where the reading unit is placed in the central equipment box. After the excavation works are completed, the overall system will be adapted for operational monitoring. The DFOS equipment boxes and corresponding connecting cables will be re-located to the maintenance cross-passages (cf. Figure 3, bottom), from where measurements can be performed without interruption during rail operation by accessing from the exploratory tunnel.

3 DFOS DESIGN AND MONITORING NETWORK

The installed fiber optic sensing network has been interrogated using the fTB 5020 from fibris Terre Systems GmbH (Germany). Based on the Brillouin Optical Frequency Domain Analysis (BOFDA) technique, this sensing unit enables distributed measurements up to 25 kilometers within several minutes per monitoring channel, a standard spatial resolution of 0.5 m and a strain repeatability of about 2–10 μm/m depending on the sensing fiber [6]. The interrogation unit is placed inside the DFOS equipment boxes, where the raw data is collected and transferred to external databases via FTP gateway.

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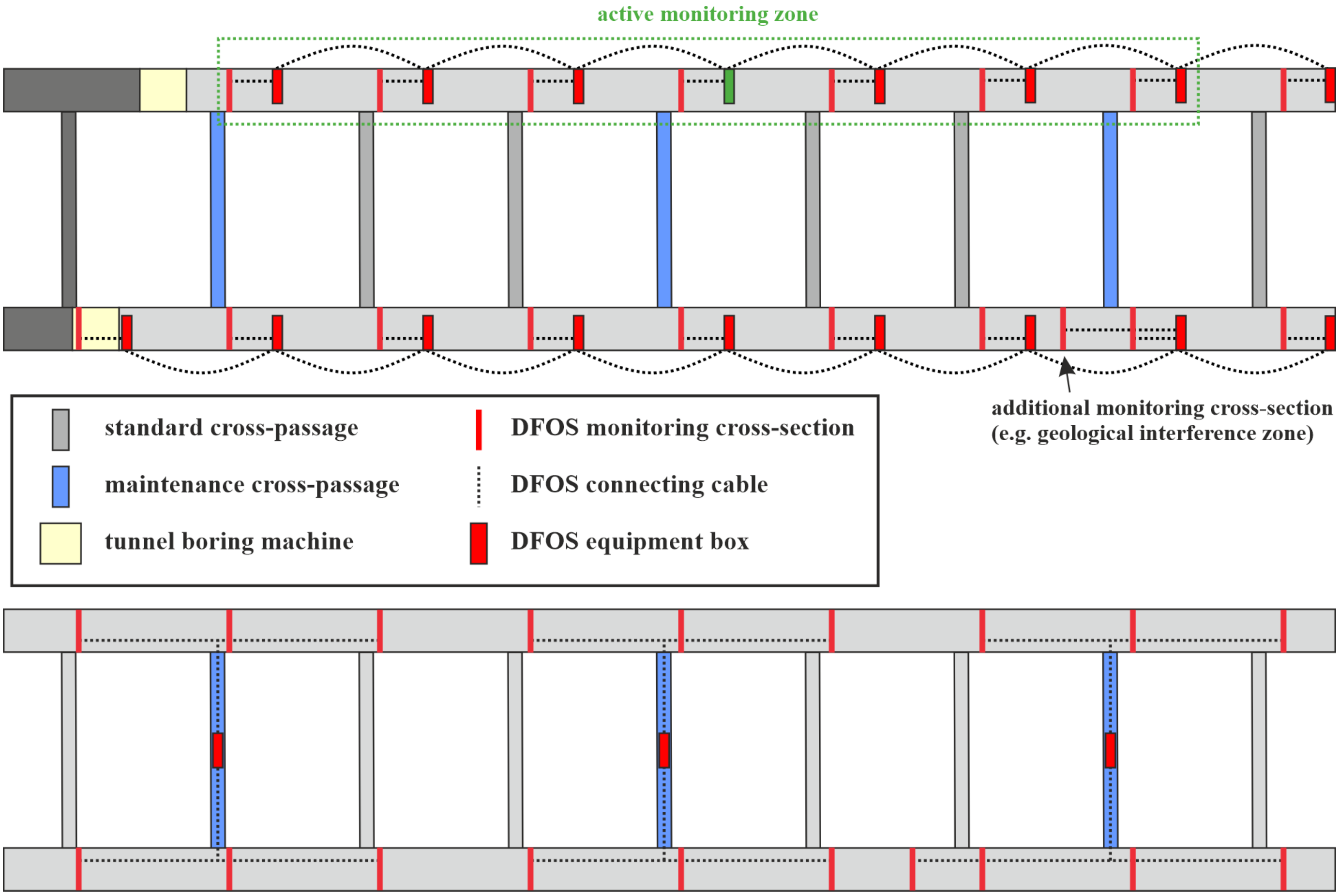

Figure 3. Schematic representation of overall monitoring setup during construction (top) and operation (bottom) [4]

The quality of the conversion from the raw measurement quantity (cf. Brillouin frequency shift) to strain (and temperature) depends on reliability of the sensor characteristics curve, usually not specified by manufacturers in detail. Using standard coefficients might however results in errors of up to several percent, cf. [7] or [8]. Therefore, each sensing cable production batch was calibrated at the unique calibration facilities at Graz University of Technology [9] to derive individual coefficients for cables installed at BBT.
Each DFOS monitoring ring delivers high-resolution strain measurements at three circumferential locations within each tunnel segment (beginning, middle and end), enabling the assessment of its circumferential total strain distribution at different locations within one monitoring ring. In addition to structural related strains, the recorded information along the individual layers includes also creepage, shrinkage and temperature-related strains. Furthermore, stress profiles are calculated from the derived strain profiles at the inner and outer layer based on the experimentally determined stress-strain behavior of the concrete [10]. This enables the integration of the circumferential normal force and bending moment distribution, which are finally compared to the internal forces of the segmental lining design to assess the rock loading conditions.

The monitoring workflow was validated by comparative DFOS measurements from loading tests of real-scale segmental loading tests [11]. These experimental studies, performed under well-documented loading conditions, depict high correlation between calculated internal forces derived from DFOS measurements and analytical models utilizing traditional load cell data.

4 CONCLUSIONS

The integration of DFOS technology at the BBT demonstrates that distributed fiber optic sensors have significantly developed within recent years and have reached the next level for civil structural health monitoring. Their capability to monitor fully distributed strain and temperature profiles with high measurement repeatability and resolution in real-time, without disrupting tunnel operation, qualify them as an ideal solution for long-term monitoring of relative deformations.

Known practical limitations can be overcome by suitable monitoring design and appropriate installation techniques, which also represent the DFOS technology path from fundamental research into innovative practice. It should be however highlighted that the quality of the monitoring approach is essentially related to its design and installation. It is therefore strongly recommended to include the monitoring design as early as possible into the project planning process, to use suitable, high-quality fiber optic components (i.e. interrogation unit and sensing cable) and to fit the sensor

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installation to the construction process and reduce any interruption on-site to a minimum.

The tunnel construction lots at the BBT project were already being tendered with enhanced fiber optic monitoring solutions, aiming to provide an overall assessment of the structural behavior. This especially beneficial with respect to long-term monitoring since arising changes in the structural performance can be detected at an early stage to plan and design predictive maintenance works in due time during the operational lifetime. The DFOS system is designed to provide measurements without any interference with the regular railway operation from the maintenance cross-passages, which can be accessed from the exploratory tunnel. This fact combined with the fiber optic's insensitivity against electromagnetic interferences are essential for reliable sensing over decades.

DISCLAIMER

This contribution is submitted as an **extended abstract** for the 13th International Conference on Structural Health Monitoring of Intelligent Infrastructure and presents an enhanced project review of the DFOS monitoring system realized at the Brenner Base Tunnel. Figures, texts and contents are therefore already partly or fully published elsewhere.

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AUTHOR CONTRIBUTIONS

ACI Monitoring GmbH: Distributed fiber optic sensing system design and execution:
Brenner Basistunnel BBT-SE: Structural health monitoring concept

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