



Large-scale distributed fiber optic sensing network for short and long-term integrity monitoring of tunnel linings

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Abstract

Structural integrity assessment is essential in modern tunneling to ensure safe construction works. State-of-the-art monitoring approaches like displacement readings of geodetic prisms are often limited in the spatial as well as the temporal measurement resolution, which is why potential safety hazards might be overlooked. This paper introduces a large-scale distributed fiber optic sensing (DFOS) network inside the tunnel lining of a highway tunnel currently under construction in Austria. The tunnel construction site faces challenging geological conditions with loose rock excavation near to the surface with minimal covering. Fiber optic sensing cables were installed along both tunnel tubes to autonomously monitor 13 cross-sections of the primary shotcrete lining, about 220 m of the tunnel in longitudinal direction and 10 cross-sections of the secondary inner lining. Measurements are continuously evaluated and autonomously transferred to the geotechnical engineer on-site for further analysis. While the construction works are ongoing, alerts are additionally sent out automatically, if pre-defined thresholds are exceeded. The paper outcomes demonstrate that the innovative DFOS system immediately responds to structural modifications and, indeed, increases safety at the construction site.

Keywords Distributed fiber optic sensors · Structural integrity assessment · Shotcrete tunnel lining · Inner tunnel lining · Digitalization · Tunnel monitoring

1 Introduction

Increasing road and railway traffic entails constructions of modern civil infrastructure worldwide. As a result of limitations in terms of space in urban or mountainous areas, tunnels are often excavated in complex geological conditions, which involves potential safety hazards. Reliable structural

integrity monitoring and corresponding data analysis is, therefore, essential to guarantee safe construction works.

In modern conventional tunneling, it is state of the art to measure displacements of geodetic targets at the tunnel's inner lining using total stations [14, 16]. This method, however, always requires a direct line of sight from the instrument to the measured object. Automated total station measurements are often not possible due to several prism targets in the field of view of the automated aiming or regular obstructions of the line of sight due to construction traffic, which is why displacement measurements are usually performed manually by the surveyor once or twice a day. Although this measurement frequency can be sufficient to understand the system behavior and, if necessary, to justify the geotechnical support model, critical events between the observations might be overlooked, which implies potential safety hazards during the excavation works. Later, in the operational phase, geodetic monitoring normally requires a physical human access, mostly resulting in partial or total closures of the tunnel. Electrical sensors, e.g. vibrating wire sensors [15] or extensometers [2], can be additionally placed inside the lining to provide continuous deformation readings.

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The number of sensors 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 Sensors (DFOS) are advantageous compared to conventional techniques as sensing can be continuously carried out along the entire sensing fiber. The sensing cable can be directly embedded inside the structure, which enables distributed strain (and temperature) measurements of hundreds of sensing points without blind spots. The sensing unit itself may be placed even kilometers away from the measurement location and measurements are possible without any interference with the regular construction and operation. Nevertheless, DFOS approaches in tunneling are always exposed to harsh mechanical impacts within the construction process and, therefore, extended DFOS tunnel concepts and realizations are still rare in literature, see e.g. [7, 21].

This paper introduces a large-scale DFOS installation concept and realization inside both linings, the primary shotcrete as well as the secondary inner tunnel lining of a highway tunnel currently under construction in Austria. The construction works face complex geology as well as legal constraints, which is why extended monitoring was set up to assess the structural integrity. In the following, the site conditions (Sect. 2), the DFOS system design as well as the sensor installation and the monitoring setup (Sect. 3) are discussed. Afterwards, innovative methods for digitalization of monitoring data in tunneling applications are introduced (Sect. 4). Results of continuous DFOS monitoring along the shotcrete lining over 1 year are presented and compared to point-wise sensing techniques and terrain changes of the surface above the tunnel route (Sect. 5). Finally, the outcomes are concluded and an outlook on progressive utilization of the DFOS approach during the final tunnel operation is given (Sect. 6).

2 Construction site

The tunnel *Rudersdorf* is part of the new highway *S07 - Fürstenfelder Schnellstraße* currently under construction by the Austrian highway operator and owner ASFINAG (Autobahnen- und Schnellstraßen-Finanzierungs-Aktiengesellschaft). After its completion, the 28 km long highway provides a safe and efficient connection of Austria's southeastern highway network to Hungary and significantly reduces the transit traffic in various villages along the existing state road [1].

The shallow tunnel construction consisting of two tubes with a length of about 3 km faces complex geology and hydrogeological conditions with loose rock material (sand, gravel and clay). Due to the legal constraints, the excavation

material must be deposited directly at the construction site above the tunnel routes at both portals to ensure noise and sight protection during the final operation. At the east portal (see Fig. 1), this increases the tunnel covering from about 6 to 13 m initially to a final terrain level of up to 33 m, which implicates huge additional loads for the tunnel lining.

This covering implicates huge additional loads for the tunnel lining in the bulk disposal, which can potentially result in extraordinary, plastic deformations and radial cracking of the lining. At worst, cracks in longitudinal direction could force the shotcrete lining to completely fail and collapse. The geotechnical observation model initially intends 3D displacement readings of five or seven geodetic targets per monitoring cross-section, evenly distributed in circumference direction. Monitoring cross-sections are separated by 10 and 15 m in longitudinal direction and manually observed by the surveyor once a day during the excavation phase. The observation interval is significantly reduced based on the assessment of the geotechnical engineer, in general, when the tunnel drive has been continued for about 100 m.

After construction start in summer 2019 and first terrain modeling works, the geodetic displacement readings revealed much higher deformations and settlements than expected in the geotechnical planning. This finally resulted in a local collapse of the shotcrete lining [17]. The tunnel owner ASFINAG, therefore, decided to significantly extend the initial monitoring concept to provide continuous distributed measurements along the tunnel lining in the terrain modeling area during the further construction. As part of this extension, the IGMS (Institute of Engineering Geodesy



Fig. 1 East tunnel portal before terrain modeling (July 2019) and after major terrain modeling (November 2020) [10]

and Measurement Systems) of Graz University of Technology in cooperation with ACI Monitoring GmbH designed a DFOS approach to monitor longitudinal as well as cross-sectional strains along tunnel lining of both tubes.

3 Distributed fiber optic monitoring system and sensor installation

3.1 Sensing cables

Distributed fiber optic sensing in harsh geotechnical environment like tunnels implies essential mechanical impacts for optical glass fibers, which must be reliably protected during installation and monitoring. In the presented application, pre-fabricated sensing cables from SOLIFOS AG (Switzerland) were used, which are specially designed for sensing in geotechnical environment and protect the sensing fiber through various protection layers. Since fiber optic sensors are always sensitive to both, strain and temperature [6], two different cables must be installed to ensure a reliable temperature compensation of the measured strain profiles.

The construction site supplies different requirements for the fiber optic strain sensing cable depending on construction process. The shotcrete tunnel lining was instrumented with the BRUsens V3 [19] (see Fig. 2, middle). This cable has a diameter of 7.2 mm and protects the optical single-mode glass fiber (I) through a metal tube (III), which is rigidly connected to the fiber by a multi-layer buffer (II). The outer protection consists of an inner polyamide layer (IV), a

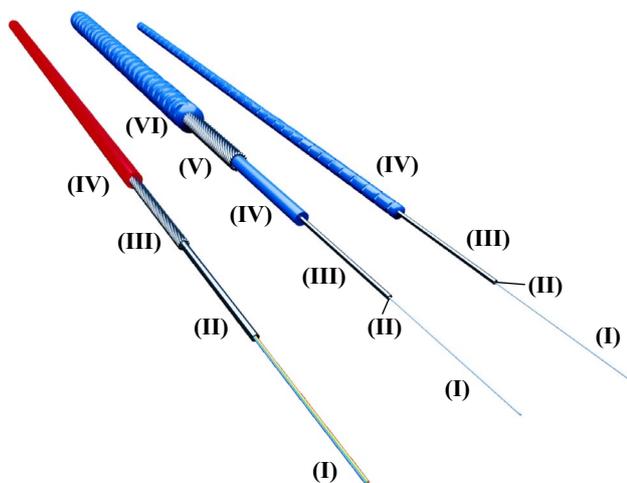


Fig. 2 Temperature sensing cable BRUsens DTS (red, left) with (I) single mode fiber, (II) loose metal tube, (III) special steel armoring and (IV) polyamide sheath; Strain sensing cables BRUsens V3 (blue, middle) and BRUsens V9 (blue, right) with (I) single mode fiber, (II) multi-layer buffer with strain transfer layer, (III) metal tube, (IV) polyamide sheath, (V) special steel armoring and (VI) structured polyamide outer sheath (based on [10])

special steel armoring (V) and an outer polyamide surface (IV). Even if these protection layers guarantee the sensing fiber's integrity during the shotcreting process, the flexibility of the cable is limited, which can restrict the installation procedure on-site. The BRUsens V9 cable [18] (see Fig. 2, right) with a diameter of 3.2 mm enables a more flexible installation due to the missing steel armoring and was, therefore, utilized inside the inner tunnel lining. Both cables provide a structured outer surface to enable a suitable connection between the cable and surrounding material. The cable layers are interlocked to each other in order to guarantee a reliable strain transfer from the outer surface to the sensitive glass fiber core.

The corresponding temperature sensing cable BRUsens DTS [20] (see Fig. 2, left) is about 3.8 mm thick. One or more temperature sensing fibers (I) are embedded into gel inside a metal tube (II). This tube has, however, a larger diameter compared to the strain sensing cable to ensure that no strain is transferred to the fiber and, hence, it is sensitive to temperature only. At the outside, a steel armoring (III) as well as a polyamide outer sheath (IV) protects the glass fiber against mechanical impacts.

3.2 Sensor installation

The installation of the sensing cables along the shotcrete lining was different compared to previous installations [12, 21] since the tunnel excavation in the area of interest was already performed and the initial shotcrete layers were already applied. For that reason, small stripes of welded wire mesh were mounted to the existing tunnel lining, where the cables could be fixed using cable ties, see Fig. 3 (left). After the cable installation, an additional shotcrete layer was sprayed onto the instrumented areas, which shall ensure a solid bond between the sensing cables and the existing tunnel lining. The mounting system was also investigated within a pre-trial to guarantee that the cables are sufficiently mounted and can withstand the harsh shotcrete impacts.

The inner tunnel lining was designed with two reinforcement layers. These could be used for an installation procedure, where the first cable layer is mounted closer to the mountain and the other one is placed next to the tunnel cavity. The arrangement can significantly extend the monitoring capabilities and enables the derivation of curvature along the lining in circumferential direction (cf. Sect. 5). The construction of concrete inner tunnel linings is usually carried out in casting blocks with lengths between 12 and 36 m. This is why the DFOS cables may not be continuously guided and must be collected inside a connecting box at each cross section (see Fig. 3, right) during the concreting process. After removing the formwork, the cables can be either accessed and measured directly at the cross-section or connected to the sensing unit using supply fibers.



Fig. 3 Installation of sensing cables along the shotcrete lining [10] (left) and inside the inner tunnel lining (right)

3.3 Sensing principle

All installed sensing cables have 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 a measurement time of several minutes, a spatial resolution of 0.5 m and a strain repeatability of about 2–10 $\mu\text{m}/\text{m}$ depending on the sensing fiber [5]. The sensing principle, however, requires a closed loop system, where a pump signal at the one side and a probe wave at the other side of the cable is introduced to stimulate the Brillouin signal and, finally, to increase the intensity of the backscattered light. As usual in practical applications, this setup was realized by a strain (and temperature) sensing forward path and a return path, which is stress-free and sensitive to temperature only.

If the measurement loop is interrupted at any location and the sensing fiber is impaired by mechanical impacts or similar along the sensing loop, BOFDR (Brillouin optical frequency domain reflectometry) measurements may be carried out alternatively. This method only uses natural backscattering with a single-ended configuration, but with significant limitations in the signal to noise ratio as well as the spatial resolution [5].

The typical backscattering result by means of the Brillouin frequency spectrum along an optical fiber under test is shown in Fig. 4 (top). The investigated fiber depicts a Brillouin frequency baseline of about 10.4 GHz, but is affected by strain and/or temperature starting at a position of about 47 m, which is why the frequency is significantly increased at this area. Based on the spectrum, the intrinsic Brillouin frequency at each position along the fiber

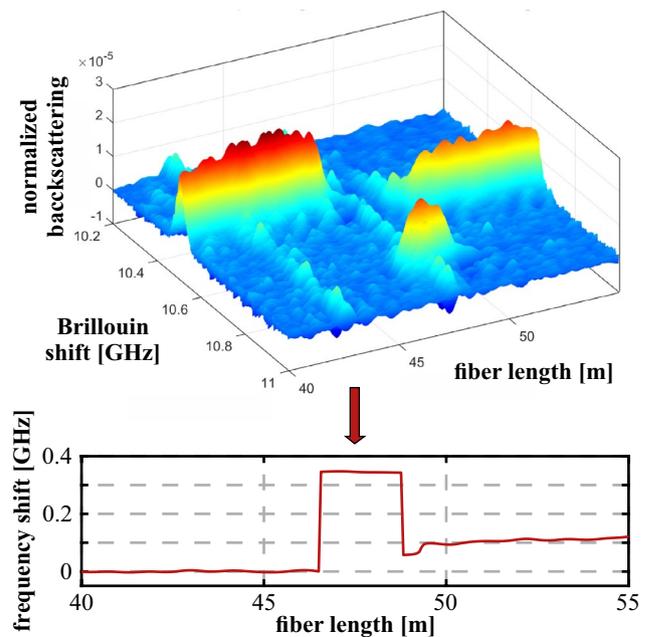


Fig. 4 BOFDA sensing principle (based on [3]): Brillouin frequency spectrum (top) and derived Brillouin frequency profile (bottom)

can be determined for each measurement epoch using e.g. Lorentzian fitting.

The further analysis of the Brillouin frequency shift $\Delta\nu$ (Fig. 4, bottom), i.e. the variations of the Brillouin frequency either with respect to the Brillouin baseline frequency ν or to a corresponding reference measurement, enables the strain ϵ and/or temperature changes ΔT along the fiber length using appropriate conversion functions. The sensor characteristic can be expressed by

$$\frac{\Delta\nu}{\nu} = C_e \epsilon + C_T \Delta T \tag{1}$$

where C_e and C_T are the sensitivity coefficients. Even if this relation is approximately linear, variations between different cable types or even between different cable batches of the same cable cannot be ruled out completely. Hence, reliable calibration is essential to guarantee the DFOS measurement quality. Buchmayer et al. (2021) presents calibration results of the sensing cables used in the actual application [3].

3.4 DFOS network and monitoring setup

The instrumentation of the total DFOS network along both tunnel tubes (Fig. 5) was an ongoing process, carried out between December 2019 and November 2021, and strongly related to the construction work on-site. Initially, the shotcrete lining of the northern tunnel tube (cf. Fig. 1) was equipped with two continuous sensing cables (one for strain and one for temperature sensing, respectively) along ten tunnel cross-sections over a longitudinal tunnel length of about 220 m. Within the gaps between the instrumented cross-sections, the sensing cables were continuously mounted along the tunnel crown. This procedure also enables distributed measurements over 220 tunnel meter in longitudinal direction. Following the construction process, three additional cross-sections were instrumented along the southern tube at the beginning of May 2020. The installation along the longitudinal roof section was, however, waived due to practical reasons and the cables were connected using non-strain sensitive supply cables mounted to the side wall.

All cables were finally assembled in a connection box next to each tunnel portal. From there, supply fibers were used to connect the sensing chains to the sensing unit, which was placed inside a measurement container outside of the tunnel next to the portal (see Fig. 1). Monitoring can, therefore, be autonomously carried out without interference with

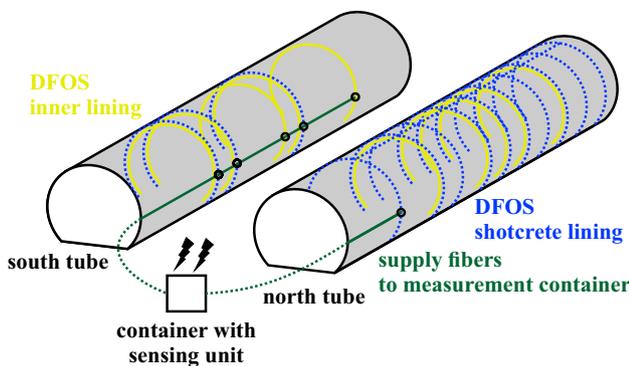


Fig. 5 Distributed fiber optic sensing cable network installed along both tunnel tubes (based on [10])

the regular construction work inside the tunnel. The entire sensing process is autonomous and does not require any user interaction for data acquisition, processing and analysis as shown in Fig. 6. This also includes an appropriate DFOS temperature compensation and the spatial allocation of the DFOS strain profiles using corresponding data from total station (TS) and terrestrial laser scanning (TLS, cf. Sect. 4). If the wireless data network is interrupted due to any external reason, the generated data and reports are locally stored at the industrial PC and are sent out once the connection is established again. Potential downtimes of the power supply at the construction site can be bridged for about 1 h by an uninterruptible-power-supply (UPS).

While the excavation and terrain modeling works is ongoing, the strain distribution along all installed sensing cables is captured every 60 min and automatically transferred to the geotechnical engineer on-site twice a day for further analysis. Remote access for general maintenance works, changes of measurement settings or supply of additional evaluations is, however, always possible. In addition, mail alerts we are sent out automatically, if sudden changes of the deformation process over time are noticed to trigger further actions, e.g. additional manual surveying at specific locations. Corresponding critical values were empirically defined within a test phase after the installation, where material was placed in defined zone above the tunnel route to obtain the strain response at certain level changes. the terrain level over the tunnel tubes was selectively modified to obtain the response of the DFOS network (Sect. 5). The relation between the observed strain changes and the recorded bulk material heights was then used to define admissible maximum strain changes over time.

After the tunnel excavation works were finished in spring 2021, ASFINAG decided to re-design and further extend the initial DFOS approach for long-term monitoring. This design also includes measurements along the inner tunnel lining to evaluate potential load rearrangements from the primary shotcrete to the secondary lining. Ten DFOS monitoring cross-sections (five per tube) were realized inside the

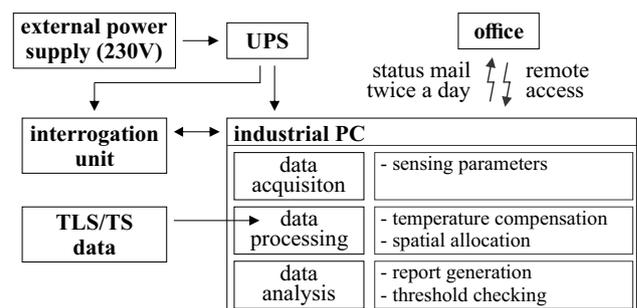


Fig. 6 Distributed fiber optic sensing system and monitoring workflow

inner lining until November 2021. At the current status, the sensing cables are connected to one continuous chain for each tube along the cable trough and monitoring can still be carried out from the container above the tunnel. As part of the next project phase, all DFOS sensors will now be included into the fiber optic network of the tunnel. This will enable distributed strain measurements directly from the tunnel's operational building without physical access during the final operation.

4 Digitalization of monitoring systems in tunneling applications

Information of the surrounding area of the sensing cable is a key element for the right interpretation of the recorded measurement results. The one-dimensional strain measurements have to be seen in their right three dimensional context for the correct interpretation of local effects as well as the documentation of the long-term behavior of the structure. Modern surveying techniques like laser scanning or photogrammetry deliver 3D models, which document the surrounding geometry and objects with a high spatial resolution.

A typical 3D data acquisition, captured by a Leica Multi-station MS60 [8], can be seen in Fig. 7 (top). This surveying instrument combines the features of a conventional total station and a laser scanner, which are both used for data collection of the monitoring installation. Both measurement technologies follow a polar measurement principle, where horizontal angles, vertical angles and electronic distance measurements are recorded and 3D coordinates are determined. Whereas the total station is aimed for precise single point measurements to specific locations, the laser scanner captures the surroundings in a full dome scan with up to 10 kHz for the (MS60) or up to 2.000 kHz with other state of the art laser scanner.

The benefit of geodetic surveying is that the instruments operates within the coordinate system of the tunnel site by measuring to corresponding targets on the tunnel wall. The line-of-sights are indicated as dashed white lines in Fig. 7. Therefore, all subsequently gathered data sets by these instruments are geo-tagged and keep their spatial relation for further investigations.

The laser scan provides high resolution information of the current surface geometry of the tunnel wall, indicates the location and depth of visible cracks and identifies damaged areas. The raw point cloud depicted in Fig. 7 has been manually cleaned from artifacts and automatically meshed with proprietary software from the laser scanner manufacturer, which has resulted in a surface accuracy of a few millimeters. Beside the usage for deformation analysis, the laser scan can also provide a full documentation of the onsite scenario. Information that has not seemed crucial at the time of

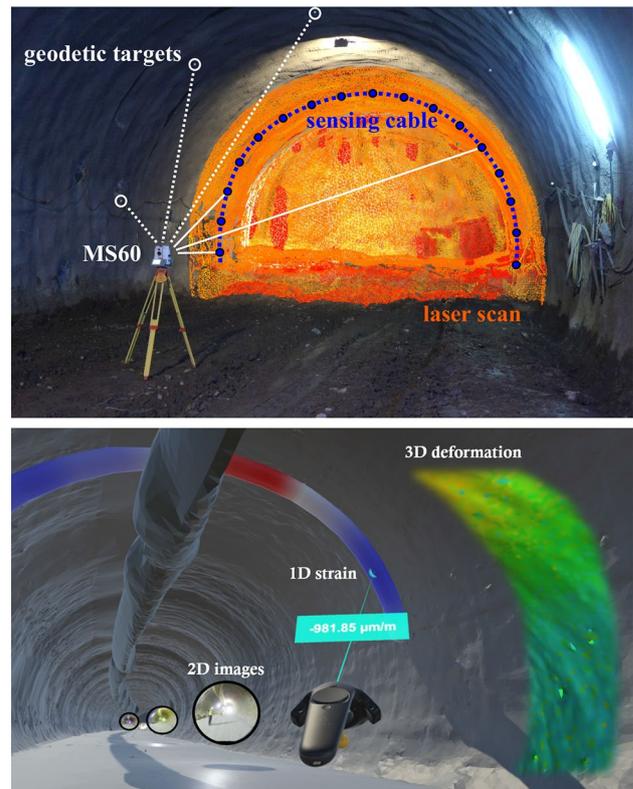


Fig. 7 Capturing the monitoring installations with a Leica MS60 (top) and virtual reality view of the digital Twin of the S07 (bottom)

data acquisition (e.g. anchors and other retaining structures) can be digitized and modeled whenever needed.

The adequate representation of 3D objects in the laser scan depends on the spatial resolution of the acquired point cloud. Due to the small diameter of the sensor cable of a few millimeters, its position is usually obtained by manual aiming and reflectorless distance measurements of the total station on-site (continuous lines in Fig. 7). The cable points can be converted into 3D polylines, where each vertex is linked to the corresponding data of the DFOS measurements at that specific location.

The uniform coordinate system enables the combination of all recorded data sets in a digital 3D environment, allowing the user to inspect and interpret 1D strain data, 2D images and 3D deformation data together in a common environment. Hence, the user can inspect deformation events represented by the strain data and relate them to the spatial environment as well as their context to other objects (e.g. digitized cracks from images) along the tunnel.

Standard 3D viewers in software products often reach their limits with complex and overlapping 3D geometries on a 2D screen. Figure 7 (bottom) depicts a virtual measurement data inspection realized in virtual reality (VR) in the coding environment Unity. The user can enter the

digital environment with a first person view and gets similar impressions of the scene as he would get on-site. The beneficial user perception of 3D scenarios with VR is already used in many other user segments, see e.g. [9].

The current development grade of the VR simulation of the S07 site supports the visualization, interaction and manipulation of acquired data sets. Future works are focused on the direct combination of the measurement data with a finite element model within the VR application. From this, the user will not only be able to inspect the measurement data, but also to assess the impact on the structural integrity of the tunnel.

5 DFOS monitoring results

The continuous monitoring campaign of all instrumented sections of the shotcrete lining of the northern tube was started on January 2nd, 2020. The recorded strain profiles,

therefore, represent the change in strain to this, so-called reference measurement. The tunnel excavation of the monitored area was already performed various months before and the terrain modeling has been already started at this stage. It must be, therefore, considered that the measured strains do not depict the entire deformation amount of the lining, but rather only the strain change after the monitoring start. Hence, the depicted strains are, almost exclusively, a consequence of the terrain modeling above the tunnel route.

Selective terrain modeling was carried out at the beginning of 2020 to capture the response of the installed DFOS approach to the applied bulk material. For this, the actual terrain level above the tunnel route was recorded several times using GNSS receivers and the displacements of the geodetic targets along the instrumented cross-sections were measured at least every fourth day with a total station. Figure 8 depicts the measurement results of all sensing technologies at two selected monitoring cross-sections. The recorded terrain level changes (top) show that the loading was performed

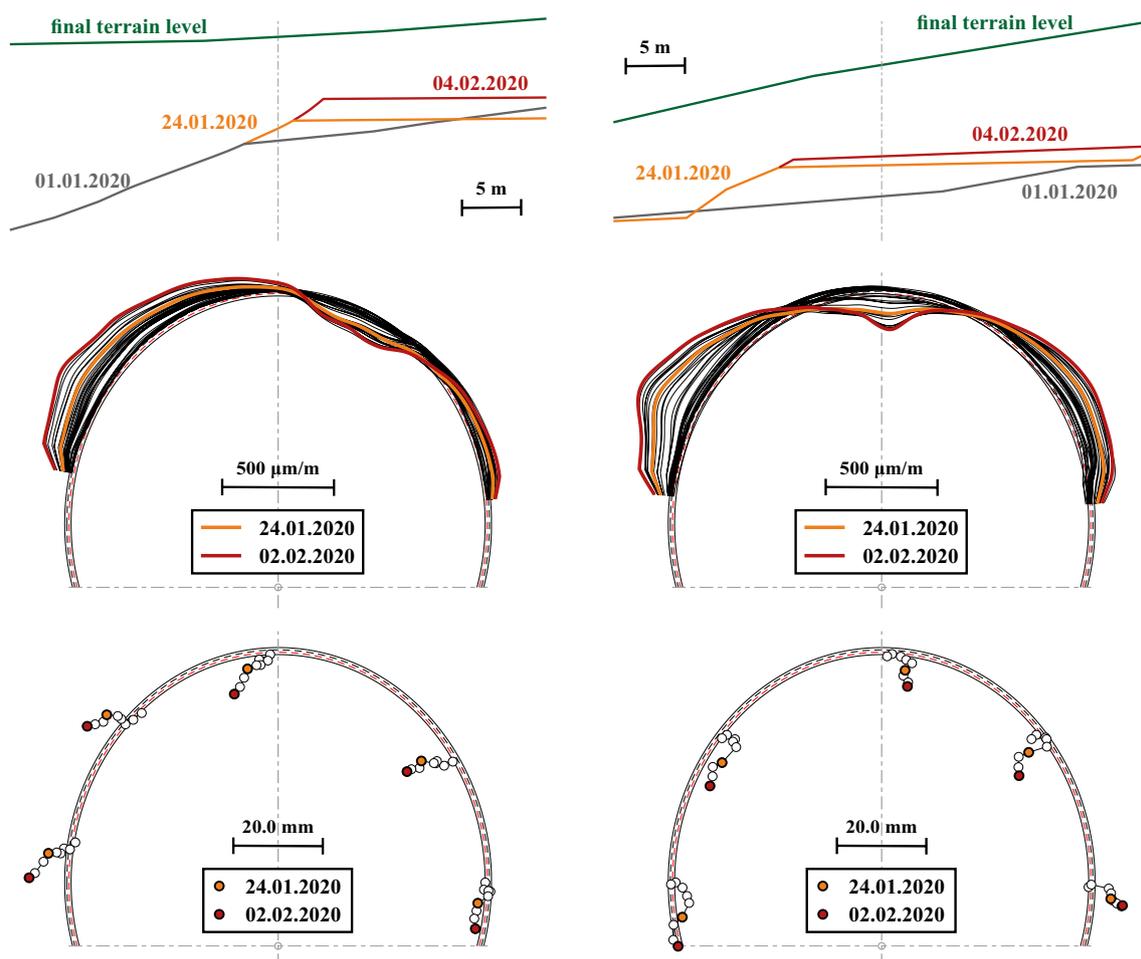


Fig. 8 Measurement results at two selected cross-sections within the first month after installation: Terrain level changes (top), derived DFOS strain profiles (middle) and geodetic displacement readings (bottom) [10]

differently: Cross-section #01 (left figures, tunnel meter 152) was loaded right to the tunnel axis, whereas the material above cross-section #02 (right figures, tunnel meter 208) was placed almost centrally.

The DFOS strain profiles (middle) are displayed for each day during the test phase between the January, 2nd and February, 2nd. Negative strain (= compression) is shown to the outside, positive strain (= tension) to the inside of the lining. Both cross-sections basically depict a similar deformation behavior with tension at the roof area and compression at the side walls. This suggests that the entire cross-section is moving downwards due to the applied material load and is contracted at the tunnel invert, which finally results in a slight horizontal ovalization of the shotcrete lining ring. The orientation of this ovalization can be clearly identified to the direction of the terrain modeling and is also confirmed by the displacement readings of the geodetic targets (bottom).

Remarkable is the fact that the bulk material amount above the cross-section may also be related to the shape of the DFOS profiles. At cross-section #02, the loading is performed almost centrally, but with higher material amount left to the tunnel axis during the test period. This

causes a higher resistance of the lining at the left tunnel shoulder and finally results in higher (negative) strain in this area. The drawn assumption is supported by the conventional geodetic readings, which display a vertical movement with slight horizontal displacement to the right, especially at the right side wall.

In addition to the cross-sectional monitoring, the DFOS approach also enables an analysis of the distributed deformation behavior in longitudinal direction. Especially for large-scale structures like tunnels, this may be advantageous since the overall behavior along the structure without major gaps between the measurement points can be captured. Compared to traditional 3D displacement readings separated by 10 m or even more in longitudinal direction, potential failures of the lining might, therefore, be observed at an earlier stage due to the distributed sensing along the structure without major gaps.

Figure 9 (top) shows the recorded terrain levels along the tunnel route of the northern tube in longitudinal direction at four selected points in time as well as the planned final terrain level. The major zone of influence of the

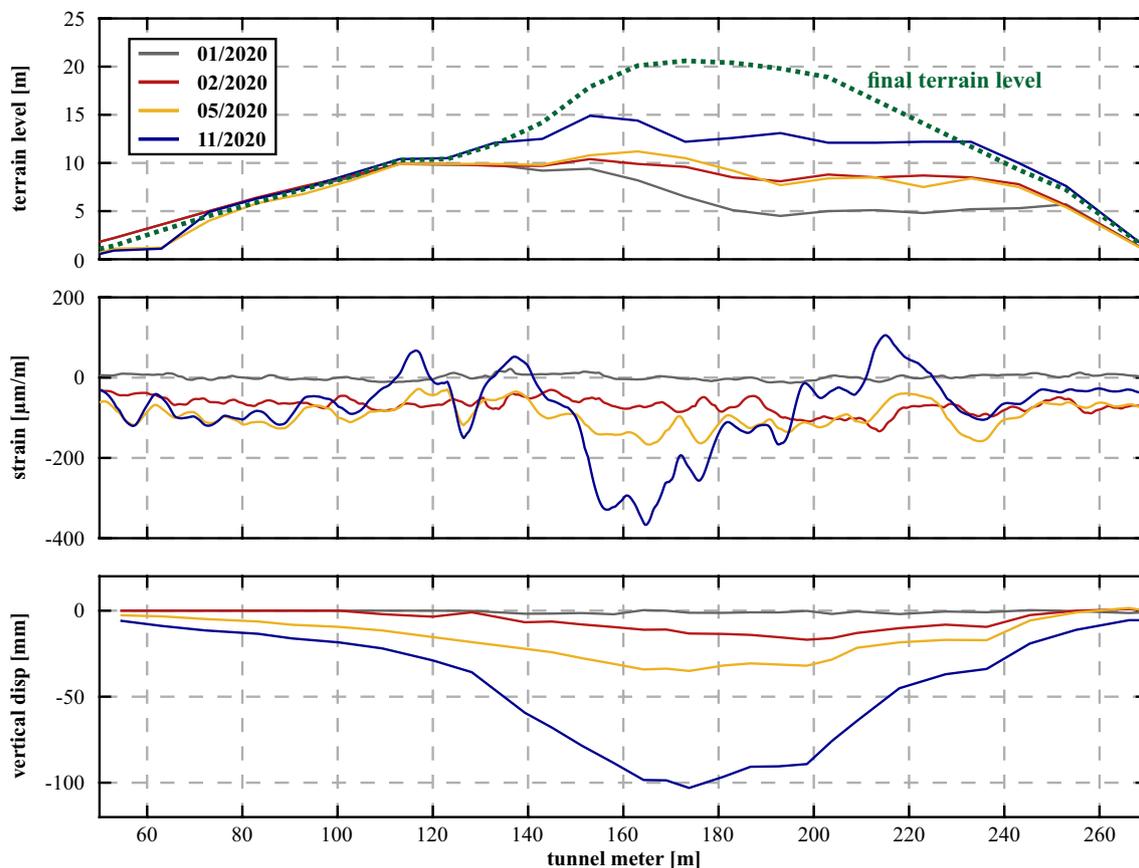


Fig. 9 Measurement results along the northern tunnel tube in longitudinal direction: Terrain level changes (top), derived longitudinal DFOS strain profiles (middle) and vertical displacement of geodetic readings at the tunnel roof point (bottom) [10]

terrain modeling with bulk material heights higher than 10 m at the final stage is visible from tunnel meter 130 to 240.

The major impact zone can also be identified in the DFOS strain profiles along the tunnel (Fig. 9, bottom), which depict a typical curvature effect in the area between 110 and 230 m. This can be mechanically compared to a thick-walled tube that is bended downwards in vertical direction. Similar outcomes using DFOS were already found along pipelines (see e.g. [4]). Outside the major deformation zone between tunnel meter 50 and 100 as well as 240 to 270, mostly constant (negative) strain, probably resulting from slight creep-age effects of the shotcrete itself, can be determined. All in all, the observed behavior suggests that the tunnel tube has been almost stable at the beginning and the end of the monitoring area over time and progressive vertical bending is recognizable at the middle with a maximum at about 170 m. This assumption can be also confirmed by point-wise readings of the geodetic roof point targets in vertical direction (Fig. 9, bottom), which display settlements of up to 100 mm in the central area. The designed DFOS monitoring approach, however, enables a direct, continuous and distributed assessment without efforts for manual geodetic readings inside the tunnel. The measured DFOS strain values could be additionally converted to distributed curvature profiles in the vertical tunnel plane by assuming that the neutral axis of the cross-section complies to the tunnel center. Subsequently, relative displacement profiles in vertical direction along the tunnel could be derived by either combining these curvature values with selected geodetic readings or by assuming that the border areas are stable. This would finally lead to additional interpretation possibilities for the geotechnical engineer on-site. A corresponding evaluation concept for distributed shape sensing based on DFOS strain sensing supported by point-wise geodetic measurements is presented in [11].

One selected cross-section of the northern tube was also instrumented with vibrating wire sensors (VWS) within the

regular tunnel construction to perform point-wise strain measurements inside the initial shotcrete lining. Although the position of these sensors is different compared to the DFOS cables, the captured deformation progress can be valuable to verify the capabilities of the designed DFOS system.

The VWS installation is usually carried out in pairs, i.e. one sensor at the outer and one sensor at the inner supporting wire mesh. Therefore, the lining's local curvature κ can be determined by combining the measured strain values $\epsilon_{out/in}$ with the distance between the sensors d :

$$\kappa_{VWS} = \frac{\epsilon_{out} - \epsilon_{in}}{d} \quad (2)$$

Even if the DFOS cable is only guided at the inner surface of the shotcrete lining, the curvature value at selected points can also be derived from the DFOS strain value ϵ by

$$\kappa_{DFOS} = \frac{\epsilon_{DFOS}}{D} \quad (3)$$

where D is the distance from the DFOS cable to the neutral axis in transverse direction (= center of the shotcrete lining). Nevertheless, this calculation principle is based on the approximation that material properties are constant along the cross-sectional profile and no strain is acting on the cross-sectional neutral axis.

The derived curvature values between May 2020 and January 2021 at the location of all (four) vibrating wire sensors within the DFOS installation area are shown in Fig. 10. These depict strong changes between mid of June and beginning of July, especially at the top point of the lining, which can be correlated with an increase of the terrain level above the investigated cross-section. After this major event, the deformation process seems to be almost constant with slight further increases in November 2020.

Both sensing technologies basically point out a good agreement in shape and magnitude, even if the DFOS system

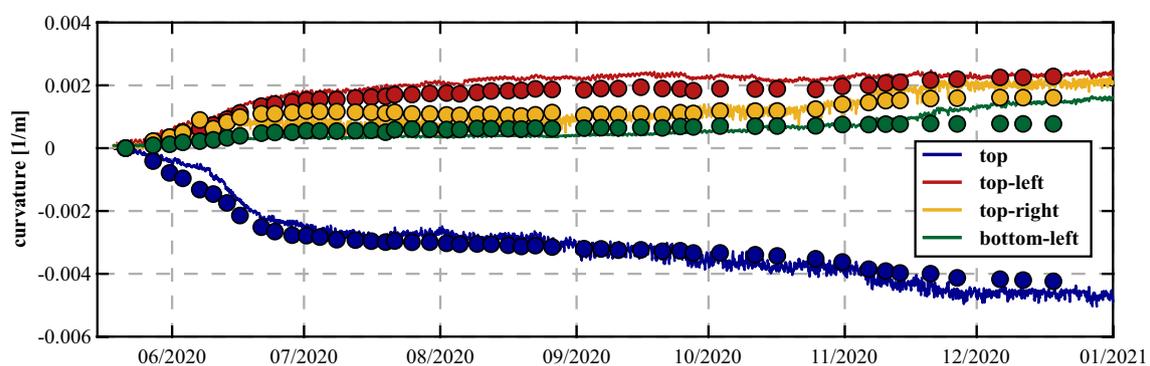


Fig. 10 Curvature values derived from vibrating wire sensors (dots) and DFOS strain measurements (solid lines) at three selected positions along the instrumented cross section [10]

partially response slower or faster to applied loading events. Beside the different location of the sensors within the cross-sectional profile of the lining, remaining variations might be related to deviations to the approximations drawn above, the different gauge length of the sensors or different positions of the sensors in circumferential direction along the cross-section. Contrary to the point-wise VWS measurements, DFOS is capable to provide distributed curvature values along the large parts of the lining. These distributed curvature profiles can be finally used to derive the full cross-sectional shape profile analogous to sensing in longitudinal direction [11].

The authors emphasizes that the monitoring results presented in this paper are limited to the shotcrete lining. Future work will be focused on the long-term monitoring of both linings over years or even decades to evaluate potential load rearrangements during the operational phase.

6 Conclusions

This paper presented the design and realization of a large-scale DFOS approach within a highway tunnel currently under construction in Austria. The geological conditions in combination with legal restrictions, which enforce the depositing of the excavation material above the tunnel route, induce challenging loads for the tunnel's integrity. Distributed fiber optic sensing cables with a total length of more than 2500 m were embedded into the tunnel lining to monitor 13 cross-sections of the primary shotcrete lining, about 220 m of the tunnel in longitudinal direction and 10 cross-sections of the secondary inner lining.

Continuous, hourly measurements of the shotcrete lining have been performed since the system was installed in December 2019. The designed system provides astonishing reliability and robustness, where less than 0.5% of the measurements failed over the entire monitoring campaign due to power outages or similar.

The presented results show that terrain level changes above the tunnel lining can be clearly identified in the DFOS cross-sectional strain profiles, which ovalizes due to the applied load. The orientation of the tunnel's ovalization complies with the loading direction and is also confirmed by the geodetic displacement readings. Curvature changes derived from strains of vibrating wire sensors inside the lining depict also a good agreement with the fiber optic outcomes. DFOS measurements in longitudinal direction enable an identification of the major deformation zone along the tunnel route and progressive vertical bending of the tunnel tube can be captured over time.

Long-term monitoring becomes significantly more important since newly constructed civil infrastructure is designed for service lifetimes of 100 years or even more and therefore, requires predictive maintenance in due time [13]. This is

why the installed DFOS system has been re-designed for long-term monitoring designed to provide long-term observations along the tunnel structure. The practical implementation is, however, closely related to the construction work on-site and still an ongoing process. As part of the next project phase, the sensing chains will be included into the tunnel's fiber optic network to access the installation directly from the operational building during the operation. From there, epoch-wise or continuous measurements can be performed at any time without interference with the tunnel traffic. The results will give further information on the long-term deformation behavior of the tunnel as well as new insights about the long-term stability of the designed DFOS system.

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Declarations

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Conflict of interest The authors declare that they have no conflict of interest.

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