Benefits of strain and temperature monitoring of conventional tunnel cross sections using distributed fibre optic sensors

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ABSTRACT

Nowadays tunnel safety and predictive maintenance of tunnel structures become more and more important. The condition of a tunnel is more degrading due to longer service lifetimes and therefore, tunnel structures must be monitored to guarantee the safety as well as to enable predictive maintenance. However, conventional methods are usually time consuming, expensive and partially require an interruption of the tunnel traffic. This paper reports about a tunnel monitoring approach based on distributed fibre optic sensing (DFOS), which allows strain and temperature measurements along the installed sensor line inside shotcrete tunnel linings with a spatial resolution of 0.5 m. The distributed method delivers hundreds of sensing points inside the structure and completely new information can be gathered to characterize the inner behaviour of the shotcrete. Measurements can be performed automatically without the need of access to the tunnel cross section and hence, the tunnel construction and operating phase are not disturbed. The developed system was installed within a shotcrete lining directly at the tunnel face of a railway tunnel under construction in Austria. Continuous monitoring started immediately after the installation and was performed over several weeks during the curing of the shotcrete and the further heading of the tunnel. In this paper, we describe the critical system installation process, show the most significant monitoring results and compare them to conventional measurements. The outcomes demonstrate the high potential of distributed fibre optic sensing in tunnel monitoring with respect to structural health monitoring (SHM), the analysis of concrete curing and fire surveillance.

I. INTRODUCTION

One of the key assets in railway transportation systems is to reach an availability rate of almost 100 %. Especially railway tunnels in the Alpine region are bottlenecks and there are practically no alternative railway routes in the case of a tunnel closure due to maintenance. This usually results in longer transportation routes and higher costs. Precise monitoring in combination with reliable data interpretation leads to a better understanding of the structural behaviour and enables the stability assessment of a tunnel for safety reasons and predictive maintenance. The monitoring system should provide information about the actual state of the tunnel structure or in other words, it should help the engineers to make an informed decision in their maintenance planning.

At present, total stations are usually used to measure displacements of geodetic targets mounted on the tunnel lining (Austrian Society for Geomechanics, 2014). This method is time consuming, requires an interruption of the tunnel traffic and gives only information about the outer tunnel lining. Hence, in geological fault sections, point wise geotechnical sensors may be installed to measure different parameters such as strain, pressure and displacements. For example, vibrating wire sensors (VWS) can be mounted on the reinforcement grid and measure strain inside the shotcrete (Dunnicliff, 1993). Other common sensors are extensometers, inclinometers, pressure cells or linear variable differential transformer (LVDT) (Figure 1). Almost all of these electrical sensors need one connecting cable to measure at one location. Therefore, the number of installed sensors in a tunnel section is limited due to practical reasons and the obtained data give only information at specific locations.

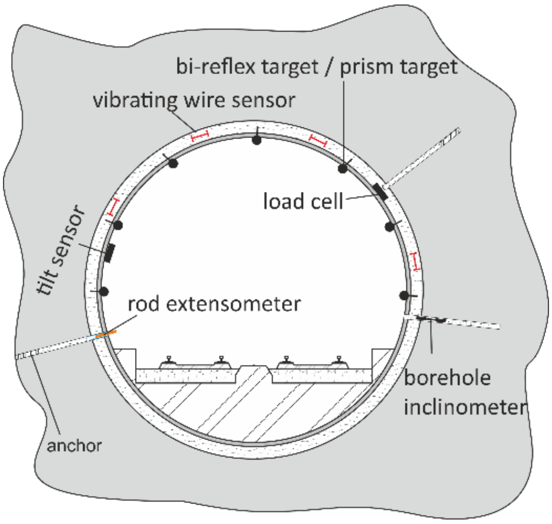

Figure 1. Various conventional monitoring methods in tunnelling

Distributed fibre optic sensing enables continuous strain and temperature measurements along an optical fibre, which can be directly embedded into the structure, e.g. a shotcrete tunnel lining. In comparison to electrical sensors, only one connection cable is necessary to measure hundreds of points inside one tunnel cross section.

This paper proposes the utilized distributed fibre optic measurement system (Sec. II) and gives information about the field installation (Sec. III) of this monitoring system in one of Austria's longest tunnels. After the installation, the system was autonomously collecting monitoring data of the tunnel cross section for several weeks. The most significant strain and temperature results of the continuous monitoring campaign are presented (Sec. IV) and an outlook on future research is given (Sec. V).

II. FIBRE OPTIC MEASUREMENT SYSTEM

One of the major advantages of DFOS systems is the fact that the optical fibre itself acts as the sensitive element. Therefore, the installation time to realize a distributed sensing network inside structures can be significantly reduced compared to the installation of several common electrical sensors. In addition, a high precision of about 1 µm/m (µε) for short range applications up to 70 m (see e.g. Luna Innovations Inc., 2019) or respectively 2 to 10 µm/m for ranges up to several tens of kilometres (see e.g. fibrisTerre Systems GmbH, 2018) can be achieved for strain measurements. Fibre optic sensors have no electrical or mechanical components at the measurement location, which can increase the survival rate in long-term monitoring installations.

In general, the principle of a DFOS system bases on natural scattering of light along the optical fibre. Some small parts of the scattered light are backscattered to the interrogation unit and can be analysed to obtain physical parameters like strain and/or temperature. Depending on the measurement principle, either the intensity (Rayleigh, Raman) or frequency (Brillouin) of the backscattered signal is analysed (Measures, 2001). In case of strain or temperature changes, these raw values alter and thus, in-situ strain and temperature variations of a tunnel lining can be derived. With the advantage to measure inside the shotcrete, it is also possible to monitor the invert and bench section. This is difficult or even impossible with geodetic methods since the bench is usually filled up again with earth material immediately after the excavation to provide a flat surface for construction traffic.

A. *Sensing principle*

In the DFOS application presented in this paper, a measurement unit based on Brillouin optical frequency domain analysis (BOFDA) from fibrisTerre (Germany) is used for sensing. This unit enables measurements up to 25 kilometres, whereby the measurement time is around several minutes (see fibrisTerre Systems GmbH, 2018). Our experiences show that the accessible precision in the field is usually in the range of 10 to 20 µm/m. The used spatial resolution in the presented application is 0.5 m.

Since the intensity of the backscattered light is low, BOFDA instruments inject a pump signal on one side and a probe wave on the other side of a sensing cable (fibrisTerre Systems GmbH, 2018). Hence, this measurement technique always needs a loop configuration to capture the distribution of the Brillouin frequency along the fibre.

Figure 2 shows the Brillouin spectrum of a 15 m fibre section of a 60 m long cable. The fundamental-backscattering frequency is about 10.4 GHz. At a position of about 47 m a frequency change arises, which is a result of a change in temperature or strain.

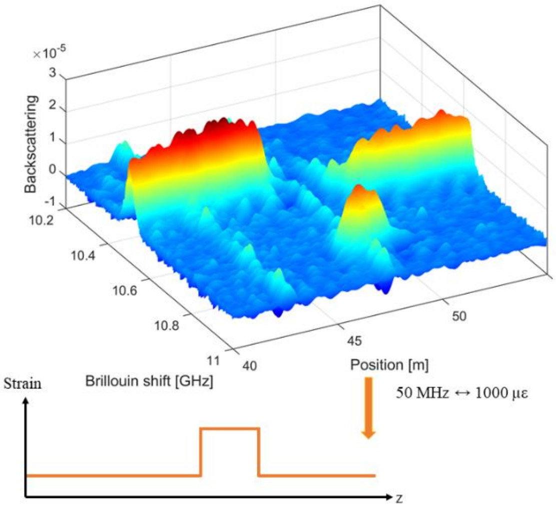

Figure 2. Brillouin Frequency Shift vs. position

To derive strain and temperature changes, it is necessary to convert the raw measurement readings (Brillouin frequency shifts) with appropriate conversion functions. Manufacturers of fibre optic sensing cables often do not provide own calibration functions and refer to literature values, which can result in errors in the range of some percent, see e.g. Moser et al., 2016. For that reason, we have developed our own calibration facility at the IGMS (Institute of Engineering Geodesy and Measurement Systems) measurement lab within the last years to reliably determine own calibration parameters for fibre optic sensing systems. For detailed information about the facility, reference is given to Woschitz et al., 2015.

B. *Fibre Optic Sensing Cables*

Since the installation is inside the tunnel in a rough environment, robust sensing cables with many different layers are needed to protect the glass fibre during the installation process and the monitoring. To differ between temperature and strain effects, usually two sensing cables are installed next to each other. One cable is tightly coupled to the structure and therefore sensitive to strain and temperature whereas the other cable is loosely installed and thus only sensitive to temperature.

The used strain sensing cable (Figure 3 left side) is about 7.2 mm thick and has five different layers that protect the optical sensing fibre (I) (Datasheet see Solifos AG, 2019a). A special metal tube (III) and an interlocking multi-layer (II) guarantee the strain transfer. The outer protection consists of an inner polyamide layer (IV) and a special steel armouring (V) which is winded around the cable. The last layer (VI) is a polyamide coating and has a structured surface, which enables a solid connection with the surrounding shotcrete. All these layers have to be connected with each other to enable a reliable strain transfer from the outside to the sensitive glass fibre core.

The temperature cable which was used is about 3.8 mm thick (Datasheet see Solifos AG, 2019b) and the fibre (I) is surrounded by a special metal tube (II). Between the fibre and the metal tube, a gel is used to guarantee that no strain is transferred to the glass fibre. The outer protection is made of a special steel armouring (III) and a polyimide sheath (IV).

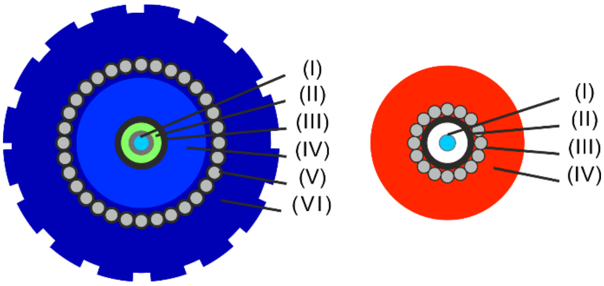

Figure 3. Strain sensing cable (Typ #01, V3; left) and temperature sensing cable (Typ #02, Temp; right)

III. FIELD APPLICATION

The field installation of the described monitoring system took place at the Semmering Base Tunnel (SbT). The SbT is one of the main elements of the European TEN-T Network Corridor, which connects the Baltic and the Adriatic Sea (Figure 4). In 2026, after 14 years construction time, the 27 km tunnel will be one of the longest train tunnels in Europe. It will represent a high-speed rail connection as part of the Southern Line and together with the Koralm tunnel (about 33 km) reduce the travelling time from Vienna to Klagenfurt to 2 hours 40 minutes (today 4 hours). Since the SbT railway track passes challenging geological conditions, novel monitoring approaches like DFOS systems can contribute to a better understanding of the rock behaviour during the construction and possibly give new insights after the completion of the construction.

IGMS already uses DFOS systems in the SbT project for monitoring of different structures like reinforced earth structures (Moser et al., 2016), pipelines (Klais et al., 2017) and tunnel linings (Monsberger et al., 2018).

Figure 4. European TEN-T Network Corridor (Source: INEA)

A. *Installation of the DFOS system*

Based on the NATM (New Austrian Tunnelling Method) the tunnel construction is usually divided in several steps, which gives the rock the possibility to stabilize by itself. The outbreak of the tunnel cross section, where the DFOS system was installed, can be divided into two parts. First, the upper part of the tunnel, the top heading, is excavated. A few days later the lower parts, the bench and the invert are removed. Directly after the outbreak of the top heading one strain/temperature sensing cable (Typ #01) and one cable only sensitive to temperature (Typ #02) were installed directly in the cross section at the tunnel face. The suitability of the cables for the applications were proven by a load test at Graz University of Technology before the installation (Henzinger et al., 2018). The cables were mounted along the reinforcement grid using cable ties to guarantee their position during the application of the shotcrete, which was applied afterwards. During the curing of the shotcrete, the strain sensing cable forms a rigid connection to the surrounding material due to its structured surface (see Figure 3, left side) and therefore, deformations of the shotcrete are transferred to the sensitive glass fibre core inside the cable. The fibre optic installation was performed in both shotcrete layers.

About 100 m behind the instrumented cross section, the BOFDA sensing unit was set up in a measurement box for the continuous monitoring. To connect the sensing cables to the unit, a conduit with supply fibres and a connection box directly inside the cross section were installed. Directly after the installation of the DFOS cables in the top heading, the cables were connected with the supply fibre and an autonomous monitoring was started immediately. Four days later sensing cables were also installed in the same way in both shotcrete layers of the bench/invert section and the new installed cables were integrated in the sensing system. In the end, this allows measurements almost along the entire cross section.

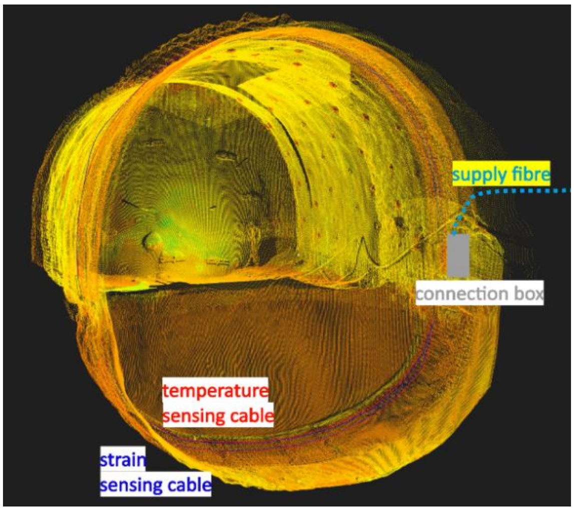

Figure 5. DFOS installation on tunnel site

Data was collected twice every hour for several weeks without any interruption of the construction work. The measurement results were retrieved via a remote access and it was possible to check the functionality of the whole monitoring system.

Laser scans were conducted during the installation of the fibre optic cables and after the shotcrete was sprayed. The point clouds and meshes give additional information, e.g. about the position of the sensing cables along the lining. Furthermore, details like the thickness of the concrete layers or anchor positions can help in the prospective data analysis of the strain changes. An overview of the installation area together with the retrieved laser scan can be seen in Figure 5.

B. *Comparison to conventional geotechnical monitoring*

The most common monitoring method in tunnel constructions is the 3D displacement monitoring. The measurements are retrieved by using targets and a total station. Either bi-reflex targets or precise mini prism targets are used to determine the location within a project or global coordinate system. Repeated measurements are executed (normally daily) to determine three-dimensional displacements. As it is not possible to measure all deformation points from one position, a linked observation scheme is needed (Figure 6, Top). Points are separated in two classes: stable reference points and moveable deformation points. To obtain the needed accuracy of ±1 mm of the measured point, requirements with respect to maximum measurement distances have to be fulfilled (Austrian Society for Geomechanics, 2014).

Since the position of the instrument and the surrounding atmosphere plays an important role regarding the achievable accuracy of the measurements, it is sometimes hard for the surveyor to find the right place and time for the total station measurements. Sightings close to the tunnel wall should be avoided, since they could produce measurement errors caused by refraction (Figure 6, Bottom). Heat sources from excavators, drill jumbos and wheel loaders may cause measurement errors due to refraction if sightings pass by the machinery (Figure 7). Moreover, measurements during strong vibrations, e.g. caused by a drill jumbo, and in dusty surroundings should be avoided.

Furthermore, fixed installed tunnel equipment such as the air ventilation system, waste water and electricity supply may block the field of view and make the measurement to the desired deformation and stable monitoring points impossible. Additionally, surveyors who perform these measurements have to be always attentive to be not overlooked by the workers driving heavy tunnel machinery. Furthermore, during some construction processes, such as blasting operations and material removal, it is impossible to measure near the tunnel face. Hence the time when it is possible to make reliable total station measurements is limited.

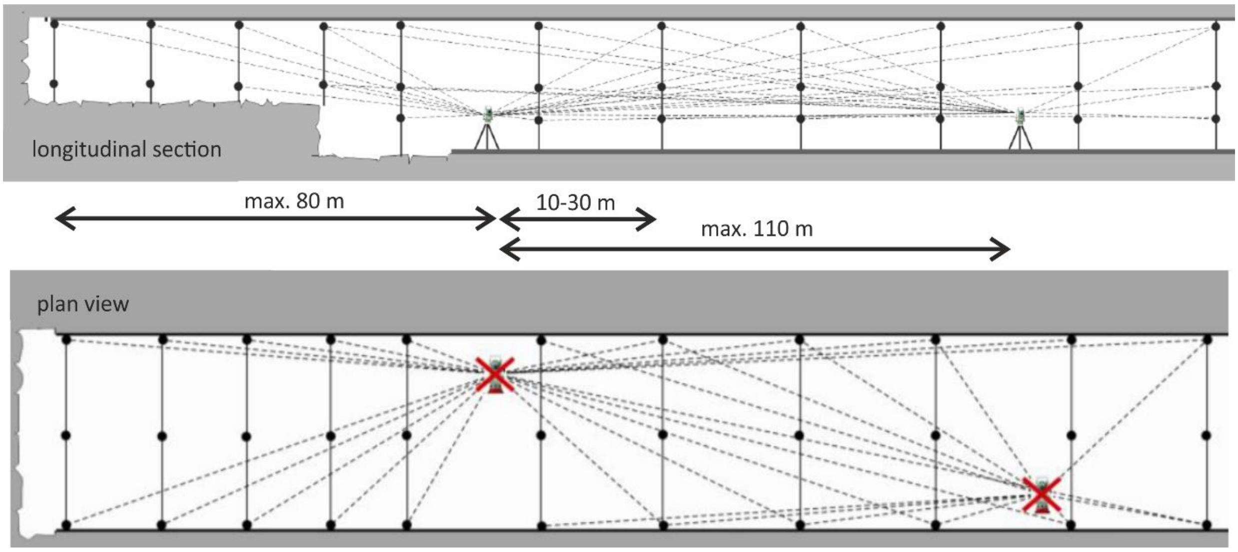

Figure 6. Top: Recommended total station observation scheme (top); unfavourable positions (bottom) (Source: OEGG, 2014)

Figure 7. Tunnel construction site

As already mentioned, the area of the bench/invert cannot be monitored with geodetic targets since it is filled up with earth and used as a road during the construction phase. To measure deformations in that area it is necessary to use geotechnical installations such as extensometers or, as presented in this paper, fibre optic cables embedded in the shotcrete.

IV. RESULTS

A. *DFOS (Strain) and geodetic measurements*

The monitoring of the cross section in the Semmering Base Tunnel started directly after the installation on February 4th 2018. Several weeks every half an hour a complete measurement of the cross section was done, which allows calculating the strain and temperature changes. Additionally to the DFOS measurements, the local surveying team measured seven bi-reflex targets spread across the section once a day. From the geodetic measurements, it is possible to calculate three-dimensional displacements (Figure 8).

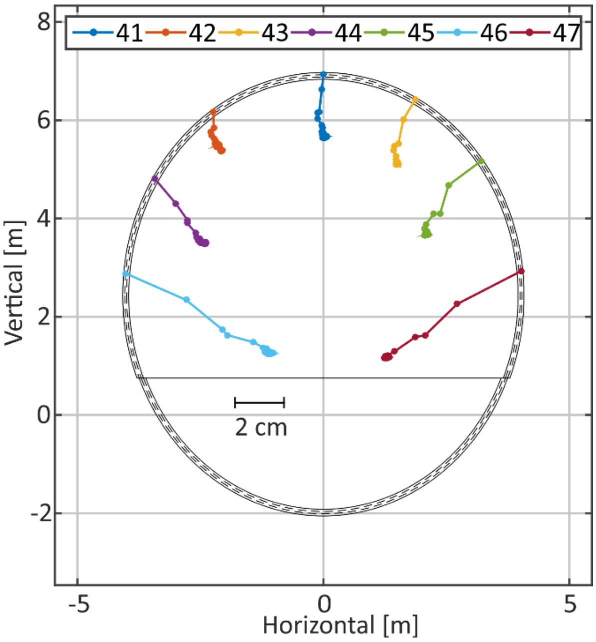

Figure 8. Displacements from geodetic measurements (daily 04.02-25.02.2018)

The results of the geodetic measurements show that the deformation of the lining is developing at a faster rate (measurement points are wider apart) at the beginning. Some days later, after the excavation of the bench/invert and the closing of the whole shotcrete ring, the displacements decrease to a minimum amount (measurement points are close to each other). The lowest targets on the left and right side wall depict the highest displacements of about 5 cm in horizontal and 3.5 cm in vertical change.

The distributed fibre optic system measures temperature and strain changes at more than 500 positions directly inside the shotcrete. With a spatial resolution of half a meter and a high distance sampling factor, every 5 cm a measurement value can be determined. In Figure 9, the measured strain profiles of seven selected epochs of the first layer (rock side layer) are shown. There is only negative strain (compression) visible due to creeping effects of the concrete and rock pressure on the tunnel lining. The maximum negative strain is about -1860 µm/m (= -1.86 mm/m). Since the outbreak was done in two steps (first top heading, afterwards bench/invert), the first two epochs are only shown in the top heading. On the left and right wall there are no DFOS measurements, since it was not possible to install any cables there, due to the separated outbreak of the tunnel. Compared to geodetic measurements the tunnel cross section can be monitored with a much higher detail.

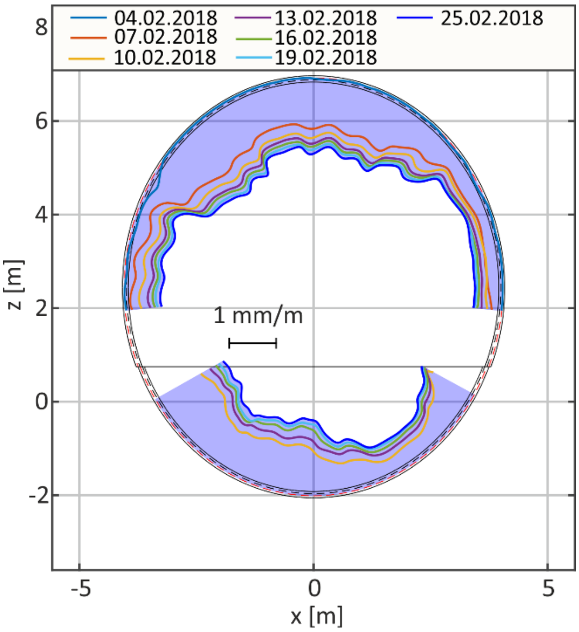

Figure 9. Strain changes in the first shotcrete layer of seven selected DFOS measurements

When comparing geodetic and fibre optic measurements, the different properties of the individual methods have to be considered. Position changes are derived from geodetic measurements whereas DFOS measurements deliver strain changes. In order to compare the different technologies, strain can be derived from the position changes of the geodetic targets. Therefore, the length variation ΔL between two measured points has to be divided by the total length L. In Figure 10, the calculated strain between the geodetic points 41 and 43 and one DFOS point in this area in each shotcrete layer is shown. The data is plotted relative to the second geodetic measurement.

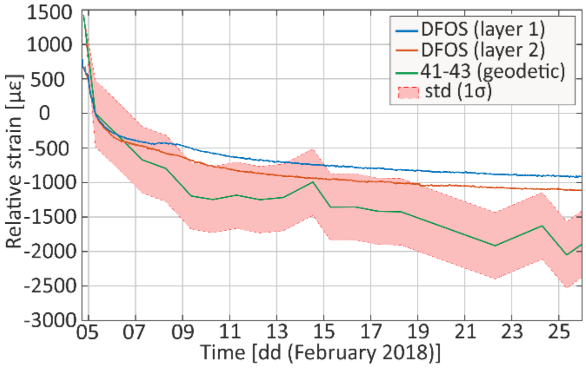

Figure 10. Geodetic (converted to strain) vs. DFOS measurements (one point) as a time series

The geodetic measurements have a standard deviation of about ±1 mm which results in a standard deviation of ±500 µm/m for the derived strain between the points 41 and 43, compared to about ±20 µm/m (µε) of the fibre optic measurements. Another point that has to be taken into account is the location of the targets and the sensing cables inside the cross section. In this case, the geodetic targets were one meter closer to the tunnel face than the DFOS system. Hence, in the further construction progress of the tunnel, the geodetic measurements recorded greater displacements than the fibre optic system. As can be seen in Figure 10, after around 20 days of monitoring the maximum strain (temperature corrected) of the DFOS system is about 1000 µm/m compared to 1500 µm/m derived from the geodetic measurements.

To verify that the position of the sensor influences the measured deformations, five bi-reflex targets were mounted on two subsequent cross sections each after a blasting operation. The distance between the two equipped cross sections was 1 m; the bi-reflex targets were monitored over a time span of 4 weeks (Figure 11). Within the cross section at 2700 m (dashed line) the measurements showed higher displacements than the cross section at 2699 m (solid line). The same effect could also be seen in a previous fibre optic installation at the SbT, where the sensing cables were mounted in a curved scheme and thus in different distances to the tunnel face (Monsberger et al., 2018).

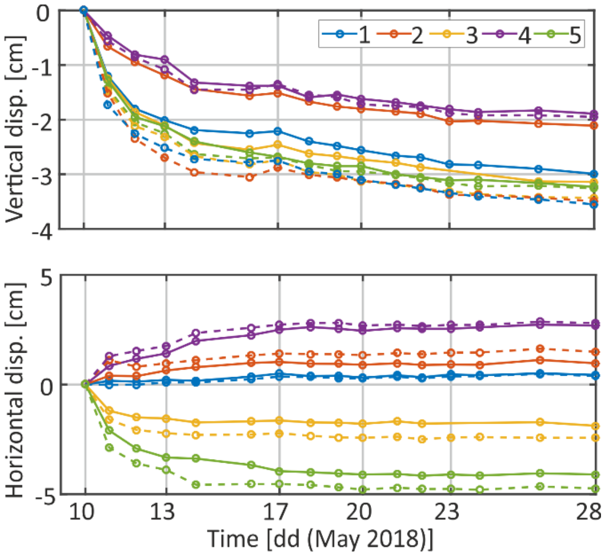

Figure 11. Comparison of two geodetic cross sections (solid line at 2699 m and dashed line at 2700 m)

B. *DFOS (Temperature) measurements*

The temperature measurements are mainly used to derive temperature compensated strain changes. Nevertheless, the temperature changes can be utilized to obtain information about the concrete curing or even for fire surveillance or a rough observation of the construction progress. According to the different machines and the construction progress that is ongoing, the temperature is changing inside the tunnel. The DFOS installation allows to record these changes inside the shotcrete. At the top point, the temperature sensing cable, which was installed in the second shotcrete layer, was able to monitor exactly at which time every blasting operation was done.

The temperature changes over the time of one point at the top of the tunnel in each installed layer is shown in Figure 12. The blue line shows that the temperature changes in the first layer are much more smoothed and smaller. This comes from the deeper placement inside the shotcrete compared to the second layer. The second layer (red line) shows changes in the range of 0.5 K to 2.5 K. The shown temperature changes can be subdivided in three areas, working with blasting operations, excavator driving and the construction of a cross passage. In area A, the tunnel was driven with blasting, which leads to bigger changes caused by the paused air ventilation system. The times of the lowest temperature coincide with the blasting operation times from the construction protocol. Afterwards, the temperature increases because the excavator is the biggest heat source needed in the NATM. In area B, the top heading was stopped and the bench/invert was constructed using only the excavator. The frequency of the temperature variations gets smaller, between the highs and lows are only three to four hours. This changed behaviour comes from the fact that the air ventilation system is permanently on and that the construction is faster compared to the top heading. Area C depicts a completely different temperature change. The construction protocol shows that the regular construction was interrupted on the 17th of February at 22:30 to excavate the cross passage to the other tunnel tube. Hence, all the machinery worked there and the air directly at the instrumented cross section cooled down in the main tunnel axis. At February 19th 2018, the regular construction started again in the main tube and the temperature increased again. These results demonstrate that also DFOS temperature measurements, which are primarily needed to compensate the fibre optic strain values, can provide additional information.

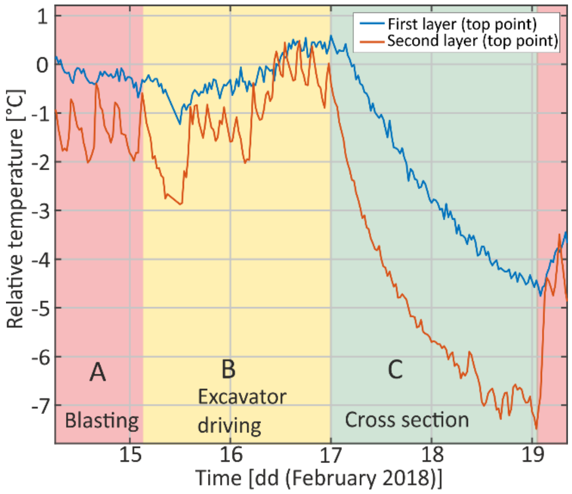

Figure 12. Temperature changes in both shotcrete layers in top point

V. CONCLUSIONS

In this paper, a DFOS system was presented, which enables in-situ strain and temperature measurements inside tunnel linings. The monitoring system of the whole sensing loop successfully performed measurements over several weeks while the tunnel construction continued without any delays caused by the monitoring. The results showed that reliable strain and temperature measurements with a spatial resolution of 0.5 m can be derived with the installed system, even in rough environments like a tunnel.

Compared to geodetic measurements, DFOS monitoring systems deliver much more details about the behaviour of the tunnel lining. Moreover, the bench/invert can also be monitored, which is not possible using geodetic measurements without any additional procedures. Hence, DFOS systems are a very valuable extension to conventional geodetic systems and can contribute to predictive maintenance for high safety standards.

Future research will focus on different DFOS tunnel installations e.g. in a shaft or in the inner tunnel lining. These installations should serve either during the construction or as a long-term system for the operating time. Finally, all the results, which can be retrieved from in-situ measurements, should make it easier to understand the structural behaviour of the shotcrete tunnel lining.

VI. ACKNOWLEDGEMENTS

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References

Austrian Society for Geomechanics (Hg.) (2014). Geotechnical Monitoring in Conventional Tunnelling. Handbook. Salzburg.

Dunnicliff, John (1993). Geotechnical instrumentation for monitoring field performance. New York: Wiley

fibrisTerre Systems GmbH (2018). Fiber-optic sensing system fTB 2505. Datasheet. Online available at: https://www.fibristerre.de/files/fibrisTerre_flyer.pdf, accessed: April 4, 2019.

Henzinger, Michael R.; Schachinger, Tobias; Lienhart, Werner; Buchmayer, Fabian; Weilinger, Walter; Stefaner, Raimund et al. (2018). Fibre-optic supported measurement methods for monitoring rock pressure. In: *Geomechanik und Tunnelbau* 11 (3), pp. 251–263.

Klais, Frank; Wolf, Petra; Lienhart, Werner (2017). The Grautschenhof contract - Construction of an intermediate access under complex local conditions. In: *Geomechanik und Tunnelbau* 10 (6), pp. 686–693.

Luna Innovations Inc. (2019). OBR 4600 Optical Backscatter Reflectometer. Datasheet. Online available at: https://lunainc.com/wp-content/uploads/2012/11/LUNA-Data-Sheet-OBR-4600-V2.pdf, accessed: April 4, 2019.

Measures, Raymond M. (2001).Structural Monitoring with Fiber Optic Technology. Vol. 1 s.l.: Elsevier professional.

Monsberger, Christoph; Lienhart, Werner; Alexander, Kluckner; Wulf, Schubert (2018). Continuous strain measurements in a shotcrete tunnel lining using distributed fibre optic sensing. In: *Structural Health Monitoring. 9th European Workshop on Sturctural Health Monitoring*.

Moser, Florian; Lienhart, Werner; Woschitz, Helmut; Schuller, Hartmut (2016). Long-term monitoring of reinforced earth structures using distributed fiber optic sensing. In: *J Civil Struct Health Monit* 6 (3), pp. 321–327.

Solifos AG (2019a). BRUsens strain V3. Datasheet. Online available at: http://solifos.nubosys.com/fileadmin/syncfiles/media/Solifos_SE-01-03_3-50-2-002_en.pdf, accessed: April 4, 2019.

Solifos AG (2019b). BRUsens temperature. Datasheet. Online available at: http://solifos.nubosys.com/fileadmin/syncfiles/media/Solifos_SE-01-01_3-50-1-001_en.pdf, accessed: April 4, 2019.

Woschitz, Helmut; Klug, Ferdinand; Lienhart, Werner (2015). Design and Calibration of a Fiber-Optic Monitoring System for the Determination of Segment Joint Movements Inside a Hydro Power Dam. In: *J. Lightwave Technol.* 33 (12), pp. 2652–2657.