The 8th International Conference on
Structural Health Monitoring of Intelligent Infrastructure
Brisbane, Australia | 5-8 December 2017

In-situ Deformation Monitoring of Tunnel Segments using High-resolution Distributed Fibre Optic Sensing

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Abstract

In modern tunnelling, geotechnical deformation monitoring is an important component to ensure a safe construction and a long lifetime of the tunnel. It is state of the art to measure displacements at the inner lining surface using total stations or terrestrial laser scanners and internal deformations with vibrating wire sensors. However, these measurements do not deliver a complete picture of the capacity within the tunnel lining and new methods must be evolved. In this paper, the authors report about a fibre optic sensing system that allows distributed in-situ deformation monitoring in tunnelling applications. Especially due to the high spatial resolution of about 10 mm, new information can be gathered.
The developed system was used to measure internal strains within tunnel segments during load tests at a specifically developed test rig. Sensing cables with lengths up to 60 m were embedded in several layers along the reinforcement and therefore, the utilization at about 6000 positions can be observed. Moreover, the high measurement resolution of about 1 µm/m enables the detection of cracks. The suitability of the system is proven with reference measurements, including camera-based systems for crack monitoring and internal pointwise strain measurements with vibrating wire sensors.
In addition to investigations of precast tunnel segments, a modified system for conventional tunnelling is presented, which is already installed in the shotcrete lining directly in the area of the working face in a geological interference zone. After installation, autonomous monitoring was performed during the curing of the shotcrete and the further excavation of the tunnel over several weeks. The results demonstrate the high potential of distributed fibre optic sensing systems and their capability to extend classical measurement methods in tunnelling applications.

1. Introduction

Motorway and railway tunnels are important parts of the civil infrastructure and their functionality is essential for a country's society and economy. For that reason, several large tunnel projects are currently being carried out worldwide, which will lead to shorter travel times as well as higher transport capacities in the near future. In Austria, three long railway tunnels are under construction: The Brenner Base Tunnel (length: 55 km), the Semmering Base Tunnel (length: 27 km) and the Koralm Tunnel (length: 33 km). All of these tunnel projects are part of the Trans-European Transport Network (TEN-T) and will contribute to a significant improvement of the European railway infrastructure.
However, long tunnel projects require large investments, typically more than 10 billion US-Dollars, and long construction times of 10 years and more. Hence, building owners are striving for a long service life of more than 100 years, which can only be achieved if every construction step is carried

out in accordance to specifications and maintenance work is performed at the right time to avoid severe damages.
To assess the structural behaviour of a tunnel, geotechnical monitoring systems are essential components for a safe construction and operation, see OeGG (2014). These include 3D displacement measurements at the inner lining surface with total stations (Rabensteiner, 1996) or terrestrial laser scanners (Fakete et al., 2010) as well as internal deformation measurements using vibrating wire sensors (Radončić et al., 2015) or extensometers (Barla, 2009). Nevertheless, the mentioned sensor systems do not deliver a complete picture of the internal load distribution of the tunnel section and therefore, local damages like cracks within the concrete lining might not be detected.
Distributed fibre optic measurement systems are advantageous compared to pointwise deformations sensors as the fibre optic cable itself acts as the sensing element. Thus, distributed measurements can be performed along the entire cable and a large number of measurement points can be realized. However, since an optical glass fibre is used for sensing, robust sensor cables as well as tailored installation techniques are required to protect the sensing element during the construction of the tunnel lining. Against this background, only a few approaches of fibre optic monitoring applications in tunnelling are currently known, in which mostly Brillouin analysers with a typical spatial resolution of 0.5 to 1 m are used, see e.g. Kechavarzi et al. (2016).
This paper reports about a distributed fibre optic sensing system based on Rayleigh backscattering, which allows distributed in-situ deformation monitoring in tunnel lining segments with a high spatial resolution of 10 mm. In the following, the basic principle of the measurement device is described (Sec. 2.1), sensing cables for applications in harsh environments are discussed (Sec. 2.2) and calibration results of the system in the laboratory are presented (Sec. 2.3). Afterwards, the utilization of the fibre optic system during load tests at a specifically developed test rig (Sec. 3) and autonomous monitoring of a shotcrete lining (Sec. 4) are introduced. Finally, the suitability of the system for tunnelling applications is discussed and an outlook on future research is given (Sec. 5).

2. Fibre Optic Monitoring System

In order to provide a suitable and reliable fibre optic measurement system for tunnel monitoring, various system components have to be considered. In this section, the characteristics of the sensing principle as well as different sensing cables for strain measurement in harsh environments are discussed and calibration results of the system in the IGMS (Institute of Engineering Geodesy and Measurement Systems, Graz University of Technology) laboratory are presented.

2.1 Sensing Principle

Rayleigh scattering is one of the major effects of intensity loss in optical fibres. It is mainly caused by variations of the refractive index profile along the fibre core and effects about 85 % of the natural attenuations (Wuilpart, 2011). The Rayleigh scatter amplitude has a random but static behaviour along the fibre. Changes in strain or temperature cause a spectral shift in the locally reflected Rayleigh pattern and therefore, a small, local fibre segment, which is transformed to the frequency domain, can be interpreted as a weak reflecting fibre Bragg grating (FBG) with a random period. Consequently, the distributed measurement system can be modelled by splitting the fibre into equidistant segments and calibrating the local Rayleigh shift in reference to changes in strain or temperature.
For tunnel lining monitoring, an optical backscatter reflectometer (OBR) from Luna Innovations Inc. was used, whose sensing principle is based on optical frequency domain reflectometry (OFDR). This interrogation unit is able to record sensing information with a high resolution of

about 1 µm/m for strain and about 0.1 K for temperature measurements. Moreover, a spatial resolution of about 10 mm or even better may be realized. (Luna, 2014a)
To form the distributed measurement system, the Rayleigh backscatter of the sensing fibre is recorded in an initial strain and temperature state. This measurement can be interpreted as a reference scan. Later, the fibre is scanned again, when the strain and/or the temperature state has changed. For data evaluation, the signals of both measurements are divided in equidistant segments, where the length of the segment Δz corresponds to the spatial resolution of the OBR and the spectrum of each segment is observed in the frequency domain. The wavelength spectra of an interval with a length of 10 mm for an unstrained reference scan and the spectra of the same segment of the fibre with an applied strain of about 1000 µm/m can be seen in Fig. 1a. The strain change causes a spectral shift between the reference and the influenced scan, which size can be determined through a cross correlation between the two spectra, see Fig. 1b. The resulting wavelength shift $\Delta\lambda$ is directly proportional to the apparent strain change of this fibre segment. By calculating this shift for each segment of the sensing fibre, it is possible to realize a distributed measurement system. Detailed information on the sensing principle and the optical network may be found in e.g. Kreger et al. (2006).

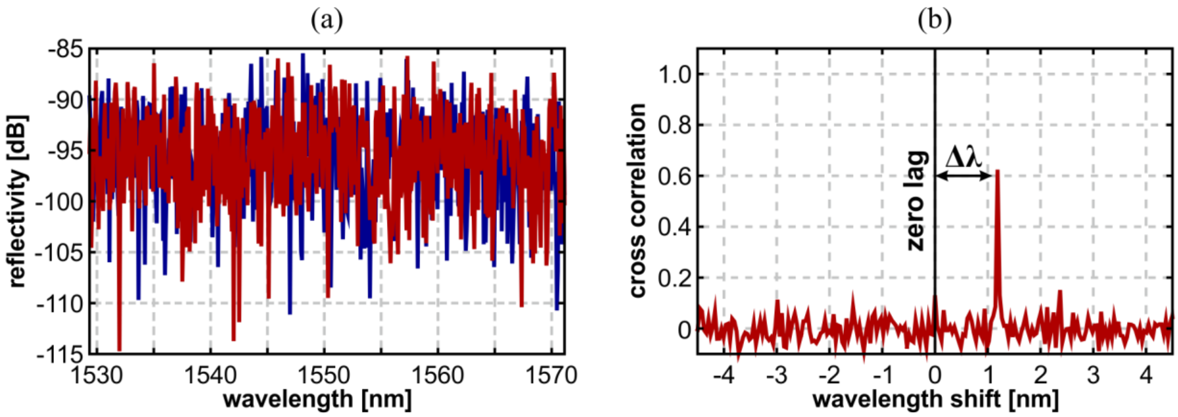

Fig. 1: Sensing principle of an optical backscatter reflectometer (Monsberger et al., 2017): (a) Wavelength spectrum for an unstrained (blue) and a strained (red) fibre segment (Δz = 10 mm) and (b) the corresponding cross correlation function

2.2 Strain Sensing Cables

As a consequence of the harsh environments for optical fibres in tunnelling applications, robust sensor cables are required to protect the sensing element during installation and monitoring. In addition, it is also important that all cable layers are interlocking to ensure the unbiased strain transfer from the outer sheath of the cable through the protection layers to the sensitive fibre core.
For fibre optic strain measurements in geotechnical projects, IGMS commonly uses strain sensing cables from Brugg Cables AG, Switzerland. Fig. 2 shows the basic structure of two selected cables for distributed strain measurements, which are especially developed for sensing in grout or concrete. Both cables protect the optical fibre through a special metal tube. Due to an interlocking multi-layer buffer, the strain transfer to the sensitive glass fibre core can be ensured. The outer protection varies depending on the cable type. Whereas type V9 (Fig. 2a) is only equipped with an outer polyimide layer, type V3 (Fig. 2b) has also a special steel armouring that additionally protects the sensing fibre against mechanical impacts. Although this armouring makes the cable more robust, the flexibility of this type (minimal bending radius, etc.) is limited and thus, the cable selection must be well adapted to the monitoring conditions. Moreover, both cables have a structured outer surface, which guarantees a solid bond with the surrounding material.

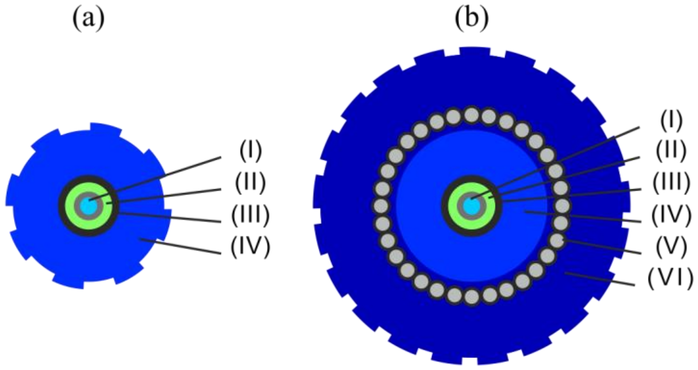

Fig. 2: Structure of strain sensing cables from Brugg Cables AG: (a) Type V9 and (b) type V3 with (I) strain sensing single mode fibre (∅ 250 µm), (II) multi-layer buffer with strain transfer layer, (III) metal tube, (IV) polyimide protection layer, (V) special steel armouring and (VI) polyimide outer sheath

2.3 System Calibration

In order to prevent systematic errors in the conversion from raw measurements to strain or temperature changes, individual calibration has to be considered as an important part within the development of a fibre optic measurement system. Many manufactures of fibre optic sensors do not specify individual calibration parameters and refer to literature values instead, which might result in errors up to 10 % (Luna, 2014b). For that reason, IGMS developed a unique calibration device within the last years, see Fig. 3a. Key components of this facility are the stable setup on a 30 m concrete bench, a linear translation stage that allows sensor elongations up to 300 mm and a laser interferometer that is used for a precise reference measurement. For details, reference is given to Woschitz et al. (2015).
As discussed in Sec. 2.1, the local Rayleigh shift between a reference scan and subsequent measurements depends on both, strain ε and temperature changes ΔT. The transfer from the measured wavelength shift $\Delta\lambda$ [nm] or the frequency shift $\Delta\nu$ [GHz] to these quantities may be approximated by the linear function

$$\frac{\Delta\lambda}{\lambda} = \frac{-\Delta\nu}{\nu} = K_\varepsilon \varepsilon + K_T \Delta T \tag{1}$$

with the normalized sensitivity coefficients K_ε and K_T and the centre wavelength λ or centre frequency ν of the scan. This equation is identically to the response of a fibre Bragg grating (Kreger et al., 2006). As the calibration facility is set up in the IGMS temperature and humidity controlled laboratory, the temperature is constant and the measurement signal only depends on strain:

$$\frac{\Delta\lambda}{\lambda} = \frac{-\Delta\nu}{\nu} = K_\varepsilon \varepsilon \,\bigg|_{\Delta T = const.} \tag{2}$$

Prior to the installation within the tunnel lining segments, individual calibrations of samples of different sensing cables were carried out on the IGMS calibration facility. Regarding the experience from past calibrations, it is important to slightly pre-strain the cables to avoid non-linearities in the lower strain regions. In addition, calibrations are usually performed in full cycles to evaluate possible hysteresis effects. To determine the different strain sensing coefficients K_ε, the distributed strain values over the strained section can be averaged and a linear regression analysis can be performed.

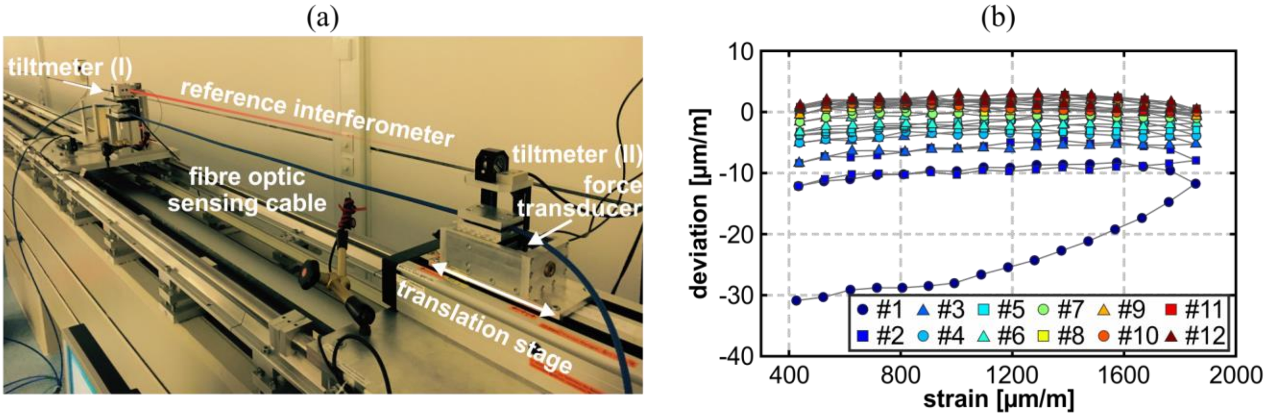

Fig. 3: (a) IGMS calibration facility for fibre optic strain sensors and (b) residuals of the linear regression analysis of cable type V3

As an example of a typical calibration result, Fig. 3b shows the residuals of the linear regression analysis of cable type V3. In the first cycle, significant drift and hysteresis effects with deviations of more than 30 µm/m become visible. Also cycle #02 does not fit exactly to the other calibration data, even if its deviations are much smaller. It can be assumed that this effect might be related to an interaction between the protecting elements of the cable during the first strain increase after production of the cable. Therefore, the first two cycles were excluded from the determination of K_{ε}. The estimated strain coefficient of cable type V3 can be specified with 0.748, which basically agrees to literature values, e.g. 0.780 (Luna2014b). Further information on strain calibration of sensing cables for geotechnical applications may be found in Monsberger et al. (2017).
Temperature compensation of the derived strain values usually depends on the monitoring application. In case of load tests, e.g. indoors or inside the tunnel, the concrete temperature will be almost constant over a relatively short testing period of some hours and the remaining influences may be neglected. In other applications, especially in long-term monitoring, an unstrained fibre installed nearby the strain sensing cable can be used to eliminate raising temperature effects.

3. Load Tests of Precast Tunnel Segments

When using tunnel boring machines (TBMs) for excavation work, concrete lining segments are applied, which are usually set up in a ring of four to eight elements. For a verification of the load-bearing and deformation behaviour of these precast segments, the Austrian Federal Railways (ÖBB-Infrastruktur AG) developed in cooperation with the Montanuniversität Leoben (Chair of Subsurface Engineering) a special test rig (see Fig. 4b), which allows biaxial testing of full scale precast tunnel segments under exact known loading conditions (Gehwolf et al., 2016). The basic measurement equipment of the rig includes wire-rope sensors to measure the vertical deformations as well as strain gauges and extensometers on the segment surface for crack detection. In addition, tests with camera-based systems for crack monitoring are carried out (Pogats, 2016). To gather information about the internal load distribution, IGMS developed a fibre optic sensing system to measure internal strains within the tunnel segments. This approach is also patented, see Lienhart & Galler (2016). Subsequently, the sensing fibre installation is discussed and some results of the load tests are presented, which demonstrate the capabilities of the system.

3.1 Production of Tunnel Segment and Fibre Optic Instrumentation

In the course of the project, tunnel segments are produced with classical reinforcement elements. For that reason, the sensing cable can be individually guided along the reinforcement bars (see Fig. 4a) without any supporting structure and thus, a grid may be built up with complete coverage of each segment. Although harsh environments are prevalent for the optical sensing fibre, the less protected cable type V9 is used to provide more flexibility. During the installation, the cable is mounted on the reinforcement using cable ties to guarantee a fixed position inside the segment. Later, a solid bond between the concrete and the cable is given due to the structured polyimide surface, which ensures a reliable transfer of the deformations to the sensitive glass fibre core. Inside the segment, a connecting box is placed, in which the optical connectors are stored during concreting. In addition, vibrating wire sensors (VWS) are installed on the inner and outer bending reinforcement, which are used to prove the suitability of the fibre optic system.

Fig. 4: (a) Installation of the fibre optic sensing cable along the reinforcement bars and (b) test rig for precast tunnel lining segments

3.2 Measurement Results

During the load test, which is described in this paper, the tunnel segment was only loaded vertically and hence, compression (negative strain) on the outer and positive strain on the inner reinforcement can be expected. The vertical load was increased in steps of 25 kN starting from 100 kN. Initially, a pre-load step at 50 kN was performed. During the test, the strain distribution inside the segment was continuously monitored with a sampling frequency of about 0.1 Hz using the OBR controlled by an individual IGMS-developed measurement software.

In

Fig. 5a, the strain profiles along an instrumented bending reinforcement bar in the inner as well as the outer layer at lower load steps up to 175 kN are shown. These results confirm the assumption that negative strains occur on the outer layer of the reinforcement under vertical load. Additional deformations are visible in the centre between ±0.5 m, which can be explained by the bearing point of the cross beam of the test rig. Along the inner reinforcement, increasing strain values can be observed with increasing load. Furthermore, local peaks in the area between ±0.7 m along the strain profiles arise, starting at the load step of 150 kN. These inhomogeneities are related to cracks in the concrete, which start to evolve at a vertical load of 150 kN.

To compare the fibre optic measurement results to these of the vibrating wire sensors, the strain values in the area of the VWS (±0.08 m) can be averaged and their time series can be analysed, see Fig. 5b. Up to a load of 175 kN (dotted line at about 55 min), the measurement data of both technologies fit well to each other, even if small linear deviations can be seen. At the following load steps of 200 kN and higher (60 min and later), the deviations increase significantly, which might be a result of a further opening of the cracks inside the concrete. This suggests that local stress events like cracks cannot be detected by VWS. The fibre optic system is able to monitor the crack opening, although the crack width of a few hundredths of millimetres results in an integrative response of the sensing cable over several centimetres.

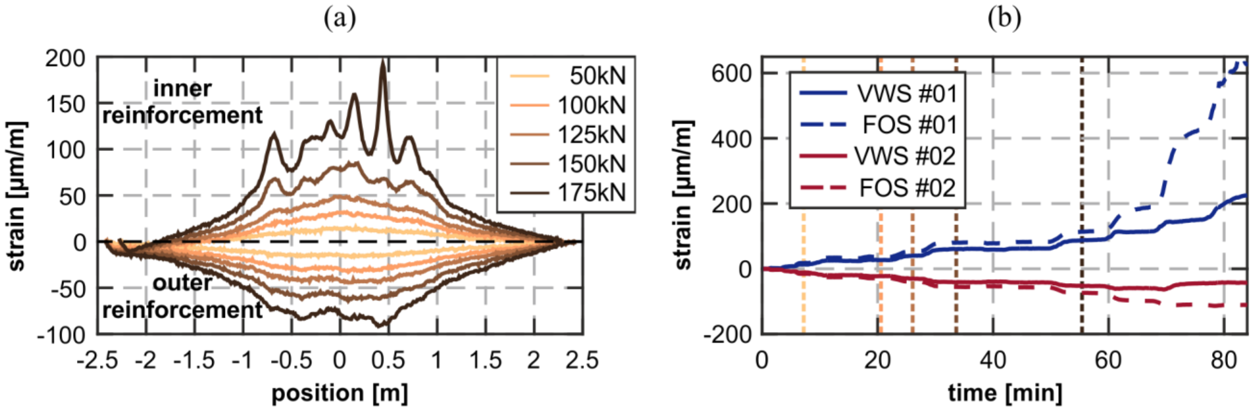

Fig. 5: (a) Measured strain profiles along instrumented inner and outer bending reinforcement bars at selected load steps and (b) comparison between fibre optic measurement system and vibrating wire sensors (dotted lines represent load steps between 50 and 175 kN)

In order to analyse the crack evolution in more detail, further load steps within the test can be considered. Fig. 6b shows the measured strain profiles along an instrumented inner bending reinforcement at different load steps from 200 to 450 kN. Within the central area from -0.7 to 0.7 m, in which inhomogeneities have already become visible at prior load steps, local strain peaks can also be observed at a load of 200 kN. However, the peak heights are significantly increased compared to other strain values along the measured profile, which indicates that a further opening of the cracks occurred. By increasing the test force up to 450 kN, cracks also arise in the area offside the centre. In general, a good correlation between crack positions and the location of the transverse reinforcement bars (Fig. 6a) can be recognized. This implies that cracks along the inner bending reinforcement under vertical load usually appear on positions, where a transverse reinforcement bar is located.

In addition to the in-situ crack monitoring through the fibre optic system, measurements with a camera-based system are performed at selected load steps by the Montanuniversität Leoben. First results in Fig. 6c show the recorded crack pattern at a load step of 300 kN, whereby various cracks in the central area of the tunnel segment are visible. Due to the limited viewpoint of the camera (approximately -0.7 to 1.1 m), cracks at outer positions cannot be recorded. The positions of the captured cracks basically agree with the fibre optic strain peaks, even if differences of some centimetres occur at some locations. However, crack positions, which are very close together (e.g. Pos. 1), may not be separated by the fibre optic system and thus, these cracks appear as one peak in the fibre optic strain profiles. In contrast, the camera system does not deliver internal crack positions, which are not visible on the surface, e.g. Pos. 2.

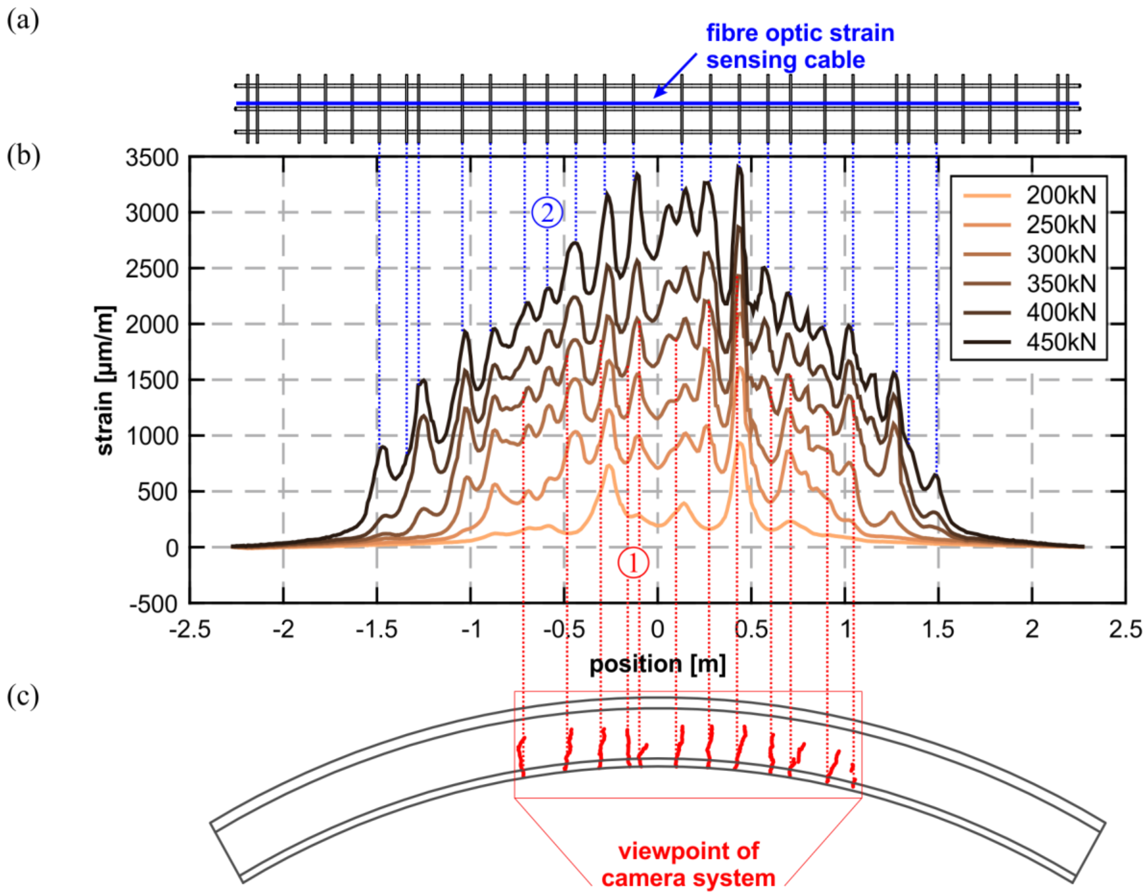

Fig. 6: (a) Schematic representation of instrumented reinforcement, (b) measured strain profiles along inner bending reinforcement at various load steps and (c) crack pattern recorded by camera-based system at 300 KN

4. Monitoring of Shotcrete Tunnel Lining

Due to uncertainties of every geological and geotechnical underground models, geotechnical monitoring and reliable data interpretation are very important in conventional tunnelling. Thereby, systematic and high-frequent monitoring techniques lead to a better understanding of the rock's behaviour, which finally results in an optimisation of the construction process and a safe construction of the tunnel. In geological interference zones, it is state of the art to measure the capacity of the shotcrete using strain gauges and pressure load cells. However, these methods do not give a complete picture of the internal utilization. First attempts to use distributed fibre optic sensors in sprayed concrete were reported by de Battista et al. (2015). As part of a research project in cooperation with the Austrian Federal Railways (ÖBB-Infrastruktur AG) and FMT (Institute of Rock Mechanics and Tunnelling, Graz University of Technology), IGMS developed and installed a fibre optic monitoring system in the shotcrete lining directly at the working face at a construction section of the Semmering Base Tunnel. In the following, the measurement concept is shortly introduced and first results of an autonomous monitoring campaign in spring 2017 are presented.

4.1 Measurement Concept and Sensor Installation

Based on the New Austrian Tunnelling Method (NATM), conventional tunnelling is usually performed in excavation sequences, which enable the rock to support itself (OeGG, 2010). The construction of the tunnel section, in which the fibre optic system was installed, can be split into two essential parts, see Fig. 7a. In a first step, the top-heading area is broken out in sequential parts

and the cross section is supported by reinforcement layers and shotcrete. Depending on the geological conditions, this construction method is carried out for several meters. Afterwards, the bench/invert section is excavated and also supported by reinforcement and shotcrete. In order to create a load-bearing ring, the invert is immediately reclosed after the construction.
Fibre optic sensing cables were installed along the reinforcement in peripheral direction of both sections to monitor the load distribution. Due to the harsh environment (e.g. shotcrete) inside the tunnel, cable type V3 was chosen to provide an optimal protection of the sensing fibre. During the curing of the shotcrete, the temperature inside the lining usually varies in a range of 20 to 30 K. For that reason, an additional sensing fibre of type V3 was loosely installed in a cladding tube nearby the strain sensing cable (see Fig. 7b) for temperature compensation. From a connecting box directly at the working face, supply fibres were used to connect the sensing cables to the measurement unit, which was placed about hundred meters behind the instrumented cross section.

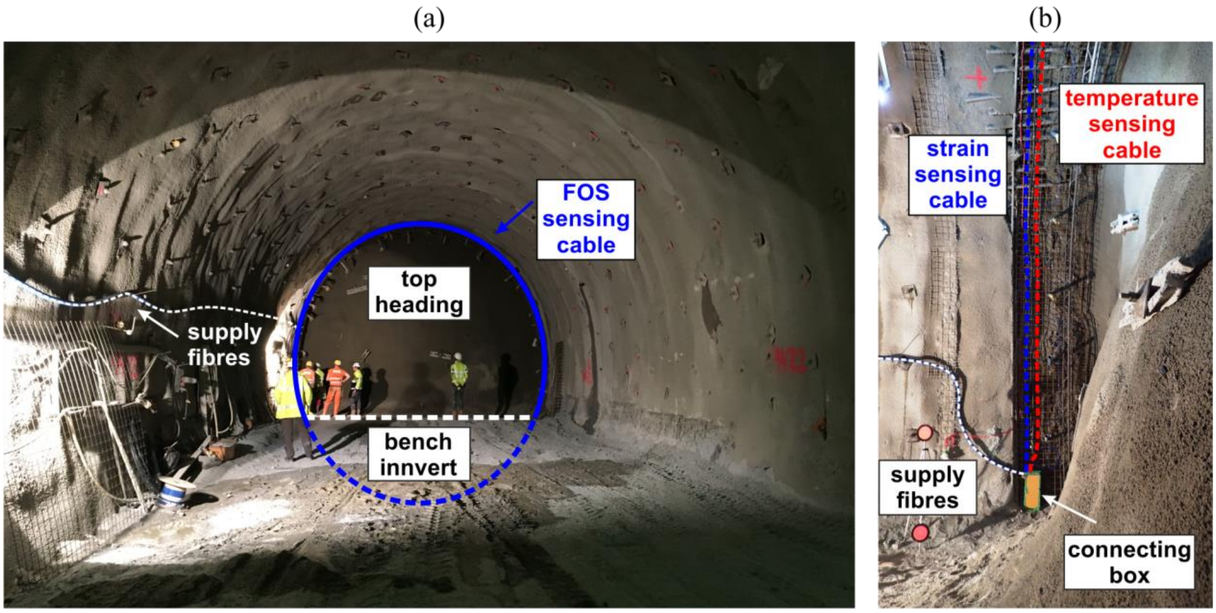

Fig. 7: (a) Overview of tunnel working face and (b) cross section with schematic representation of installed sensing fibres

4.2 Measurement Results

In order to gather complete information about the rock deformation, continuous monitoring of each section was started immediately after applying the shotcrete using the OBR in combination with an own-developed measurement software. The temperature-compensated strain values of the instrumented tunnel profile at selected times are plotted in Fig. 8. It can be seen that first compression zones become visible at the crown and the shoulders (top-left, top-right) shortly after the top-heading construction (Fig. 8a). Compressions in these areas were already known from displacement measurements on the surface at prior cross sections, but could not be located exactly before installation of the distributed fibre optic system. About 48 hours after the top-heading construction (Fig. 8b), the compressions in these selected zones have increased further up to -1100 µm/m. In addition, almost the entire cross section shows negative strain values due to the curing of the shotcrete. The bench/invert was excavated about five days after the top-heading section. Before the refilling of the invert about six hours after construction (Fig. 8c), the strain profiles along the bench/invert section show slight compression with one local inhomogeneity in the bottom area. This might be a result of distortions caused by overlaying reinforcement layers or other sensors (pressure load cells) in this area. In the top-heading section, further compression is visible due to the interacting rock pressure and the curing of the shotcrete. After the invert was reclosed (Fig. 8d), the compression values in the bottom area are significantly higher than these of the sidewall of the bench. In addition, the deformation progress in the top-heading is progressive, but seems to be almost constant along the entire section. This suggests that the installed supporting ring forms a load-bearing system and a uniform distribution of the rock pressure is performed.

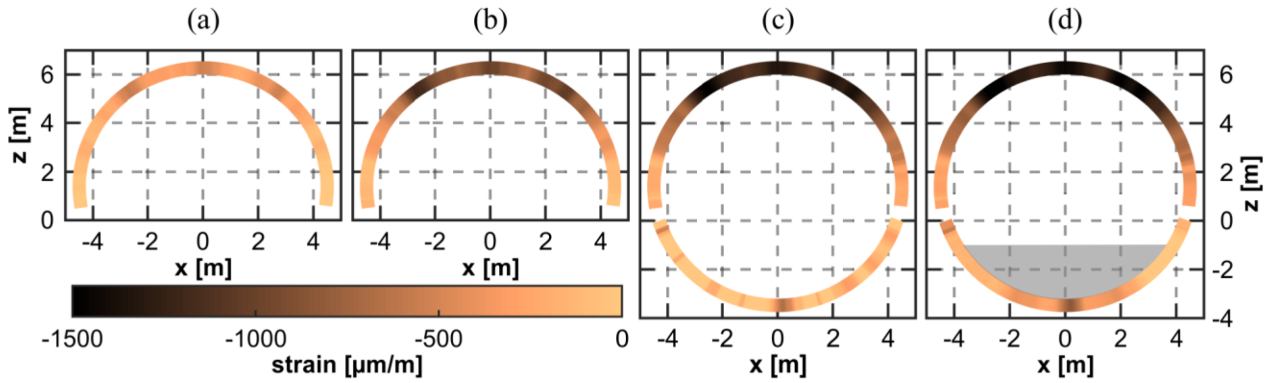

Fig. 8: Distributed strain profiles along top-heading and bench/invert: (a) 6 hours after top-heading construction, (b) 48 hours after top-heading construction, (c) 6 hours after bench/invert construction and (d) 48 hours after bench/invert construction (invert refilled)

The distributed strain profiles measured by the fibre optic system show that various compression zones arise as a result of the interacting rock pressure. In order to analyse this behaviour, five positions along the instrumented cross section are selected (see Fig. 9a) and considered over the entire monitoring campaign of five weeks. Fig. 9b depicts the temporal sequence of the strain values at these locations. By this, it is evident that the positions along the top-heading section (#01-04) show first compressions shortly after the construction. However, the compressions at all positions, expect of #03, remain constant or even decrease after about 18 hours, see period t_1 in Fig. 9b. The further excavation of the tunnel or the curing of the shotcrete might be possible reasons for this progress, but a detailed analysis is still pending. Due to the construction of the bench/invert (period t_2 in Fig. 9b), a similar relaxing of the lining appears at locations along the sidewall (#01-03). The selected position in the invert (#05) shows an immediate reaction to the covering of the shotcrete and the subsequent reclosing. Although the excavation of the entire cross section is finished afterwards, a continuous increase of the compressions can be observed at all selected positions over the remaining period, which is still progressive when the fibre optic interrogation unit was dismantled. For that reason, successive measurement epochs will be carried out in 2017 to assess the further development of the deformations inside the shotcrete lining.

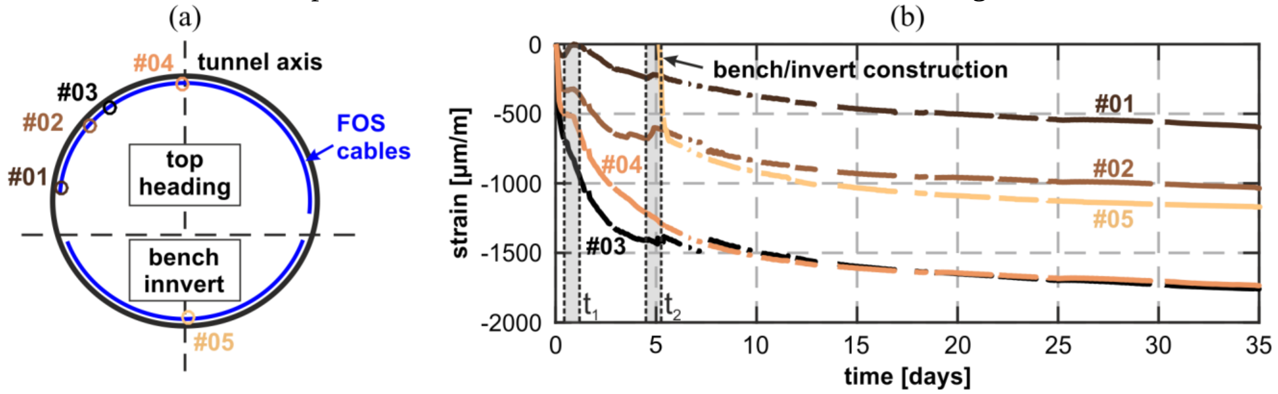

Fig. 9: (a) Schematic representation of fibre optic installation and (b) continuous measurements at five selected positions along the instrumented cross section

5. Conclusions

In this paper, a fibre optic sensing system based on Rayleigh backscattering was introduced, which enables distributed in-situ deformation monitoring with a high spatial resolution in tunnelling applications. For this, robust fibre optic components as well as installation techniques were found to ensure a reliable system within the harsh environments on site. Before the installations, strain calibrations were carried out in the IGMS humidity and temperature-controlled laboratory in order to assess the performance of the fibre optic system. These calibrations show that the derived strain sensitivity coefficient deviates up to 5 % from standard parameters, even though these values are specified for bare fibres.

The developed fibre optic system was utilized in various tunnelling applications and distributed information could be gathered, which cannot be measured using other sensing techniques. During load tests of precast tunnel lining segments at a specifically developed test rig, the in-situ evolution of cracks along the bending reinforcement could be observed and the crack positions were verified by measurements of a camera-based system on the surface. Moreover, an installation in the shotcrete lining directly at the working face in a geological interference zone demonstrates that the fibre optic system is sufficiently robust for tunnelling applications.

Future research will be focussed on the long-term monitoring of the instrumented cross section to assess the further deformation development inside the shotcrete lining. In addition, the fibre optic system is already installed inside a complete ring of tunnel segments, which will be placed into the Koralm tunnel in summer 2017. The results of this operational phase will give new insights into the deformation behaviour of a segment ring and will finally lead to a better understanding of the load distribution within tunnels that are constructed using boring machines.

Acknowledgement

The authors would like to thank the Austrian Federal Railways (ÖBB-Infrastruktur AG) for funding the research project to develop a fibre optic measurement system for tunnelling applications and the opportunity to realize installations within current tunnel projects in Austria. Furthermore, special thanks to the project partners, the Chair of Subsurface Engineering (Montanuniversität Leoben) and the Institute of Rock Mechanics and Tunnelling (Graz, University of Technology), for their support during the load tests and the field installations.

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