Long-term Deformation Monitoring of CERN Concrete-lined Tunnels using Distributed Fibre-Optic Sensing

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ABSTRACT: The Centre for European Nuclear Research (CERN) uses large and complex scientific instruments to study the basic constituents of matter by operating a network of underground particle accelerators and appurtenant tunnels. Long-term safety and structural health of this critical infrastructure highlighted the need for a sensing plan that could provide remote monitoring and resistance to high radiation. A pilot Distributed Fibre-Optic Sensing (DFOS) system using Brillouin scattering was used to instrument 8 tunnel sections and obtain a first set of short-term readings. These preliminary readings show minor tunnel ovalisation and will be used as baseline for future long-term readings.

KEYWORDS: Fibre-optic sensing, Tunnels, Soil-structure interaction, Brillouin scattering, Long-term monitoring.

1. INTRODUCTION

At the European Centre of Nuclear Research (CERN), the well-known deep particle accelerator is hosted in a circular underground facility made of shafts, caverns and tunnels, excavated in a sedimentary rock mass in Geneva basin. The complexity of the ground conditions, characterised by a sequence of sandstones and marl layers, greatly affects the earth pressure distribution on the tunnel lining and hence results in critical tunnel damage such as cracks and heaving in tunnel invert. These problems have drawn the attention of CERN engineers and highlighted the necessity for establishing a long-term structural health monitoring strategy. Extensive studies and a comprehensive understanding of the cracking behaviour have become a necessary step to undertake for the maintenance of the existing infrastructure under particular service conditions. Therefore, a novel monitoring plan was devised for a selected critical CERN tunnel called TT10 for evaluating the stress conditions of its existing lining.

This paper presents a pilot monitoring trial which is part of a long-term strategy for assessing the behaviour of critical sections of CERN's tunnel network. The main objective of this research study is to obtain an in-depth understanding of the tunnel lining mechanism of deformation through spatially continuous distributed fibre-optic strain measurements. The following sections describe the monitoring method adopted and present the main results obtained to date.

2. LITERATURE REVIEW

Recent improvements in the area of smart technologies have greatly contributed to the development of a range of sensors configurations for the long-term monitoring of infrastructure in terms of strain measurements. In particular, among different monitoring techniques, Distributed Fibre-Optic Sensors (DFOS) have been extensively deployed in a variety of projects for monitoring the performance of piles (Klar et al., 2006; Mohamad et al., 2007; 2011; Ouyang et al., 2015; Pelecanos et al., 2015; 2016; 2017), concrete tunnel linings (de Battista et al., 2015; Di Murro et al., 2016; Soga et al., 2017), masonry tunnels (Mohamad et al., 2010) and arches (Acikgoz et al., 2016; 2017) and other geotechnical infrastructure. Mohamad et al. (2012) described the monitoring of a precast segmental tunnel lining in proximity of the excavation of a second tunnel by using Brillouin optical time-domain reflectometry (BOTDR) strain sensing. The capability of innovative optical sensors was also demonstrated in the evaluation of the overall strain regime of an existing London Underground concrete-lined tunnel, where the obtained measurements seem to be in agreement with the conventional instruments (Cheung et al. 2010).

To monitor the response of the existing Royal Mail tunnel in London due to the new tunnelling works, Gue et al. (2015; 2017) recently instrumented several cross-sections including DFOS for a qualitative assessment of the tunnel lining deformation mode. Tensile and compressive strains were recorded at springlines and crown respectively, suggesting an observed ovalisation mechanism of tunnel deformation.

Moreover, the maintenance of tunnels requires a deep understanding of their long-term behaviour (Wongsaroj, 2005; Laver, 2010; Wongsaroj et al., 2013; Li, 2014; Laver et al., 2016). As the first attempt, Wongsaroj (2006) devised a method to predict long-term surface settlement for single tunnels excavated in London Clay, showing the importance of tunnel lining permeability relative to that of the surrounding soil. His work was improved by Laver (2010) by proposing a new prediction method for both vertical and horizontal surface settlement for twin-tunnel long-term interaction. More recently, Li (2014) investigated the importance of the long-term performance of the tunnel lining deformation with time of a cast-iron cross-passage tunnel in London Clay, highlighting the causes of the structure deterioration.

The principal aim of the present paper is to evaluate the stress distribution on a concrete tunnel lining at CERN by adopting innovative instrumentation which makes use of optical sensors that allow measurements of full strain profile using standard optical fibres.

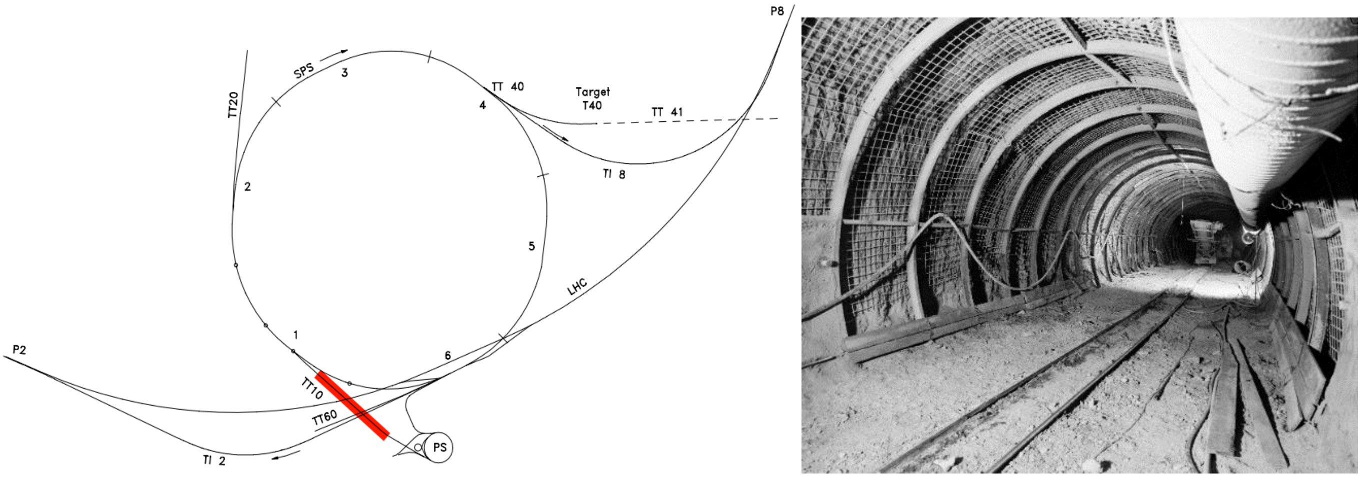
3. CASE STUDY: CERN TT10 TUNNEL

3.1 Introduction

In the network of underground particle accelerators, TT10 tunnel is an inclined transfer beam tunnel linking the beam accelerator of the PS (Proton Syncrotron) circular tunnel to the 7 km Super Synchrotron Protons called the SPS ring. It's located at the French-Swiss border in Geneva area (Figure 1a) and its diameter is 4.5 m.

The excavation of TT10 tunnel started in December 1972. It was performed in multiple stages by using short excavation steps of 1.2 m and immediate installation of the temporary support to the excavated surfaces with sprayed concrete. The primary lining was then put in place, made by steel arches with a IPN 120 profile and steel mesh when weak ground layers were found, followed by the construction of permanent lining with a waterproofing membrane PVC sheet (Figure 1b). In addition, the tunnel is considered to be fully drained as it is provided with a drainage pipe located at the bottom of the tunnel invert.

The formation in the area of TT10 tunnel consists of highly weathered and extremely heterogeneous sedimentary rock called the *red molasse*. The geomechanical characteristics of these interbedded



(a) (b)

Figure 1 a) CERN underground network: location of TT10 tunnel b) TT10 tunnel excavation (Photo credit: CERN)

rocks vary significantly, going from relatively very stiff sandstones to soft marls with considerable swelling potential of the very weak lumpy marl layers. The large differences in the rock strata can lead to problems for the stability of the infrastructures. The molasse is overlain by glacial Moraine deposits, which comprise essentially sands and gravel with varying amounts of clay and silt (Laughton, 1990). In addition, due to its compact structure, the molasse shows a really low permeability, which results in a rather undrained behaviour.

3.2 The problem and the monitoring approach

Recent tunnel inspection records revealed a number of compressive and tensile cracks in several locations of TT10 tunnel: the former developed at the tunnel crown, the latter at the shoulder of tunnel lining. Furthermore, due to the susceptibility to swelling in presence of water of the weak layers of marl, heave on the tunnel floor was also observed after tunnel construction (Lombardi, 1979).

In order to gain a better understanding of the tunnel lining deformation which could lead to tunnel lining failure and hence potentially affect the alignment and the integrity of the particle accelerator beamline, a long-term monitoring sensing plan was designed. Distributed Fibre-Optic Sensors (DFOS) were considered to be the most applicable monitoring technique to be used, as they are found to be exceptional tools for the long-term monitoring in harsh conditions, enabling distributed strain and temperature measurements along the tunnel lining.

Unlike remote monitoring electronic devices, which would require not only maintenance but also measurements limited to short shutdown of CERN undergrounds, fibre-optic (FO) sensors offer the remarkable advantage of being immune to the electromagnetic field and therefore they can be exposed to ionising radiation generated by the physics experiments of the Large Hydron Collider (LHC) at CERN.

The radiation tolerance of the fibre and its response during gamma ray exposition in TT10 tunnel, however, was considered to ensure that the levels remain consistently well below the radiation acceptance level.

In fact, due to ionising radiation, the properties of Brillouin sensors change (Alasia et al., 2011). The effects of ionising radiations on the characteristics of the Brillouin gain spectrum in standard Ge-doped telecom single mode fibres have been widely investigated up to very high gamma dose (10 MGy) (Alasia et al., 2011). The samples were gamma-irradiated with the Brigitte facility of SCK-CEN in Belgium up to 10 MGy and the results show a clear dependence of the Brillouin scattering on the ionising radiation due to a silica compaction phenomenon, modifying the Brillouin scattering properties.

The results show that the frequency variation is about 5 MHz for the most irradiated, which would correspond to around 5 °C error in the temperature measurement. Therefore, the radiation-induced shift of the Brillouin frequency can be essentially negligible (Alasia et al., 2011).

A strong decrease in the Brillouin spectrum amplitude with the radiation dose was also noticed. In fact, in silica-based glasses, radiation mainly leads to three different mechanisms: Radiation-Induced Attenuation (RIA), Radiation Induced Emission (RIE) and change in the refractive index (Girard et al., 2013). The RIA phenomena, which corresponds to an increase in the glass linear attenuation through an increase of the linear absorption due to radiation-induced defects, causes a reduction of the Brillouin amplitude. The RIA mechanism strongly affects the sensor’s distance range (Phèron et al. 2012). Under radiation also a light emission is caused through the Radiation-Induced Emission.

Phèron et al. (2012) also investigated the performance of strain in Brillouin-scattering based optical fibre sensors by irradiating various fiber types. His results show that the amplitudes and kinetics of the RIA response strongly depend on the composition of fibre core and cladding. The results show that under radiation conditions some compositions have to be avoided, implying the use of radiation-hardened optical fibres (e.g. fluorine-doped fibers) in radiation environments. A single mode fibre (SM28) exhibits a shift of 4 MHz under 10 MGy radiation dose, acceptable response for the radiation levels (Phèron et al. 2012).

The level of gamma ray exposure in TT10 tunnel was measured by installing appropriate radiation dosimeters which were attached at the tunnel crown (Figure 2).

Two measurements were taken so far: the first one in June 2015 and the second one in July 2017. Both readings show minor gamma ray dose (Table 1), reaching a maximum value of 30 Gy in 2017, assuring that the value is well below the tolerance radiation level of 100 kGy for a single mode fibre (Alasia et al., 2011). However, the fibre composition should be carefully chosen in order to minimize its vulnerability to the radioactive environment.

4. FIBER-OPTIC MONITORING

4.1 Monitoring scheme

For monitoring the performance of the TT10 tunnel, the Brillouin optical time-domain analysis (BOTDA) technology was adopted.

Figure 2 Radiation dosimeters installed in TT10 tunnel

Table 1 Gamma ray dose measurements taken in TT10 tunnel (Credit: CERN)

Date of measurement	Gamma ray dose [Gy]
15/06/2015	1.5 - 3.3
15/06/2017	25 - 30

This technique provides spatially continuous distributed strain measurements using standard optical fibres. As a light is launched in the optical fibre, a small amount is back scattered toward the launch. In the case of Brillouin scattering, the frequency of the back scattered light is shifted and it's considered to be linearly proportional to the axial strain applied to the optical fibre. By analysing the back-scattered signal in the frequency domain, the strain profile along the length of the fibre can be obtained (Mohamad, 2008). The strain experienced by the optical fibre is caused not only by a mechanical change but also by thermal loads. Consequently, a FO installation requires two types of fibre cables: one for the strain measurements, sensitive to both mechanical and thermal loads, and the second one for the temperature measurements, which is only influenced by thermal changes (Soga, 2014). As the temperature in TT10 tunnel was constant, however, only a strain FO cable was put in place. A detailed description of the theory behind the DFOS technology and its applications in the field can be found in the literature (Kechavarzi et al., 2016).

A section of 100 m length was selected for the installation of eight fibre-optic tunnel sections. The fibre-optic cable is attached to the circumference of the tunnel lining in pre-tensioned gauge lengths by using a hook-and-pulley system to create several loops in the circumferential directions (Figure 3). A schematic of a typical cross-section instrumented with FO is shown in Figure 4.

(a) (b)

Figure 3 FO field installation: (a) Circumferential FO cable loops, (b) Method of attachment of the FO cable: hook-and-pulley system

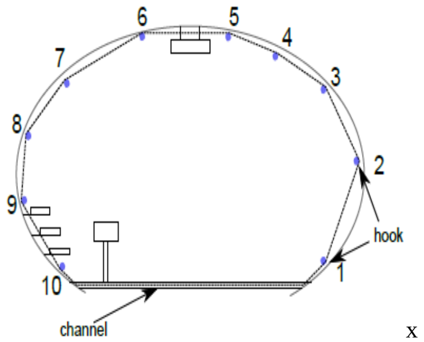


Figure 4 Cross-section of FO installation (with permission from Kechavarzi et al., 2016)

The FO installation, which took place in March 2014, started with the pre-tensioning of the interested sections of the fibre as shown with a bold line in Figure 5, whilst the loose cable sections are drawn with a dashed line. Both ends of the fibre were then spliced to an extension cable and routed out to a control monitoring area through a vertical shaft. By connecting the fibre to the BOTDA analyser, a continuous strain profile along the entire cable length is obtained. The Omnisens DITEST interrogator was used for this project (Omnisens, 2013).

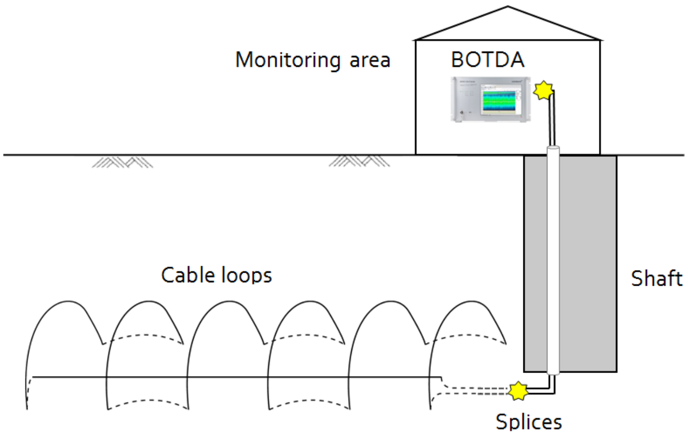


Figure 5 Installation scheme of FO sensors (with permission from Kechavarzi et al., 2016)

5. RESULTS

As mentioned previously, the primary data obtained from a FO monitoring installation is the measured peak Brillouin frequency shift experienced by the optical fibre caused by the application of a strain along the whole length for the eight instrumented cross-sections. Figure 6 show the raw Brillouin frequency FO data obtained from the BOTDA analyser. It may be shown that there are 8 discrete sections of high frequency which is due to the applied pre-tension. Also, it may be observed that there is a long section which is due to the longitudinal pre-strain applied.

A baseline reading was taken when the installation was completed in July 2014 and further progress readings were taken from August 2014 until October 2017, providing a data set of 3 years of monitoring measurements with an interval of 2-3 months as shown in Table 2. To acquire the accumulated response in terms of Brillouin frequency, the set of progress readings were subtracted from the baseline reading (July 2014) and then converted into axial strain. The axial strains experienced by the FO cables were plotted against the cable distance for the following circumferential loops: loop1, loop2, loop5 and loop7 (Figure 7).

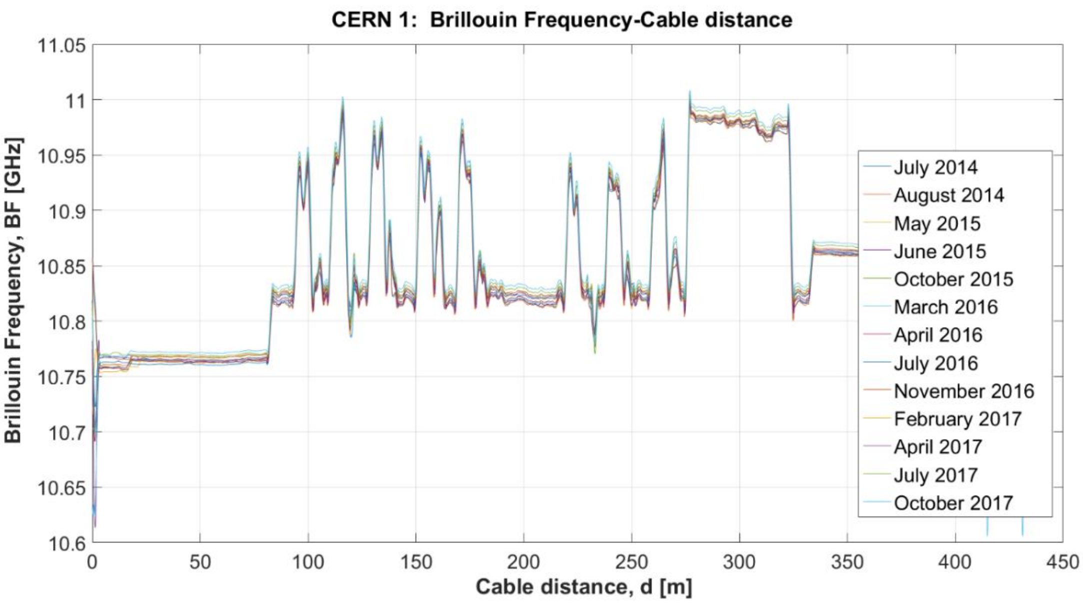


Figure 6 Brillouin Frequency profile along the FO cable distance

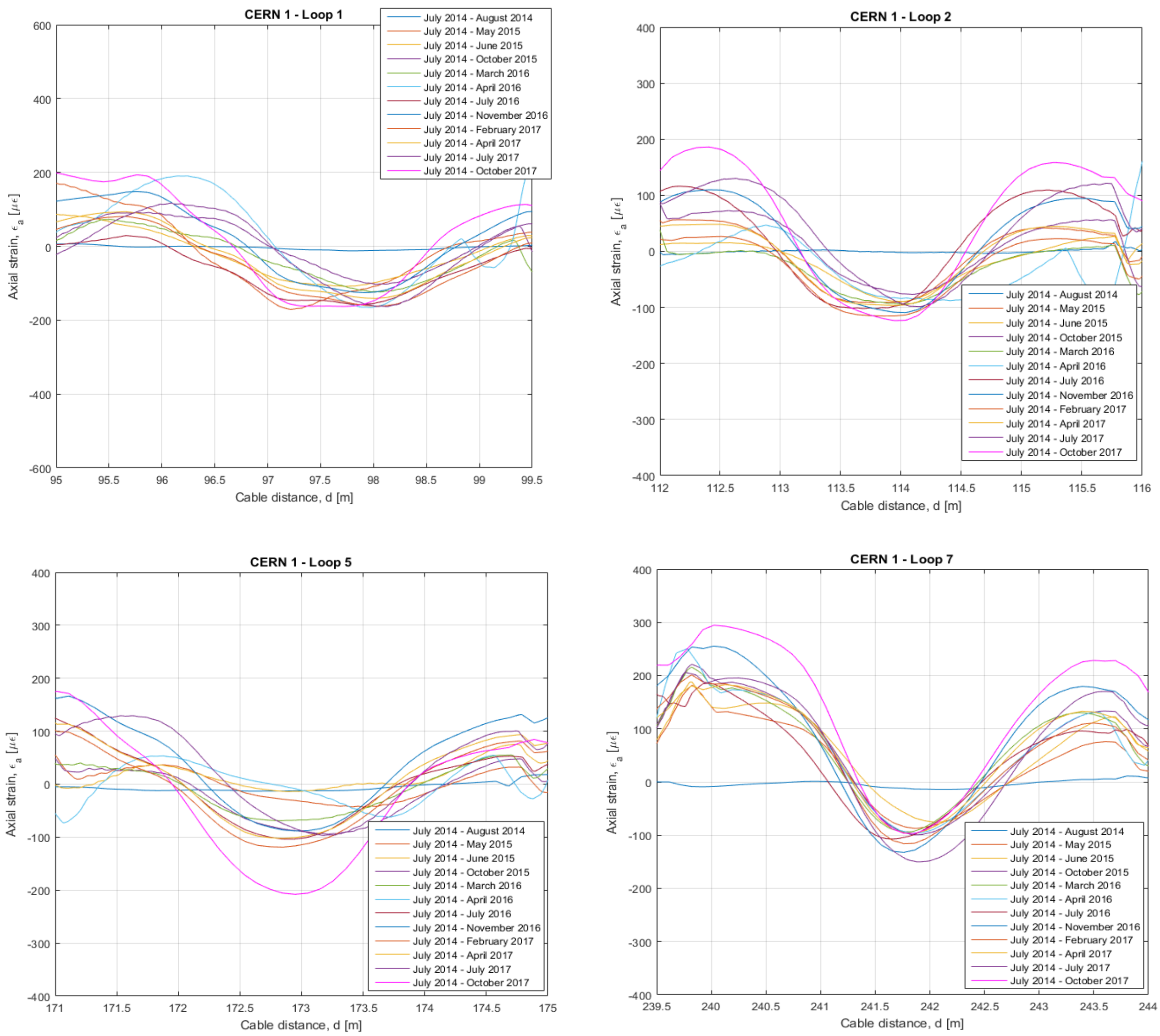


Figure 7 Fibre-optic axial strain: loop1, loop2, loop5 and loop7

The graphs show that positive (i.e. tensile) axial strains developed at the two lateral sides of the tunnel lining, which correspond to the start and the end of the x axis, whereas negative strains are recorded at the central part of the section (crown of the tunnel). Minor strains developed after a month from the installation of the sensors (July 2014 – August 2014) for all the selected loops. The axial strain profiles plotted after 3 years of measurements (July 2014 – October 2017) seem to be approximately regular for all the FO tunnel loops. The compressive peak strain values were larger at the lateral tunnel sides than those at tunnel crown, reaching a maximum strain value of 200 με for loops 1, 2 and 5 and 300 με for loop7. The incremental response, where each measurement taken during the monitoring period was subtracted from the previous one, in terms of axial strain was also plotted along cable length (Figure 8). For the selected loops, the plotted FO results show that there is insignificant incremental development of ovalisation over the considered time periods which are relatively short, which therefore may suggest that tunnel deformation develops slowly and over the longer term.

Overall, the FO results suggest that the tunnel lining is experiencing a vertical tunnel ovalisation (Figure 9), with some compressive axial strain (negative) at tunnel crown and tensile strain (positive) at tunnel axis. This would be due to the horizontal normal stresses being larger than the corresponding vertical stresses.

The observed flexural behaviour of the tunnel lining detected by the FO results seems to agree with the in-situ stress distribution of the molasse region surrounding TT10 tunnel, characterized by high horizontal stresses.

Table 2 Fibre-optic readings: baseline and progress readings

Monitoring section	**Readings**	
	July 2014	Baseline
	August 2014	
	May 2015	
8 circumferential loops	June 2015	
	October 2015	
	March 2016	
	April 2016	Progress
	July 2016	
	November 2016	
	February 2017	
	April 2017	
	October 2017	

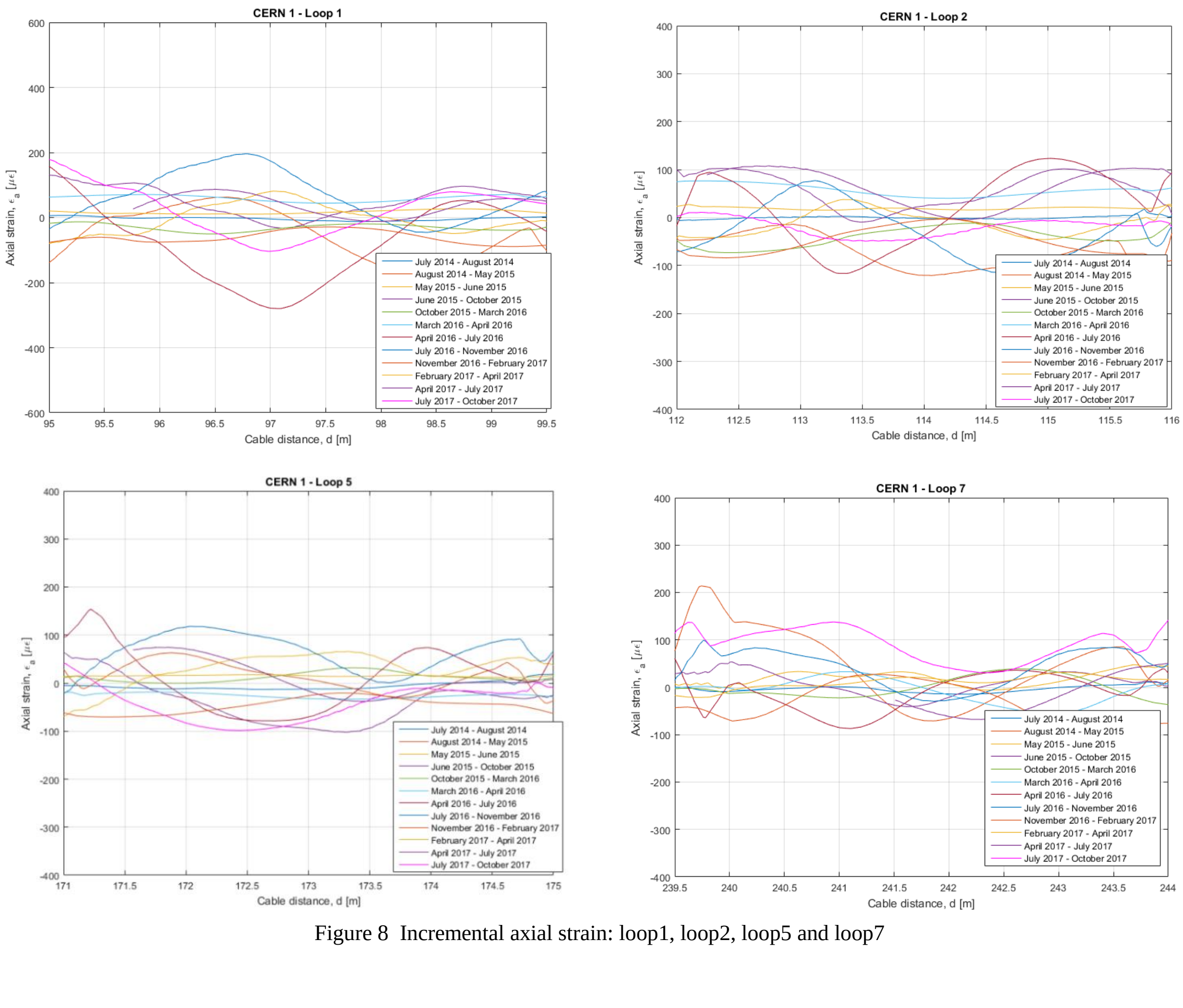


Figure 8 Incremental axial strain: loop1, loop2, loop5 and loop7

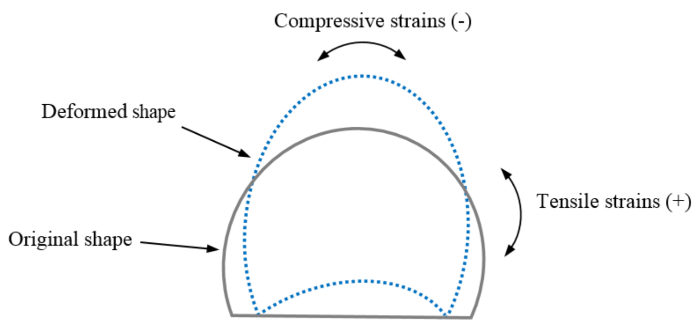


Figure 9 Mechanism of deformation of tunnel lining: vertical tunnel ovalisation

6. CONCLUSIONS

The short-term behaviour of a concrete-lined tunnel at CERN was investigated by using distributed fibre-optic sensors as a monitoring technique. Brillouin optical time-domain analysis was used to help understand the stress regime on the tunnel lining in the long term. Complete strain profiles were derived by deploying several monitoring sections, 8 circumferential FO tunnel loops. The initial baseline reading exhibited a clear signal in the different sections of interest because of initial pretension in the cable, which was helpful in identifying the precise location of these sections. After the first set of measurements taken in July 2014, eleven subsequent progress readings were taken. The results obtained show that peak values of axial strains do not exceed 200 με for the various tunnel loops.

This set of monitoring data allows understanding of the tunnel lining deformation mode with time: a vertical tunnel elongation mechanism of deformation as negative compressive strains was observed at tunnel crown, whereas both tunnel shoulders exhibit tensile positive strains. However, the progression of this strain patterns, observed for all the tunnel loops, and therefore the actual movement of the tunnel lining is very small over the three-year monitoring period.

The current readings and the deployed monitoring scheme are planned to be used for further future long-term structural health monitoring of this CERN tunnel. The clearly observed trend in the current data offers confidence that DFOS can be used for long-term monitoring of complex tunnel behaviour and relevant soil-structure interaction.

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