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Distributed fibre optic long-term monitoring of concrete-lined tunnel section TT10 at CERN

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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. Several tensile cracks have been observed within a section of a concrete lined tunnel called TT10. As a result, there were concerns about the safety and structural health of CERN infrastructure and a long-term sensing plan was designed to monitor the behaviour of these tunnels. Additionally, two big challenges had to be met: (a) remote monitoring due to tunnel inaccessibility during the operation of the experiment and, (b) potential instrument malfunction due to high radioactivity. Therefore, there was a clear need for radiation-resistant monitoring instruments that could be operated remotely. Distributed Fibre Optic Sensing (DFOS) proved to be the most appropriate monitoring method as it appeared to satisfy the abovementioned requirements. Eight tunnel circumferential loops and one longitudinal were monitored with distributed fibre optic (FO) cables. In the progress readings taken so far, the circumferential tunnel loops showed some minor values of axial strains in the FO cable (peak absolute strain no more than 150με) and a somewhat consistent profile of the strains for all circumferential loops with high values of (minor tensile) strains at the sides and negative-compressive strains at the crown of the tunnel. This strain pattern would suggest a vertical tunnel elongation mechanism of deformation, i.e. there is compression at the tunnel crest and extension at the lateral two sides of the tunnel. Finally, the values of all observed axial strains seem to be insignificant suggesting no major movement or deformation of the tunnel lining over the relatively short monitoring period.

1 INTRODUCTION

The maintenance of tunnels requires a deeper understanding of their long-term behavior (Wongsaroj, 2005; Laver, 2010; Li, 2014).

The principal aim of this study is to investigate the long-term behaviour of an existing concrete-lined tunnel called TT10 at CERN, by adopting the new distributed fibre optic strain measurement technique developed at Cambridge University.

TT10 tunnel is a 700m long injection tunnel connecting the tunnel of the Proton Syncrotron (PS) ring to the main ring tunnel known as Super Synchrotron Protons (SPS), as shown in Figure 1.

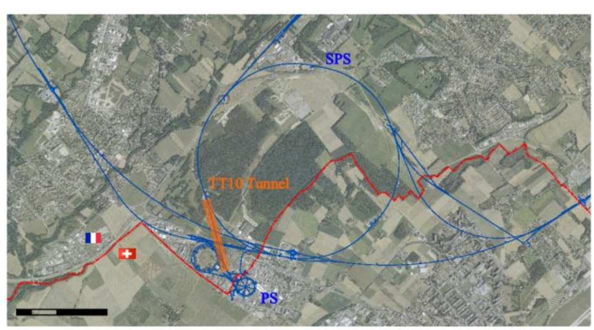


Figure 1. The injection tunnel TT10.

The excavation of the tunnel was executed in December 1972 by using an alpine boring machine called road header (Figure 2). The cross-section of the tunnel has an internal diameter of 4.5m and has a horseshoe shape.

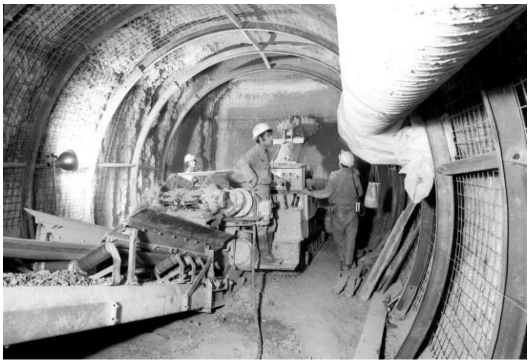


Figure 2. Excavation of TT10 tunnel.

2 INSTALLATION OF FIBRE OPTIC SENSORS

The main tunnel deformation mechanism observed in TT10 tunnel is localized compression and tension areas in the crown and in the shoulders of the tunnel respectively (Figure 3). Cracks on the floor of the tunnel were also observed in certain areas. In addition, ongoing tunnel deformation which is leading to lining failure can potentially affect the alignment and the integrity of the particle accelerator beam/line magnets.

For this reason a long-term sensing plan was designed to provide continuous monitoring for a long-term, in order to have a better understanding of the tunnel deformation. The monitoring method adopted makes use of innovative distributed fibre optic sensing (DFOS) system which showed to be the most suitable for a radioactive environment such as the one at CERN.

a) b) c)

Figure 3. Observed cracks in TT10 tunnel lining: a) localised compression cracks on the crown of the tunnel; b) tension cracks on the shoulder of the tunnel and c) cracks on the tunnel floor.

2.1 Method of monitoring

The monitoring of CERN tunnels was carried out by using the distributed fibre optic sensing (DFOS) system, which has had applications in a wide range of engineering structures and the results have successfully been compared with other conventional instruments.

The principle of this technology is that a light is launched into a fibre optic cable from a Brillouin Optical Time Domain Analysis (BOTDA) analyzer. The Omnisens BOTDA analyser was used for CERN installation (Omnisens, 2013). When analysed in the frequency domain the backscattered light amplitude has a peak at some constant value of Brillouin frequency (Figure 4). If at any point the fibre optic cable is experiencing some strain, the value of Brillouin frequency for which the peak amplitude occurs is shifted. The frequency shift of the backscattered light is related to the strain and the temperature conditions of the cable through a linear relationship. The calculated strain can then be translated to other engineering quantities, depending on the type of the engineering problem (Hisham *et al.*, 2007; Hisham, 2008; Hisham *et al.*, 2010). Further studies will be carried out in the near future in order to translate the axial strain into displacements for CERN case study.

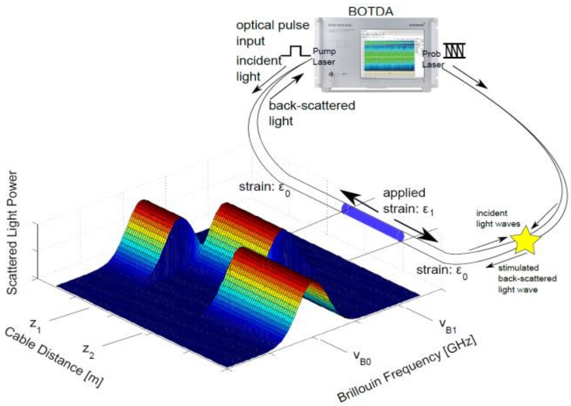


Figure 4. Principles of Distributed Fibre Optic Sensors.

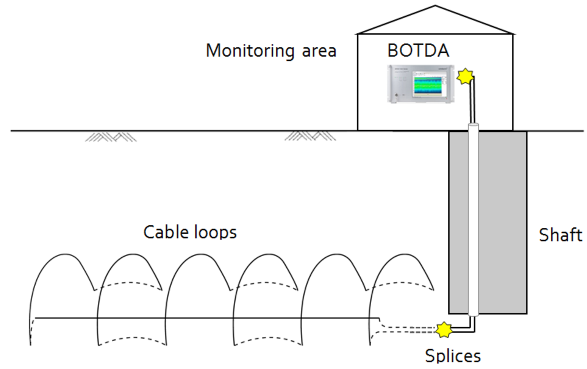


Figure 5. Installation scheme of FO sensors.

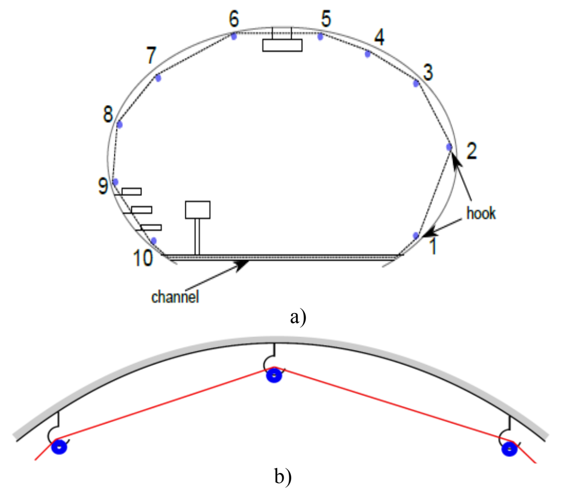


Figure 6. a) Cross section of FO installation. b) Method of attachment of FO cable: hook-and-pulley system.

2.2 *Monitoring scheme*

A section of TT10 tunnel of about 100 m length was chosen to be initially monitored. The FO cable runs in both the longitudinal and circumferential directions of the tunnel, forming several (eight) circumferential loops and one straight cable section in the longitudinal direction. The cable sections of interest are pre-strained (Figure 5) where a bold line refers to pre-strained section whereas dashed line refers to loose cable section. The pre-strained cable allows for accommodation of any compressive strain without cable buckling. The cable is attached on the tunnel lining using ten hook-and-pulley systems as shown in Figure 6. At the bottom of the tunnel the cable passes through a 5mm cut section in the floor concrete and then covered with glue and the section is then grouted.

At the end of the monitoring section the two ends of the FO cable are routed out of the tunnel section via a 50m vertical shaft (Figure 5) reaching a control room on surface and no further access is then required into the tunnel.

The monitoring was planned to be taken approximately every 2-3 months for the first year and depending on the outcome of the readings the long-term monitoring plan would be designed.

3 CURRENT MONITORING DATA & RESULTS

The primary data obtained from the fibre optic sensors is the Brillouin Frequency, which is linearly proportional to the axial strain that the fibre optic cable is experiencing. The Brillouin frequency readings in the fibre optic cable provide a continuous signal through a closed FO loop and hence they exhibit a full continuity of the FO data.

The baseline readings were taken when the fibre optic sensors installation was completed in July 2014 and then further progress readings were taken in August 2014, February 2015, May 2015 and June 2015 as shown in Table 1.

The progress monitoring data (August 2014, February 2015, May 2015, June 2015) were subtracted from the July 2014 baseline reading in order to obtain the accumulated response in terms of Brillouin Frequency.

Table 1. Fibre optic readings: baseline and progress readings.

Monitoring section	Readings	
8 circumferential loops + 1 longitudinal section	July 2014	Baseline
	August 2014	Progress
	February 2015	Progress
	May 2015	Progress
	June 2015	Progress

The developed axial strain profile is plotted against the fibre optic cable distance for four selected representative circumferential loops within the examined TT10 tunnel section: loops 1, 2, 5 and 7 (Figure 7).

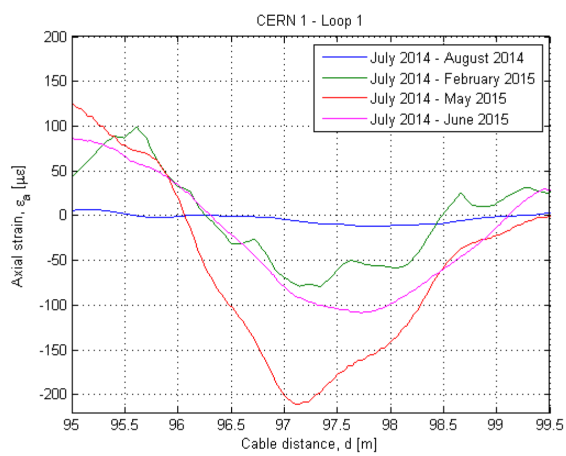
The two ends of the section (i.e. start and end of the plot's x-axis) refer to the two sides of the tunnel cross-section, whereas the middle of the section refers to the crown of the tunnel.

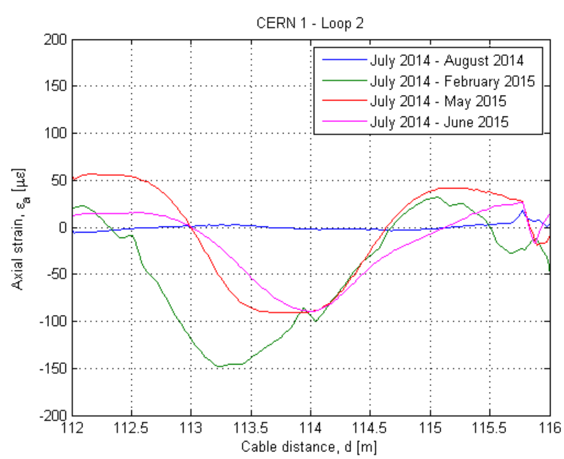
The graphs in Figure 7 show negligible strains developing within the first month (July 2014 – August 2014) after the deployment of the sensors, as the recorded values of axial strain do not seem to exceed about 20με for all the loops. Moreover, after seven months (July 2014 – February 2015) some notable values of axial strains can be seen in the FO cable. From the data collected after almost one year of monitoring (July 2014 – May 2015 and July 2014 – June 2015) small values of axial strains are experienced by the fibre optic cable, which do not go beyond around 100με for the mentioned loops.

The circumferential tunnel loops also seem to show a somewhat consistent profile of the strain s for all the examined loops. The lateral sides of the tunnel seem to experience larger strain values than those at the crown of the tunnel. A consistent strain profile of strain value peaks at the tunnel lateral sides and a strain value trough at the tunnel crown is observed.

Besides, there seems to be a pattern of some flexural behaviour of the tunnel lining: some compression (negative axial strain) at the inner side of the tunnel crown and some tension (compressive) of comparable magnitude at the lateral tunnel sides.

This mechanism suggests that the tunnel may be deforming in a vertical elongation shape as the distance of the lateral sides is decreasing and the crown seems to experiencing some hogging moments (Hisham, 2008). This behaviour would be compatible with a load pattern consisting of horizontal lateral stresses being larger than the corresponding vertical stresses, a case not uncommon in an over-consolidated soil environment (Figure 8).





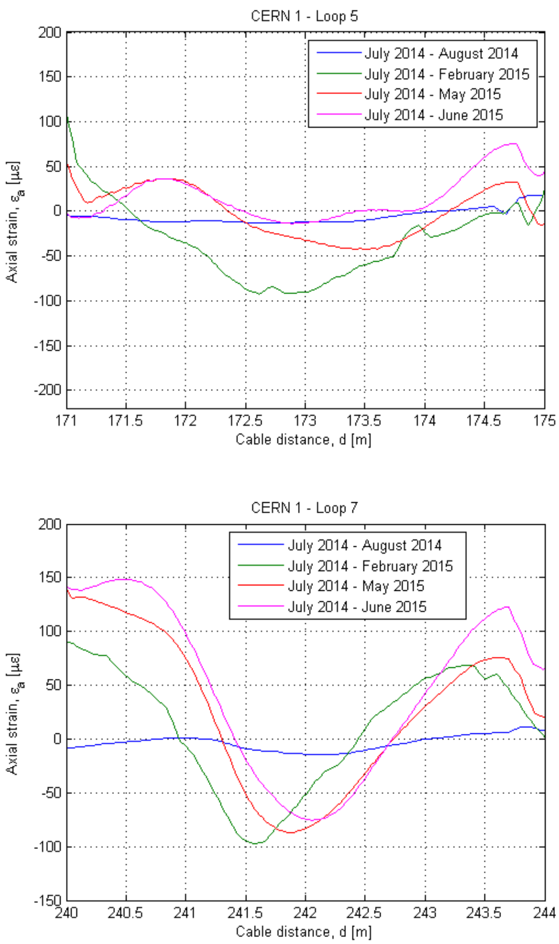


Figure 7. Fibre optic axial strain data: loops 1, 2, 5, 7.

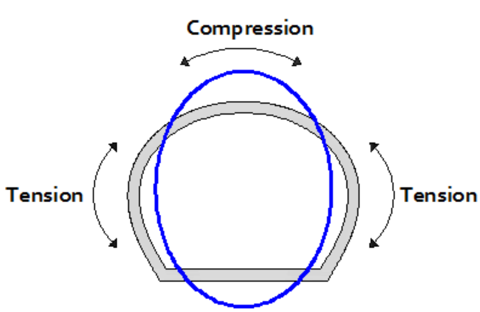


Figure 8. Tunnel deformation: elongation.

4 CONCLUSIONS

This paper describes the geomechanical investigation on the long-term behavior of CERN tunnels, by adopting an advanced monitoring system.

A novel technique of distributed strain sensing is introduced using Brillouin optical time-domain analysis to examine the performance of a concrete-lined tunnel called TT10. The fibre optic installation was deployed with a number of spatially distributed monitoring sections: 8 circumferential tunnel loops with a longitudinal section within the tunnel.

Initial baseline readings showed a good signal transfer and a clear trend in defining the various sections of interest. Five readings have been taken so far: the first set of baseline readings (July 2014) and four progress readings (August 2014, February 2015, May 2015 and June 2015).

The results from the circumferential tunnel loops suggest that the axial strains developed in the tunnel lining do not exceed peak absolute strain values of 150με.

The negative compressive strains at the crown of the tunnel were larger that the tensile strains at the sides of the tunnel. This strain pattern may have been caused by a vertical tunnel elongation mechanism of deformation, as the compression at the tunnel crest and extension at the lateral two sides of the tunnel are observed.

Finally, the values of all observed axial strains seem to be insignificant suggesting no real movement or deformation of the tunnel lining. This was expected as the purpose of this monitoring scheme is long-term tunnel deformations and no substantial strains would be anticipated over a period of ten months.

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