Strain-monitoring of a concrete tunnel lining with distributed optical fiber sensors

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ABSTRACT: Despite their advantageous performance and reliability, distributed optical fiber sensors (DOFS) still constitute a recent technology and their reliability and accuracy when applied to real world structures is still under probation since there is still room for improvement and for widening their applicability. In general, standardized guidelines need to be developed to ensure success in every DOFSs deployment regarding fiber bonding to the structure, temperature affections on readings, post-processing of reading anomalies, among other factors. However, real applications, as in the one presented in this paper, show that DOFS are anticipated to have a very important role in Structural Health Management of tunnels in the near future if correctly understood and developed. This paper addresses the implementation of a Distributed Optical Fiber Sensor system (DOFS) to the existing TMB L-9 metro tunnel in Barcelona for Structural Health Monitoring (SHM) purposes as the former could potentially be affected by the construction of a nearby residential building. The results show a good performance of this novel technique in the monitoring of strain along the whole affected sections during the construction of a nearby building. In fact, the DOFS readings reproduce very accurately the tunnel deformation process. The tendencies observed by the sensors were forecasted by a simple theoretical model. The monitoring of the strain at many points in the critical section allowed to conclude that the nearby construction only slightly affected the lining stresses and that safety was guaranteed during the whole monitored period.

KEY WORDS: tunnel lining, distributed optical fiber sensor, structural health monitoring.

1 INTRODUCTION

Tunneling is on the increase around the world not only in terms of work volume but also considering that the demands of modern transport networks require longer and wider tunnels through increasingly difficult ground conditions. Moreover, the increasing awareness of the sensitivity of tunnels to seismic activity and the presence of tunnel length under densely populated areas require very high standards of safety. Therefore, SHM for tunnels appears to be particularly important, both during construction and operation. Already in 1988, Dunnicliff [1] presented the conventionally required instrumentation for tunnel structural monitoring during construction and operation.

Traditionally, the safety assessment of tunnels and underground structures, existing or under construction, focuses on ensuring safety regarding two aspects: the underground structure itself and its surroundings (mainly controlled through surface monitoring). There are two possible cases in which this kind of structures would benefit from accurate monitoring: one considering the effects of the structure's construction on its surroundings and the other, looking at the structural response of the tunnel due to external actions applied nearby. Both situations imply the alteration of the primary stable geotechnical equilibrium which leads to stress concentration and redistribution that should be continuously monitored for a quick warning alert.

The tunnel surroundings can experience changes in their geotechnical conditions that appear due to the construction of the tunnel itself (causing settlement or holes at ground level, affections on groundwater drainage, among others) or due to external effects (such as new ground level constructions, excessive rain periods, among others). These effects can be monitored by controlling pore pressure, earth pressure, deformation, superficial settlement, and all the factors characterizing the soil mechanics of the area. For that, a wide range of instrumentation is available: piezometers, observation wells, vibrating-wires, inclinometers, extensometers, single point monuments, heave and strain gauges, among many others.

On the other hand, the tunnel will be subject to stress state variations both when it is being constructed and once completed due to external actions. Monitoring of the structural state of the tunnel usually consists of levelling measurements of particular points of the tunnel or convergence measurements of the contour caused by external effects. This is usually achieved by means of optical or mechanical technologies such as extensometric wires or total station surveys [2]. Extensometric wires, also known as invar wires, are connected to opposite sides of the tunnel section at its internal surface allowing for the measurement of their elongation / compression with a 0.1mm resolution. Total station surveys involve laser theodolites that allow for the acquisition of 3D scanned data on the tunnel geometry and usually focus on deformation measurement or feature extraction [3]. This technique is interesting since the change in the tunnel's profile is able to be fully characterized and the areas of the anomalous movement easily identified for posterior study.

Besides the aforementioned global monitoring tools, some local ones are: a) extensometers, commonly used to punctually monitor the settlement of structures or displacements between substructures (for example, consecutive concrete lining segments), b) crackmeters or fissurometers, being of a similar nature as the extensometers, are also used for structural monitoring since they provide insight into the time-related development of cracks, if these are present, and finally, c) inclinometers used to monitor angular inclinations of the tunnel inner surfaces.

A clear advantage of the previously presented monitoring tools is their wide applicability, which is very useful given the uniqueness of each constructed infrastructure. However, this conventional technologies present significant drawbacks that difficult structural assessment and need to be addressed.

One of the major difficulties with SHM technologies is managing the large volumes of data that the installed sensor scheme generates. Meanwhile, visual inspections and evaluations are obviously insufficient regarding the determination of the structural state of the studied infrastructure.

Another major drawback is that the mentioned monitoring schemes require, in general, the interruption of the infrastructure service or the ongoing construction /maintenance works, given their time-consuming installation process, their strict installation requirements that ensure accurate readings and their significant spatial occupancy. Regarding, the measurements execution it is worth noting that most of the conventional technologies do not involve an automated real-time measuring tool, i.e. most require specific activities every time a measurement is to be taken.

The last significant drawback is that the majority of the sensing tools developed and proven to be reliable so far, provide only localized measures where the sensor is deployed and a large amount of sensors have to be installed in order to provide a global overview of the structure's condition consequently implying a major cost increase and difficult data management. On another note, sensing techniques that provide a global monitoring of the structure´s condition fail to localize the damaged zone. In conclusion, technological innovations regarding monitoring techniques able to assess both the local and global structural performance are of interest.

The use of Fiber Optic Sensors (FOS), Global Positioning Systems (GPS), radars, Micro-Electro-Mechanical Systems (MEMS) and Image Processing Techniques has opened the doors to the extraction of structural information that could not be acquired before Regarding tunnel convergence monitoring in particular, several innovations have arisen in the last years [4,5].

The first reference to Optical Fiber Sensors (OFS) dates back to the first half of the twentieth century regarding flexible endoscopes and boosting innovation in the medicine field [6]. After that, the development of long distance telecommunications technologies in the eighties allowed for the exponential growth of this technology from which a significant variety of sensing applications started being derived and to which we owe the modern age low-loss optical fibers [7]. Within the variety of monitoring technologies, SHM systems based on OFS have gained importance in the field during the last decades and their advantageous characteristics are becoming increasingly acknowledged.

The main assets characterizing OFS when compared to traditional monitoring instruments are their reduced dimensions that allow for easy integration in structural components, their immunity from electromagnetic influences and chemical aggressions which significantly widens their applicability, their ability to form sensor chains using a single fiber allowing for distributed sensing, and their rapid data transmission, which enables real-time monitoring [8-10].

The fundamental principle behind OFS is the propagation of light through a medium. This medium, in the case of OFS, is a cable of optical fiber which has a diameter of 125μm and its main components are the core and the cladding. Figure 1 displays the common structure of this type of cables and shows how the core, with a diameter of 5-10μm, is embedded in the cladding.

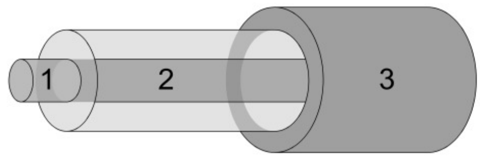

Figure 1. Structure of a typical optical fiber: 1. Core (5-10μm), 2. Cladding (125μm) and 3. Buffer or coating(250-900μm)

Most OFSs, such as Fiber Bragg Grating sensors (FBG) [11] or Fabry-Perot sensors [9], are discrete and can only provide local measurements. Discrete short-gauge sensors provide useful and interesting data regarding local behavior but might omit important information in structural areas that are not explicitly instrumented. Additionally, even though a particular failure is detected by means of a discrete sensor, pinpointing its location and magnitude can be tedious if it is not located exactly on the instrumented point. To understand the global behavior of a structure by means of discrete sensors, a high number of sensors would have to be installed producing a dense network of monitored points on the structure. This immediately translates into a very expensive and difficult to deploy SHM system with complex data acquisition and an excessive amount of wiring and measuring devices.

To deal with the mentioned limitations, optical fiber monitoring has been exploited to develop the last group of sensors, the Distributed Optical Fiber Sensors (DOFS), which are the focus of the present paper. DOFS have the same advantageous characteristics as the rest of OFS but with the added value of allowing for distributed monitoring of strain and temperature variations along the entire optical fiber length. Additionally, this type of sensors only requires a single cable connection to communicate the collected data to the reading device [7].

1.1 DOFS applied in tunnels

During the construction of the large Crossrail platform tunnel in London, the Royal Mail tunnel was found in the surrounding alterable area being located directly above the soon-to-be constructed tunnel line at Liverpool Street Station [12]. In this case, Brillouin Optical Backscatter Reflectometry (BOTDR) was used. The attachment of the DOFS was performed through continuous gluing with the layout shown in Figure 2. The relatively innovative monitoring technique was complemented by the installation of an Automated Total Station with the aim of comparing their respective readings.

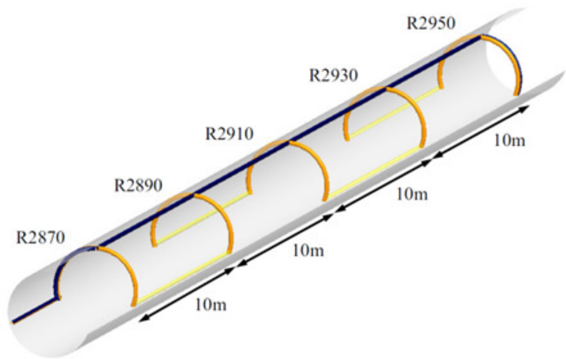

Figure 2. Optical fiber cable instrumentation at Royal Mail tunnel (from [12])

The monitoring process of a highway tunnel in Žilina (Slovakia) by means of distributed fiber-optic technology is presented in [13]. The article describes and analyses real measurements performed within a period of 5 months covering the whole process of building a new tunnel. Being located in unstable agricultural land, forests and meadows, the 867m long structure was to be surrounded by claystone and clayey soil. The soil conditions already anticipated issues related to the excavation progress and unstable overburden of the structure and, for that, Metrostav (the construction company) required the monitoring of the development of the load changes over time.

The tunnel was excavated using the New Austrian Tunnelling Method (NATM). The tunnel lining consists of two parts, the primary lining (built right after the excavation works) and the secondary lining (usually a ferro-concrete shell and quite often involving the use of prefabricated components) separated by a waterproofing spacer.

The optical fiber was placed on two iron bars of the braced girder of the tunnel, which became a part of the primary lining after being sprayed with concrete (see Figure 3). The installed distributed sensors were based on Brillouin scattering (BOTDR).

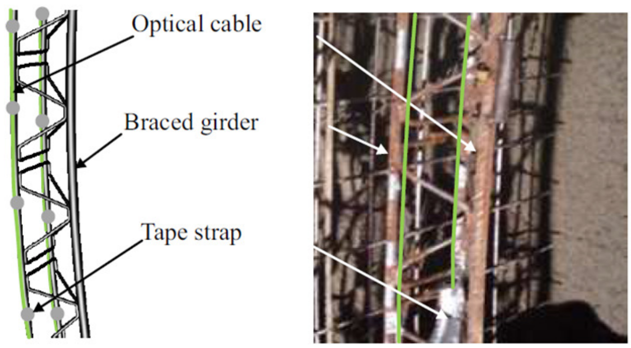

Figure 3. Optical fiber implementation on iron bars of the braced girder on the primary lining (from [61])

2 DOFS INSTALLATION IN CONCRETE LINING OF L-9 TUNNEL

The city of Barcelona has, in recent years, faced several problematic situations regarding underground infrastructure. The fatidic ground collapse in the Carmel neighborhood in January 2005 due to the TMB metro line L-5 extension works marked a turning point in public infrastructure execution. Since then, all construction works and projects taking place in the metropolitan area of Barcelona that may affect existing tunnels are subject to stricter and more exhaustive inspection protocols for which in-depth structural justifications, geological studies and monitoring protocols have to be presented ensuring safety of the construction site and its surroundings.

The object building of this paper was being constructed in the Bon Pastor neighborhood of Barcelona and it was no exception to the aforementioned safety regulations, especially considering that its extension partially covers the TMB L-9 metro tunnel layout.

2.1 Project Description

The building under construction is located between Novelles, Tallada and Sant Adrià streets, forming an angle of approximately 60º with the 4th section of the L9 Metro Sagrera TAV-Gorg tunnel's layout. The TMB L-9 is a 47.8km long (43.71km of which are underground) automated (driverless) metro line aimed at connecting the perimetral metropolitan areas of el Prat de LLobregat, l'Hospitalet de Llobregat, Badalona and Santa Coloma de Gramenet to the metro service of Barcelona.

The tunnel structure was executed by means of a Tunnel Boring Machine with an Earth Pressure Balanced shield type to ensure operability in soft soil [14] and, as the perforation proceeds the 35cm thick tunnel ring is executed resulting into an 11.60 m diameter tunnel that enables the construction of the stations and auxiliary installations in the tunnel itself. Such vast diameter allows for the trains to run at two levels, i.e. one above the other, separated by a supplementary slab (see Figure 4).

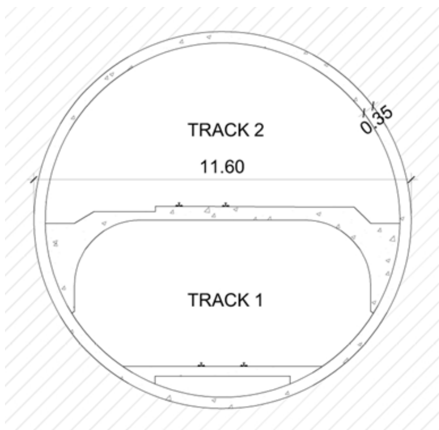

Figure 4. Tunnel cross section

The new building, located slightly above the L-9 tunnel layout is a residential building composed of a basement floor (to be used as parking space), the ground floor and four floors above it rising up to approximately 18.10m above ground level. As can be seen in Figure 5, the building site's dimensions are approximately 83x20m (1660m²) of which roughly 37m² can be found right above the L9 tunnel section covering, at the most critical location, half of the tunnel layout.

An approximate total soil volume of 6500m3 is removed during the excavation works in order to execute the foundations

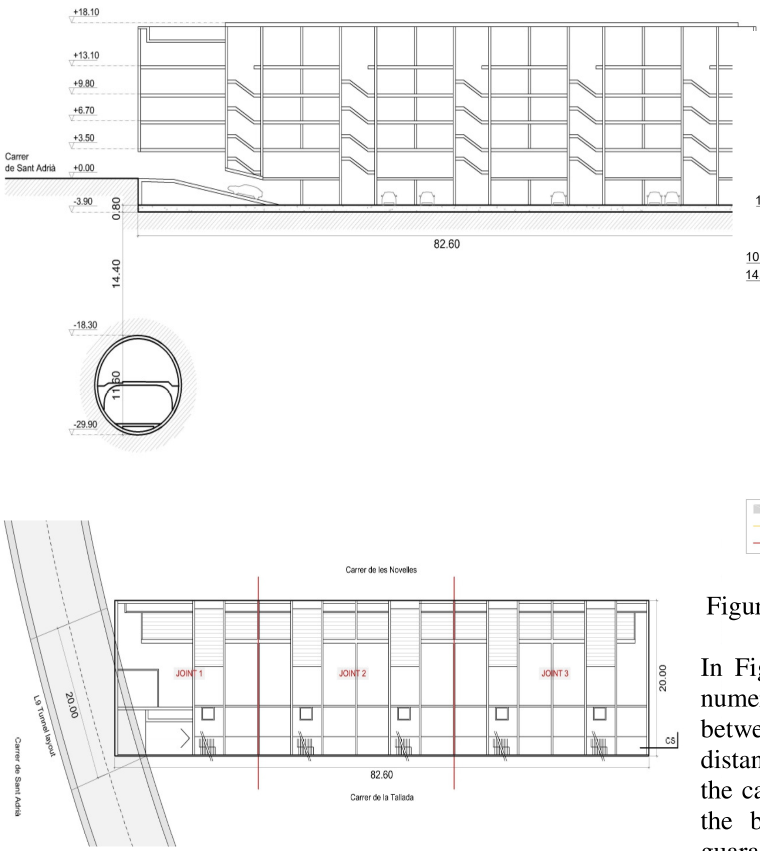

Figure 5. Cross-section and plan view of L9 tunnel in relation to the building

The 20m long measurement along the tunnel axis in Figure 5 is aimed at determining the possibly affected section of the underground structure, i.e. tunnel length to be monitored and controlled during construction. To perform a continuous follow-up of the tunnel's strain and tensional state, a DOFS based monitoring scheme of the tunnel's section was proposed as described in the following section.

2.2 *Monitoring set-up*

The objectives of complementing the theoretical models and calculations with monitoring tools are ensuring structural safety by:

- Increasing damage detection probabilities by simply observing and assessing the measured data.
- Easing decision making processes in light of damage detection through assessment of historic and present measurements.
- Calibrating the existing theoretical models consequently improving their prediction abilities.

The presented monitoring scheme involves the installation of a DOFS measured with a spatial resolution of 1cm bonded to the inner lining structure of the tunnel to reproduce the strains experienced by the tunnel concrete lining due to the unloading (during ground excavation) / loading processes happening 14.40m above the construction site. The geometry of such monitoring scheme is presented in Figures 6 and 7.

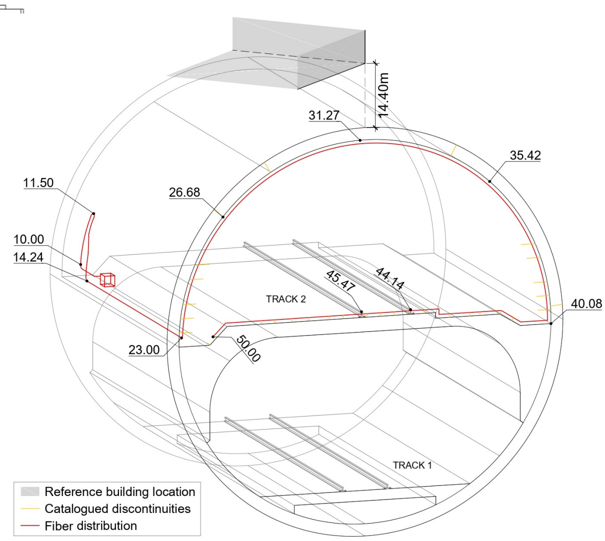

Figure 6. 3-D representation of the DOFS monitoring scheme

In Figure 6, the optical fiber is represented in red and the numerical values around it are a reference to the distance between the indicated point and the beginning of the fiber, i.e. distance to the monitoring device. The orange lines represent the catalogued discontinuities, which refer to points in which the bonding of the fiber to the concrete surface is not guaranteed mainly due to difficult accessibility. These discontinuities are usually found in corners and joints, under rails and behind pipes, preventing the required attachment to the structure from being executed and, thereby compromising the quality and reliability of the readings in that point.

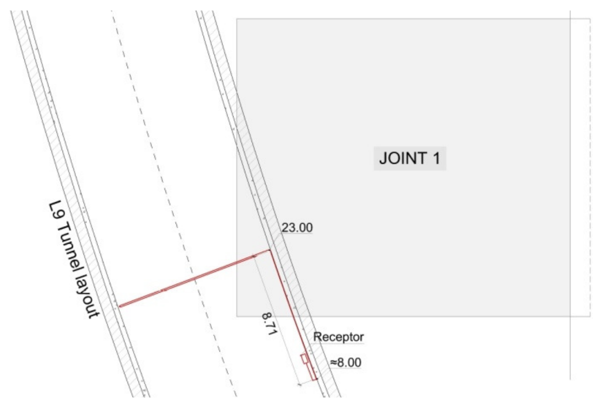

Figure 7. Plan view of DOFS location with respect to building site

2.3 DOFS installation

In order to properly install the optical fiber and ensure its good performance, it has to be appropriately bonded to the structure. The usual procedure implies a delicate preparation of the concrete surface as described in [16,17]. The entire fiber length is fixed to its position by means of punctual adhesives being later covered by a thin layer of epoxy resin that bonds it to the concrete lining. Protective measures need to be applied to avoid possible damage. In this case, duct tape was applied covering the whole length of the fiber and additional protective measures were taken regarding the floor and the fiber discontinuities, for the presence of punctual non-bonded segments in which physical integrity can be easily compromised.

2.4 Construction timeline and monitoring period

The excavation works started in the 8th October 2018 and in mid-November the ground excavation was finished, starting the construction works in a sequence defined in Figure 8.

The monitoring periods are defined with the aim of covering the main construction periods separately: excavation, foundation, execution of ground floor, first floor, etc. The monitoring intervals are presented below:

- From 4th October to 7th October: every 30 minutes.
- From 18th October to 7th November: every 6 hours.
- 13th December: 2 measurements separated by 30 minutes.
- 24th January: 2 measurements separated by 30 minutes.
- From 21st February to 25th March: every 15 minutes.
- From 16th April to 17th April: every 30 minutes.
- 17th May: 5 measurements separated by 10 minutes.
- From 16th July to 6th August: every 30 minutes.

The irregularity in the monitoring periods was due to the problems of accessibility to the reading unit and because the automatic recording was several times interrupted due to maintenance operations in the tunnel. Also the data could not be automatically sent to the data storage because at that time no internet connection was yet available in the tunnel.

3 RESULTS AND DISCUSSION

The strains along the tunnel ring's inner surface and slab's upper fiber were monitored through a 50 m long DOF sensor (bonded to the concrete surface) by means of an OBR ODiSI-A (Optical Distributed Sensor Interrogator) manufactured by LUNA Technologies [17]. The ODiSI uses swept-wavelength coherent interferometry to measure temperature and strain. The spatial resolution selected for this case study is 1cm and the time interval between measurements depends on the monitoring period (see previous section).

The post-processing of the data results on strain measurements along the whole length of the fiber with a resolution of 1cm and for every corresponding time as presented in Figure 9. In this figure, post-processing algorithms as presented in [18] were applied to a better interpretation of the recorded raw data.

A simplified numerical model was used to simulate the effects of the construction on the tunnel [19]. At the beginning of monitoring, the concrete lining segments are under compression. Therefore, all the compressive or tensile effects in the model represent the variations applied to the initial state, meaning that, when the model presents tensile stresses it does not imply that the concrete lining segment is working in tension, but rather that it is being slightly decompressed.

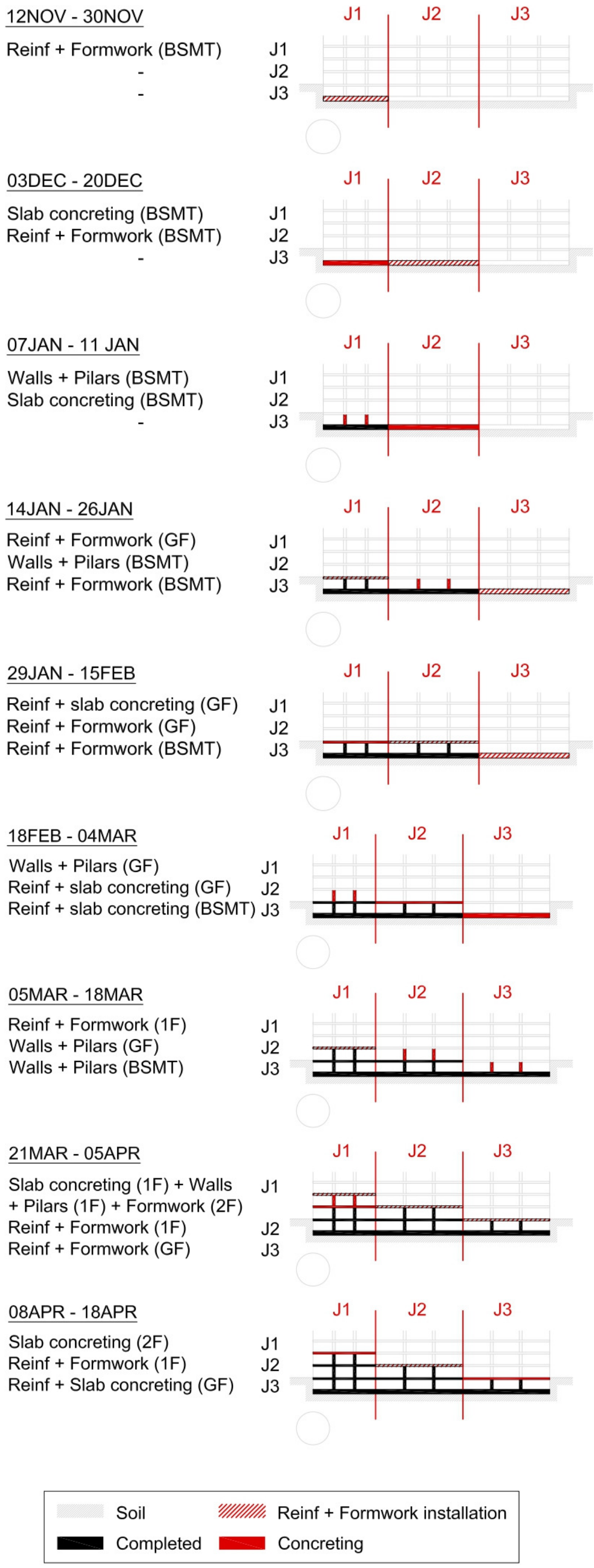

Figure 8. Construction time-line

Given that the inner fiber of the tunnel concrete lining is being monitored, it can be expected that when unloaded (excavation) this fiber will experience compression and, when it is loaded, tension. For that, it can be deduced that the strain evolution in time will have a negative slope for as long as the soil surrounding the underground structure is transmitting the excavation effects to it. After that, the strain readings should reach a maximum compressive state and start reproducing the effect of the construction works by adopting a positive slope representing decompression.

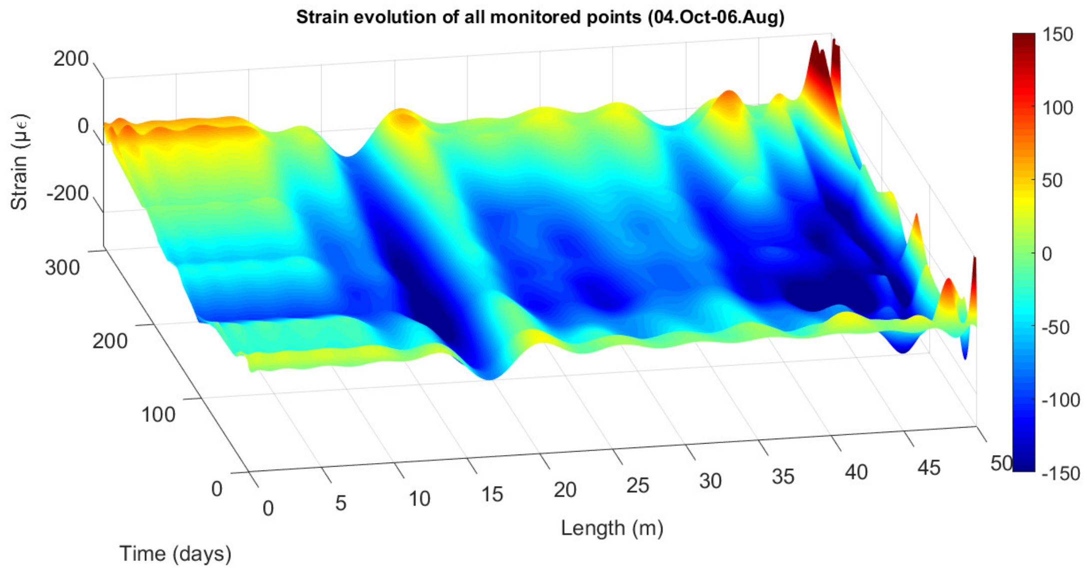

Figure 9. Graphical representation of results obtained during all monitoring time

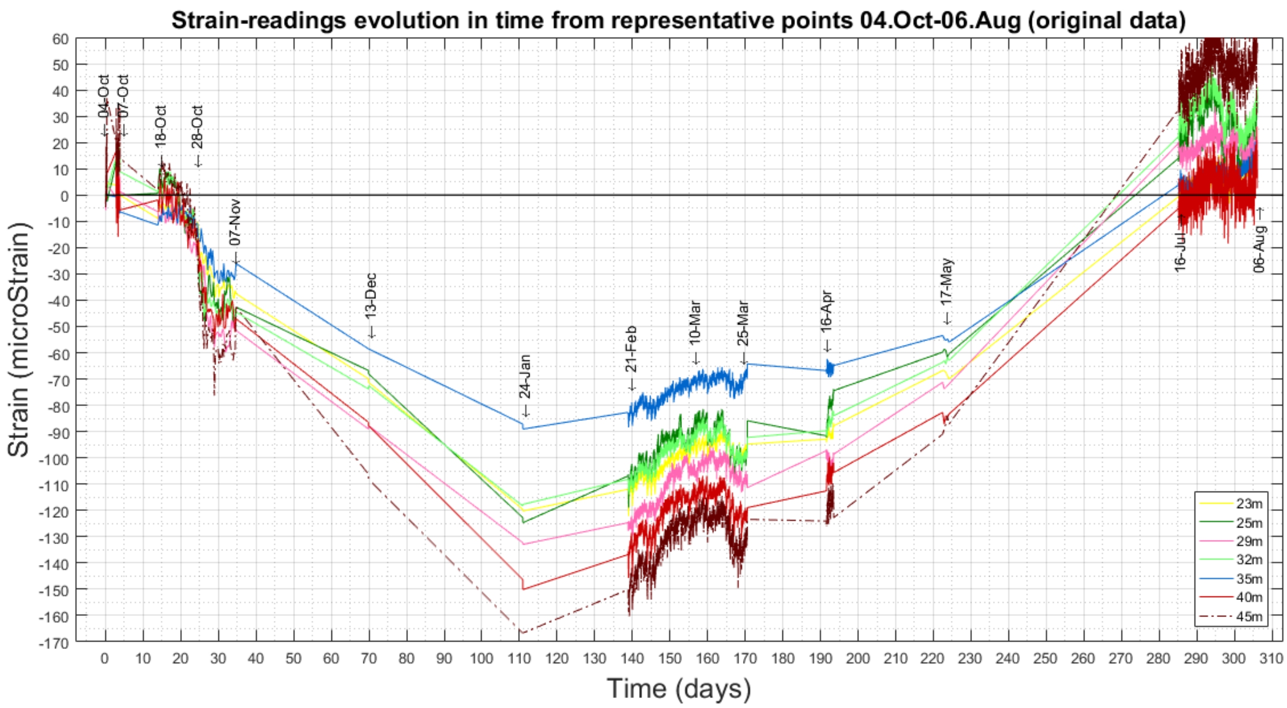

Figure 11. Strain evolution of representative points in figure 10 from 4th October 2018 to 6th August 2019

The effect of the different construction works on the tunnel concrete lining is better observed by means of the so called representative points. These are determinate measures located in the structurally differentiable segments of the tunnel cross section identified in the numerical model. Conclusions regarding the structural behavior of the tunnel lining can be easily extracted and understood from these particular points presented in figure 10.

In order to check the accuracy of the strain readings, figure 11 was developed showing the strain evolution of the representative points during the whole monitoring period (from 4th October 2018 to 6th August 2019).

The initial measures (between 4th and 7th October, before the excavation works started) were conducted with small time intervals between them (30 minutes maximum) and, considering the metro traffic frequency of 10 minutes, it is logical that the point profiles present irregularities in those times, even being representative points specially selected. Later on, the monitoring period that covers the excavation works that took place from the 7th October till the 9th November, presents a strong increase of the compressive strains (downwards) clearly reproducing the unloading effects of the excavation works. These effects are observed during the two following monitoring episodes on the 13th December and 24th January. The next measures, taken between the 21st February and 25th March, already present the compensating effects of construction works (decompression); therefore, the real compression maximum is found close to the 24th January marking approximately two and a half months between the end of excavation works and their final effects on the structure. This aspect reflects the soil consolidation effect. The construction works that are causing the change of tendency started around the end of December with the joint 1 foundation slab, completed on the 20th December and followed by the one in joint 2, finished by the 10th January. By the beginning of March, the ground floor slabs of joints 1 and 2 were already executed as well as the walls and pillars of the first floor in joint 1 and the foundation slab in joint 3. Therefore, significant works had been executed preceeding the March monitoring period, clearly enough to compensate for the excavation unloading and to start decompressing the lower fiber of the tunnel lining.

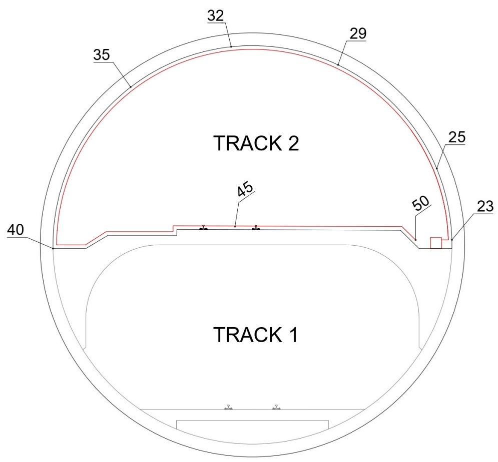

Figure 10. Representative points in the tunnel cross section

At the end of March, a reduction in the strain decompression slope can be appreciated, which, after some thought process regarding the timeline of works, was possible to explain as follows. As mentioned in the construction timeline, the works present at all times advanced development in joint 1 (the one above the tunnel) compared to the other two, with an advantage of 1 floor with respect to joint 2 and two with respect to joint 3. The works in joint 3 started around the end of February, from which it can be deduced that the loading of the further area from the tunnel layout slightly unloaded the soil corresponding to joint 1 by inducing a balanced sort of behavior between joint 1 and 3, explaining the decompressing profile slope reduction.

After that, the tendency observed after the 16th April and 17th May monitoring episodes is still of decompression but with a minor slope being the zero-axis overcome during the first half of July, meaning that the inner surface of the structure starts being in tension.

The evolution of each representative point shown in Figures 10 and 11 is as follows:

- **Point 45** is located in the slab segment and presents the highest compressive state as was expected since the slab is supposed to work in compression during the unloading phase.
- **Point 40** comes next as it is the second most compressed point, which makes sense given its location in the left-hand side corner, really close to the slab but located on the concrete lining surface, which, according to the theoretical model, is supposed to experience high compression as well but slightly less than the slab.
- **Point 29** is located close to the keystone of the tunnel slightly to the right. It is the closest point to the application of loads and, since the tunnel section deforms towards the load application area, point 29 presents the second highest compressive state.

As can be seen, points 40 and 29 have similar strain evolutions, in fact, up to the 13th December, point 29 is more compressed than point 40, which might be explained by the sequential loading of the tunnel, meaning that the loading processes get first to the upper concrete lining and later to the points below.

It is also noticeable that points 23, 32 and 25 present similar tendencies even while being located in different areas.

- **Point 23** is found in the right hand side corner, roughly 50cm above the floor slab.
- **Point 25** is located above point 23 and corresponds to a section with slightly higher traction (barely noticeable at determinate times) than 23. Even though it is located in the centre of what could be identified as the first quadrant of the tunnel cross section, the experimented traction is not the highest.
- **Point 32** is found in the second quadrant of the tunnel cross section really close to the keystone. It represents the beginning of the fiber segment that experiences higher tensile strains.
- **Point 35** belongs to the least compressed segment between lengths 33 and 38 m of the fiber setup. Except for the initial measurements, the strain readings are the lowest in absolute value during all times.

4 CONCLUSIONS

The application of DOFS to the monitoring of a tunnel lining affected by a nearby construction was presented showing a good performance of this novel technique in the monitoring of strain along the whole affected sections. The DOFS readings reproduce very accurately the tunnel deformation process both during unloading (excavation of the ground) and loading (construction of the nearby building). The monitoring of the strain at many points in the critical section allowed us to conclude that the nearby construction only slightly affected the lining stresses and that safety was guaranteed during the whole monitored period.

The outcome of the data post-processing involved two strain readings data sets; the first one can be used to detect local damage observing the strain peaks evolution, and the second one to interpret the global behavior of the structure (since it provides a very smooth surface of strain tendencies).

Given the lack of a continuous monitoring tool, i.e. nonstop readings during the whole construction process, the particular effects on the strain profile slopes of each constructive step (for example, the conclusion of each floor in the nearby building under construction), are very hard to appreciate in the strain profiles. Even the concreting works, understood as a superficially distributed load applied in a significantly reduced time interval and considered as the largest loading events, are difficult to observe in the strain profiles of each monitoring point.

As discussed during the analysis and post-processing of the recorded data, the structural response of the tunnel due to a determinate action at ground level can be monitored logically only after the soil consolidation period. This time interval can involve several months. In the case study, even if the excavation works were concluded around the 10th December 2018, the unloading effects were still being detected in the readings (reproducing structural compression) at the beginning of February 2019.

Despite their advantageous performance and reliability, DOFSs still constitute a recent technology and their reliability and accuracy when applied to real world structures is still under probation.

In general, standardized guidelines need to be developed to ensure success in every DOFSs deployment regarding fiber bonding techniques to the structure surface, temperature affections on readings, post-processing of reading anomalies, among other factors. This newly developed technology can still be considered as an under-researched field because there is still room for improvement and to further investigate its potential implementations. However, real applications as the one presented in this paper show that DOFS are anticipated to have a very important role in Structural Health Management of tunnels and concrete structures in the near future if correctly understood and developed.

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