Application Note

SysTunnel

Optical Monitoring System for Strain and Convergence Measurement

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Content

1 Introduction

Overview

The presented document describes the SysTunnel Monitoring System, the technology behind it and two application examples: Rossio Railway Tunnel and São Paulo Metro Tunnel.

The SysTunnel is a remote monitoring system based in Fiber Bragg Granting (FBG) technology that performs strain and temperature measurements on the inner contour of the tunnel, allowing the estimation of convergences through the MEMCOT method.

This solution is suited for tunnels in operation because it does not require the traffic to be interrupted to take measurements and has a marginal impact on the clearance gauge (less than 5 cm reduction). Measuring campaigns of conventional convergence measuring methods can only be performed while there is no traffic inside the tunnel [1].

Sensing Technology

<u>Fiber Bragg Grating Sensors</u>

The FBG technology is especially suited for use in train applications, where electrical sensors experience interferences. Bragg sensors are immune to EMI/RFI, hence performing properly near a train catenary.

These sensors have high sensibility, reduced dimensions and little weight. Such characteristics make it possible to monitor existing tunnels without reducing the cross-section area.

There are two greater characteristics to the Fiber Bragg sensors which are their multiplexing and self-referencing capabilities. This results in several sensors, with different functions, connected in series on a single fiber without signals being confused, thus making the necessary cable length considerably smaller. Being the measurement of each grating a reflected wavelength, which is an absolute parameter, there is the possibility of turning off or changing the interrogator without the need to calibrate or determine a new “zero”.

A fiber Bragg grating is a microstructure of small dimensions (~1cm) that can be printed inside the core of an optical fiber ($ø_{core}$ ~10 µm, $ø_{fiber}$ ~125 µm) by several methods using UV radiation. This microstructure is a small periodical change of the refractive index of about 0.1% on a determined location. The incident radiation originates a physical mechanism called photosensitivity which is particularly intense on fibers that have high doses of germanium or those that have been submitted to high-pressure hydrogen treatment [2].

A phase mask is a diffractive element produced on a fused silica basis that is transparent to ultraviolet light. When the mask is lightened with a perpendicular UV radiation beam, the waves that correspond to the two efficient orders of diffraction interfere right after the mask creating interferences of high visibility. If a photosensitive optical fiber is placed in front of the mask, changes on the refraction index will occur where the interferences are maximal. These changes create the periodic microstructure that is the Bragg Grating.

This refractive index modulation makes the Bragg grating a wavelength selective mirror. The grating reflects a narrow band of an incoming broadband spectrum that is centered at the Bragg wavelength, λ_B, determined by the equation (1), where n_{ef} is the effective core refractive index and Λ_B is the period of the grating.

$$\lambda_B = 2n_{ef}\Lambda_{\mathrm{B}} \qquad (1)$$

Since the wavelength of the grating is a function of the refractive index and of its periodicity, wavelength variations can also be written in function of the parameters that can change these two values: temperature and mechanical stress.

The sensor response to temperature can be obtained by differentiating the previous equation (1) that states the Bragg condition (2), where ΔT is the thermal sensitivity coefficient of the fiber, α the thermal expansion coefficient of the fiber (which is the same as pure silica 0.55x10-6 /ºC) and ς a coefficient that establishes the variation of the efficient refractive index with temperature (6.7x10-6 /ºC for temperatures below 200ºC and infrared wavelengths). The approached sensitivity for wavelengths around 1550 nm is 11 pm/ºC.

$$\frac{\Delta\lambda_B}{\lambda_B} = \frac{\Delta\left(n_{ef}\Lambda\right)}{n_{ef}\Lambda} = \left(\frac{1}{\Lambda}\frac{\partial\Lambda}{\partial T} + \frac{1}{n_{ef}}\frac{\partial n_{ef}}{\partial T}\right)\Delta T = (\alpha + \varsigma)\Delta T = \beta_T \Delta T \qquad (2)$$

The same approach can be performed in order to determine the sensor response to strain as a result of deformation due to mechanical axial stress (3).

$$\Delta\varepsilon = \frac{\Delta l}{l} = \frac{\Delta\Lambda_B}{\Lambda_B} \tag{3}$$

So, differentiating equation (1) in order to strain and taking (3) into account we can write equation (4), where p_e is the photo-elastic constant of silica (≈-0.22). With a sensor's wavelength of 1550 nm the strain sensitivity is 1.2 pm/με.

$$\frac{\Delta\lambda_B}{\lambda_B} = \frac{\Delta\left(n_{ef}\Lambda\right)}{n_{ef}\Lambda} = \left(1 + \frac{1}{n_{ef}}\frac{\partial n_{ef}}{\partial\varepsilon}\right)\Delta\varepsilon = (1 + p_e)\Delta\varepsilon = \beta_\varepsilon\Delta\varepsilon \tag{4}$$

When both temperature and strain are combined, the wavelength shift can be described as the following linear relationship (5) [3]:

$$\frac{\Delta\lambda_B}{\lambda_B} = (\alpha + \varsigma)\Delta T + (1 + p_e)\Delta\varepsilon \tag{5}$$

When there is the need to isolate strain variation from a Bragg grating that is also subjected to a variation of temperature, we can use several techniques [4]. One of them is the use of two fiber Bragg gratings where both experience the same temperature change and one is immune to strain (hence a temperature sensor). Imagine two different gratings with different wavelengths (6).

$$\begin{cases}\Delta\lambda_B^1 = \beta_T\lambda_B^1\Delta T^1 + \beta_\varepsilon\lambda_B^1\Delta\varepsilon^1\\ \Delta\lambda_B^2 = \beta_T\lambda_B^2\Delta T^2 + \beta_\varepsilon\lambda_B^2\Delta\varepsilon^2\end{cases} \tag{6}$$

If one of them is immune to strain and they are both subjected to the same temperature change we can state (7).

$$\begin{gathered}\Delta T^1 = \Delta T^2 = \Delta T\\ \Delta\varepsilon^1 = \Delta\varepsilon\\ \Delta\varepsilon^2 = 0\end{gathered} \tag{7}$$

Replacing (7) in (6) we get (8).

$$\begin{cases} \Delta T = \dfrac{\Delta\lambda_B^2}{\beta_T \lambda_B^2} \\ \Delta\varepsilon = \dfrac{\Delta\lambda_B^1}{\beta_\varepsilon \lambda_B^1} - \dfrac{\Delta\lambda_B^2}{\beta_\varepsilon \lambda_B^2} \end{cases} \tag{8}$$

This is the reason why there is at least one temperature sensor on each cross-section in the SysTunnel. With this technique the temperature induced wavelength change on the strain sensors is compensated and the real strain is determined.

2 Monitoring System

System Architecture

The SysTunnel monitoring system gives great flexibility allowing the combination of the system components in different quantities and spatial distribution. The main components are the sensors, the stainless steel bars with the sensors, the measurement system and the software, see Fig. 1.

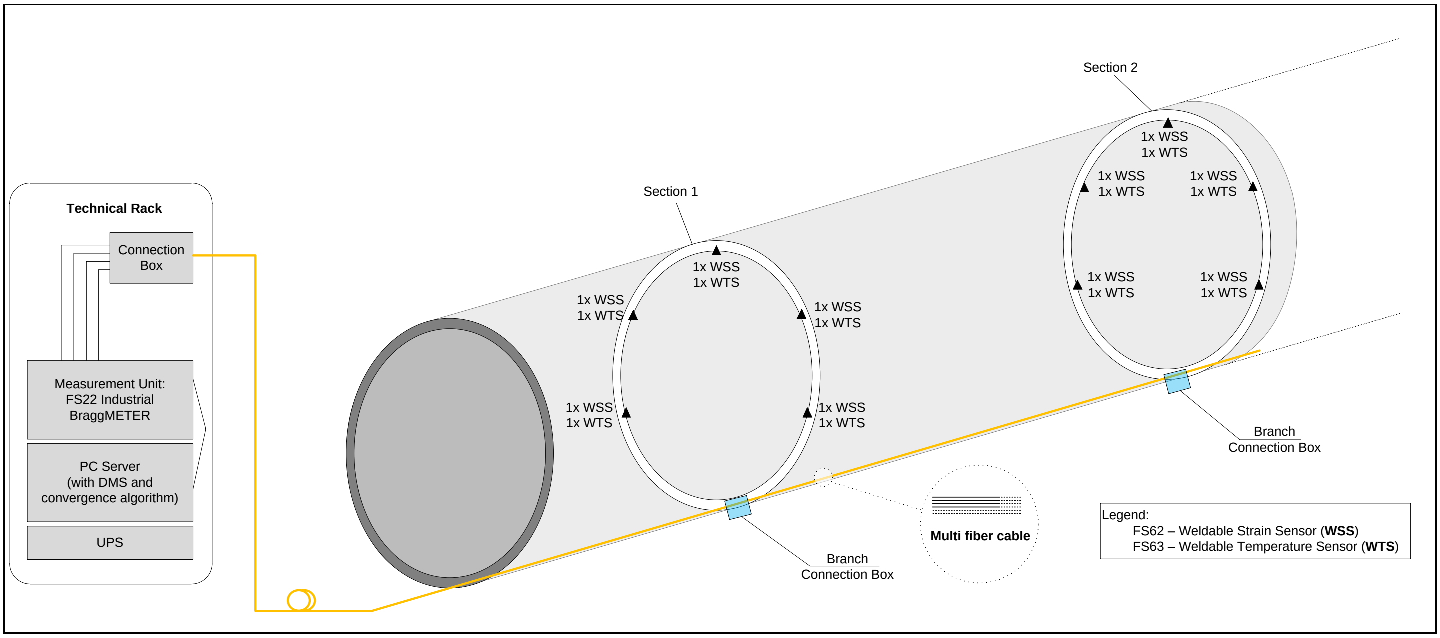

Fig. 1: System Architecture

Stainless Steel Bars with the Sensors

Strain Sensor

The FS62 Weldable Strain sensor is a fiber Bragg grating strain gage. It consists of a capillary stainless steel tube containing the sensing element, which is laser welded to a thin stainless steel base that is used for direct spot welding onto the metallic structure. A protective stainless steel cap is directly welded to the structure by using the same hand-probe spot welder. From this cap, input/output fibers can enter/exit already protected with 3 mm PVC buffer with internal stainless steel coil.

Temperature Sensor

The weldable temperature sensor (Fig. 3) has exactly the same mechanical design as the strain one (Fig. 2), but the sensing element inside the capillary stainless steel tube is properly strain isolated.

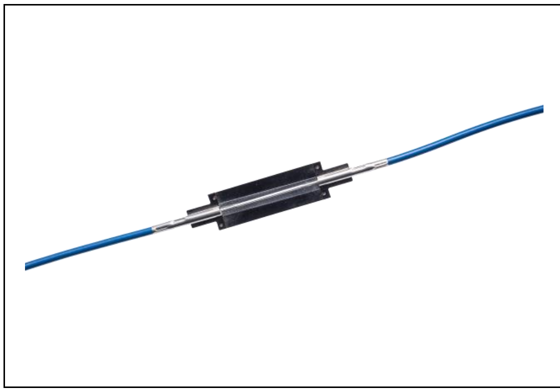

Fig. 2: FS62 Weldable Strain Sensor

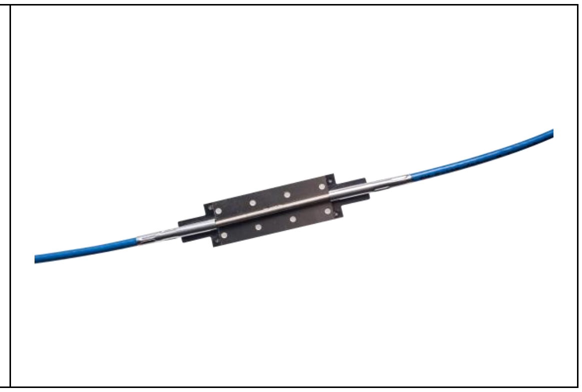

Fig. 3: FS63 Weldable Temperature Sensor

Stainless Steel Bar

For materializing the tunnel contour as a continuous perimeter, a flexible stainless steel bar (e.g. with 40x4 mm) is used. The profile is divided into smaller bars for transport, storage, production and handling purposes. The number of elements can be chosen depending on the perimeter of the tunnel section.

Link within the Section

Between each sensor there is a connection box where the sensors are joined together. Some junctions can be performed during the sensors' production in HBM FiberSensing facilities, while the remaining connections have to be made during the installation of the profile on the construction site, butt-joined or spliced. This means that after production every bar is an array of sensors that is prepared to be joined and connected at the installation site.

The stainless steel bar with sensors materializes an instrumented section. Each monitored section is usually instrumented with five or seven strain sensors and at least one temperature sensor for compensation of the temperature effect on the strain measurement. Sensor positioning on the section is user definable (within some physical constrains), as well as the alignments in which to estimate convergence. In Fig. 4, the placement of sensors in common usual cross section is shown.

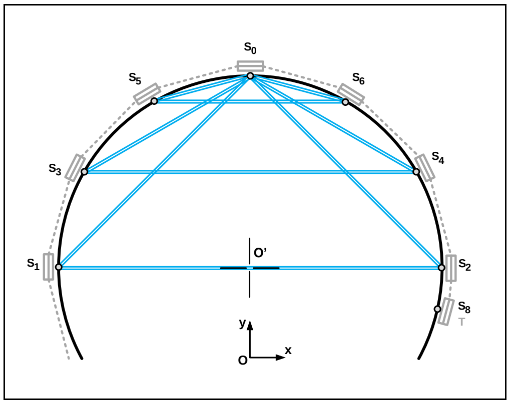

Fig. 4: Sensor placement

Measurement System

Interrogator

Combinations of FS22 Industrial BraggMETERs (Fig. 5) and Optical Multiplexer Expansion Units (Fig. 6) can be used to interrogate the sensors. The Multiplexer works as a switcher which makes it possible to illuminate one optical channel at a time.

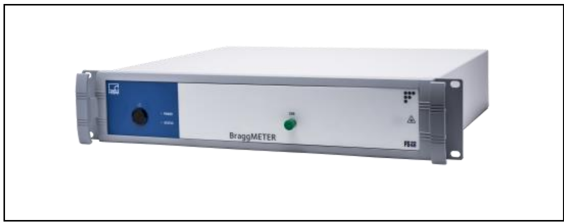

Fig. 5: FS22 Industrial BraggMETER

Fig. 6: Optical Multiplexer Expansion Unit

Rack, UPS, PC Server and Other Third Party Components

As option there are several components that the SysTunnel solution can include. Examples are:

- a 19” rack for accommodating the measuring equipment;
- a drawer for optical cable termination and connection to the measuring equipment;
- a PC for control and data storage or connection to an external server through Internet or Ethernet;
- a UPS for power stability

- a screen and keyboard

Optical Cable

To connect the monitored sections to the interrogators, optical fibers are deployed along the tunnel. Normally there are already infrastructures for protection and placement of the optical cable(s).

The cable(s) must be protected from outdoor aggression. Close to each section a single fiber is pulled out from the cable and connected to a pigtail inside a protection box. On the measurement system extreme individual fibers from the optical cable(s) also need to be terminated with a pigtail for connecting to the interrogator(s).

Software

Data Management Software

All collected data can be stored and managed with a Data Server Application running on a dedicated server.

The application is developed in order to receive process and save the acquired data:

- Data is processed with the programmed algorithm so that the wavelength shift is transformed into strain, convergence, temperature and other measurable variables
- Changes are synchronized between the interrogator and the user inputs through a database
- An Internet user interface allows registered users to access the database anytime anywhere

User Interface

The Internet interface allows searching for results in various combinations. Data can be viewed in graphics and/or spreadsheets, also different sensors can be joined in several different ways.

The access to the web page is limited to authorized users. There are two user levels: administrator and regular user.

The interface is divided into two main areas: administration and search.

- On the first area, to which only administrators have access, the main characteristics of the project can be configured. Administrators can create, edit or erase elements of the system such as the project, interrogators, sections, sensors, alarms and users.
- On the second area, all registered users can search for results. Data can be searched using the sensor's name or its position on the tunnel's alignment. The results are then showed as a graph and/or as a table which can be printed or saved as a .txt format. Since every variable is a function of time, it is also possible to have information and graphical representation of its velocity and acceleration. When searching, data can be shown as a deformed shape of the tunnel contour, which is an advantage of this method of calculating convergences in tunnels.

3 MEMCOT Method

Overview

The Extensometric Method for Monitoring Convergences in Tunnels (MEMCOT) [5] consists in continuously assessing the displacement of the tunnel support by measuring deformations along the contour and transforming them with an appropriate algorithm. It allows the quantification of convergences (relative displacements) of the support and its geometric evolution throughout time.

Mathematical Model

The method was initially developed based on the Theory of Materials. It has gone through several updates due to testing results in reduced scale models and in field applications.

The mathematical model was updated to the Theory of Bending of Initially Curved Bars. This theory allows the quantitative modeling of radial displacement in function of the axial strain that is being measured.

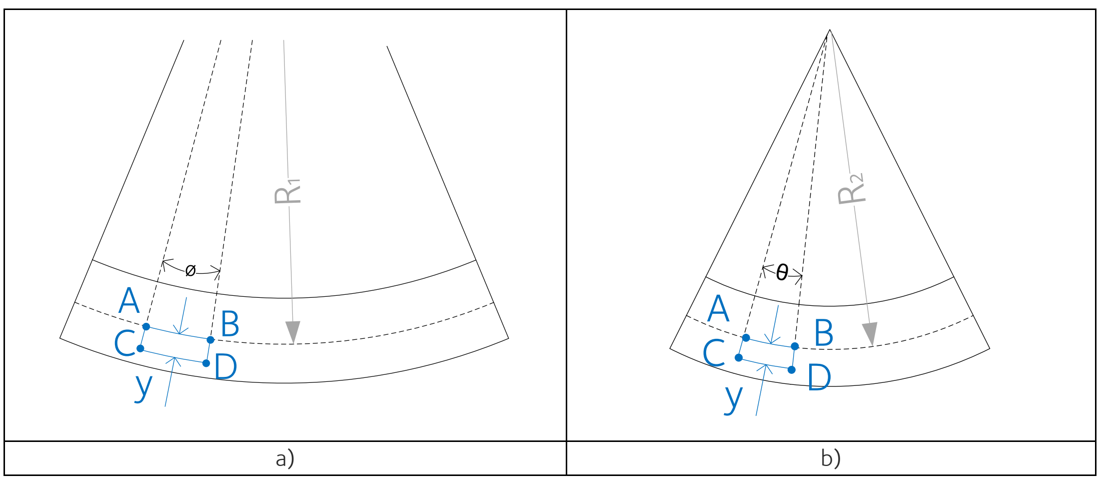

Fig. 7: Bending of initially bended bars: a) before bending; b) after bending

If a beam, with an initial radius of R_1, is submitted to an external load or moment, it bends to create an axial strain ε_x at a section located at a distance y from the neutral axis. Consider the curved bar unloaded and subjected to bending in Fig. 7. Assuming that plane cross sections remain plain after loading, the strain at a small segment CD at a distance y from the neutral axis is given by equation (9).

$$\varepsilon_{CD} = \frac{\Delta \ell_{CD}}{\ell_{CD}} = \frac{(R_2 + y)\phi - (R_1 + y)\theta}{(R_1 + y)\theta} \tag{9}$$

We can write equation (11) because there is no change in length (10) for an element on the neutral axis,

$$R_2 \phi = R_1 \theta \tag{10}$$

$$\varepsilon_{CD} = \frac{y(\phi - \theta)}{(R_1 + y)\theta} \tag{11}$$

Finding the angle ø with (10) and replacing in (11) we determine strain (12).

$$\varepsilon_{CD} = \frac{y\left(\frac{R_1}{R_2}\theta - \theta\right)}{(R_1 - y)\theta} = \frac{y\left(\frac{R_1}{R_2} - 1\right)}{(R_1 + y)} = \frac{y(R_1 - R_2)}{R_2(R_1 + y)} \tag{12}$$

The radial displacement is calculated through equation (13).

$$\delta = R_1 - R_2 = \frac{\varepsilon_x R_1 (y + R_1)}{\varepsilon_x R_1 + y(1 + \varepsilon_x)} \tag{13}$$

The strain sensors, together with the temperature sensor, measure temperature compensated strain in five/seven known positions of the tunnel cross-section. This is represented by ε_x in each location.

Once the metallic profile is glued to the structure surface and the structure is in contact with the surrounding ground, the distance to the neutral axis y is difficult to estimate. After *insitu* tests performed by the Centro de Geotecnia of the Instituto Superior Técnico of the Universidade Técnica de Lisboa (CEGEO) on the Falagueira Tunnel, the theory could be confirmed if the “pressure arch” concept is considered. This concept postulates the existence of a decompressed volume of ground above the tunnel that transmits its load to the support system, [6]. This assumption involves the joint action of ground and support, deforming

together under a compressive state.The above mentioned variable y depends on the thickness of that pressure arch, as proposed by Terzaghi, later on modified by several authors.

Based on the numerical values in Fig. 8, the main curve is given by the expression (14), where R represents the RQD of the surrounding ground, with a correlation coefficient of 0.9926:

$$n = -5 \times 10^{-6} R^3 - 0.0725R + 2.69 \qquad (14)$$

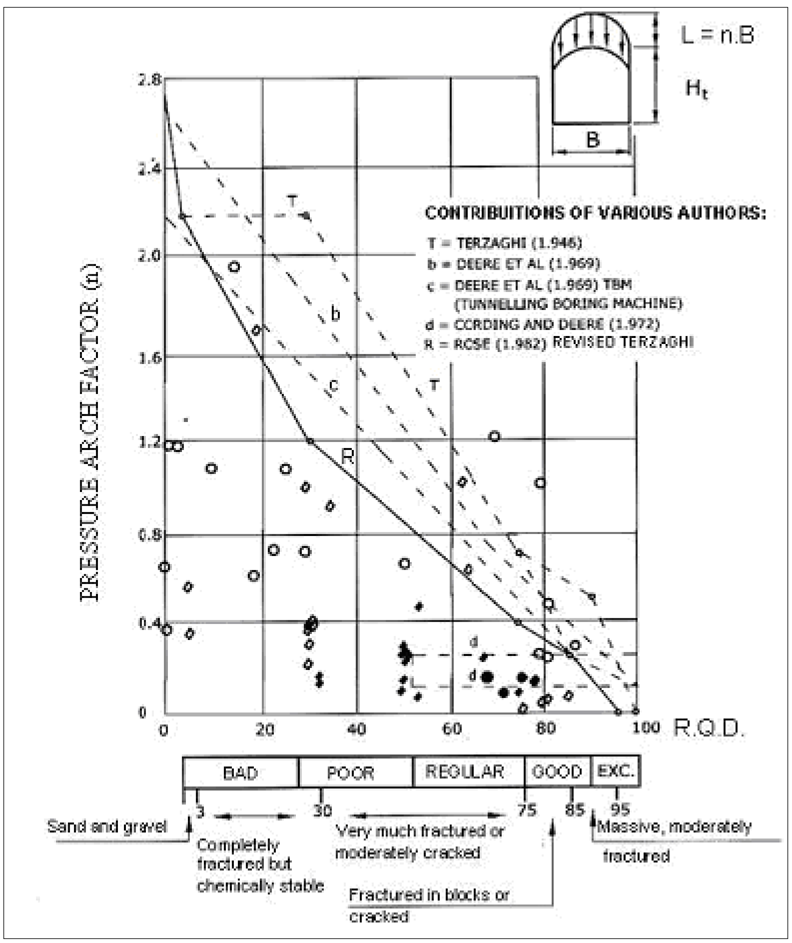

Fig. 8: Pressure arch factor [6]

Knowing the sensors (x; y) coordinates, we can determine the center of the circumference they belong to (using tree points belonging to the same circumference we have enough constants to solve the circle parametric equations) and their initial radius R_1. With geotechnical data we estimate y as explained.

Having each point's radial displacement, several variables such as the new coordinates can be found. With the new coordinates the tunnel deformation and the convergence between two points can be estimated.

Because MEMCOT measures absolute displacements of each point, geometrical changes on the section shape can be detected. With traditional convergences measurements there is the assumption that the movements are symmetric. Assessing the shape of the deformation is another advantage of this method against traditional ones.

Validation, Calibration and Preparation

A real scale model was designed in order to calibrate the method and also to test the system before the first contracted installation. Two models were designed to represent both cross sections configuration of the Rossio Tunnel:

- The masonry section, corresponding to the original shape of the tunnel shaped as circular arch supported by vertical walls;
- And the concrete section, that is the new structure, with a perfect circular section.

The models consisted on HEA120 metallic profiles, designed so that punctual loading could be performed without danger of plasticizing or collapsing. The profiles were attached to the floor by the means of mechanical anchors. In Fig. 9, the erected sections can be seen.

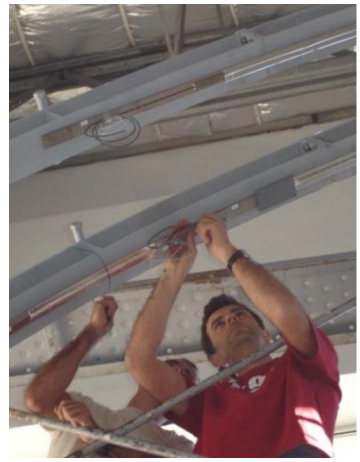

Fig. 9: Model Sections Fig. 10: Sensor installation on the model

Algorithm Validation

The testing campaign had the purpose of validating and calibrating the programmed algorithm.

The tests consisted in punctually loading each model with load-unloading cycles while strain was being measured together with relative displacements of the seven instrumented points. For loading, two hydraulic jacks equipped with a nanometer for load control and metallic chains anchored to the floor were used. A portable BraggMETER was used for the signal acquisition. Fig. 11 shows the interrogator while being used. The acquired data was then processed to have a single value for each loading step. The real displacement was measured using a total station that can be seen in Fig. 12. Reflecting targets were glued to the sensors location as reference.

Fig. 11: BraggMETER Portable interrogator

Fig. 12: Total station

Results

Fig. 13 and Fig. 14 show the results registered for sensor S_0 for both arches and for vertical loading tests. The vertical load was applied in steps with an increment of 40 N each up to 320 N on the model for the masonry contour and 360 N for the concrete model.

There is a straight relationship between the measured relative displacement and the weldable sensor readings. As expected, the linear correlation coefficient is near one, as shown in Fig. 14 and in Fig. 16.

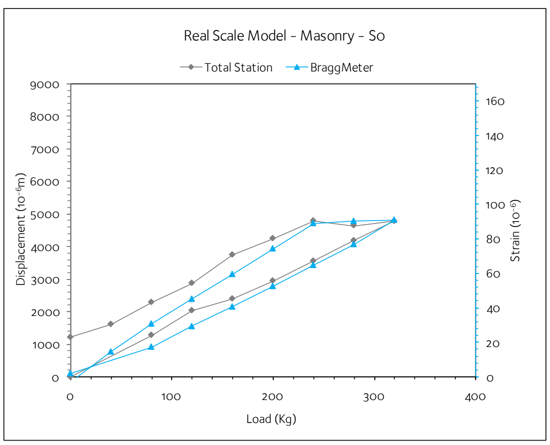

Fig. 13: Results

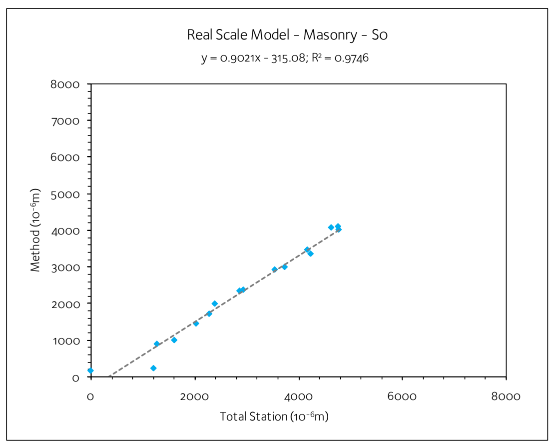

Fig. 14: Results

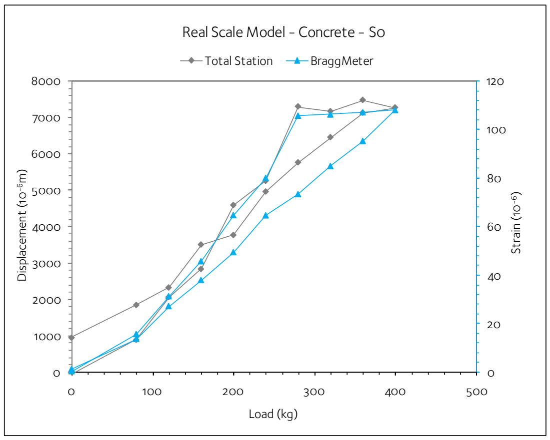

Fig. 15: Results

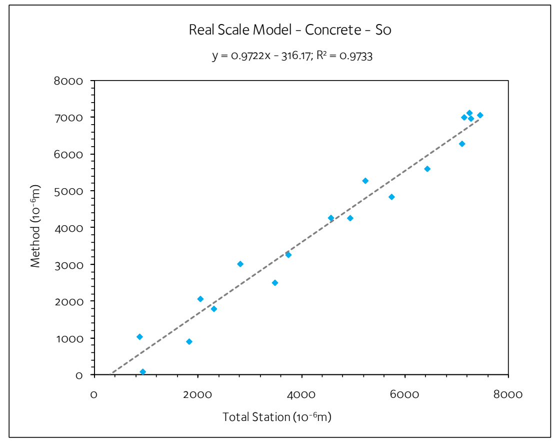

Fig. 16: Results

For the performed tests, it is possible to calculate the maximum distance between the expected value and the value calculated with MEMCOT using sensor readings. For all seven sensors, the “error” was never greater than 2 mm and the average value of the difference is below 0.7 mm. Since the total station itself has an accuracy of 1 mm we can say that these are excellent results.

Overview

Rossio Tunnel is a centenary railway tunnel, 2.6 km long, built between 1887 and 1890 in Lisbon, Portugal. At the time, the construction of the Tunnel and the Rossio Station was considered the biggest Portuguese engineering achievement of the XIX century (Fig. 17). It interconnects Rossio and Campolide Train Stations being a major railway artery for the city's public transportation network.

Fig. 17: Rossio Train Station during construction (1890)

Fig. 18: Rossio Train Station after rehabilitation (2008)

The first report of structural damage in the Rossio Tunnel dates from 1926. The information present in the report was of "deformation and displacements of 25 cm in Pm 2 020". Excavated in a calcareous massif, the tunnel's structure was made of masonry in bricks on the arch, and rocks on abutment. It is common that this combination of material and shape progressively deforms without cracking.

Before the decision to rehabilitate the tunnel in 2004, the growing deformation and displacements of the arch raised concern. The existing deformations on Pm 2 020 evolved negatively and the structure was considered in pre-collapse.

Given the importance of this structure it was decided to install an automated large-scale convergence monitoring system throughout the entire length of the tunnel, in a total of 109 convergence sections. Several solutions were evaluated based on different market-available technologies. Taking into account both technical and cost factors, a final decision was taken to install an all-fiber optic based sensing system to continuously monitor the structural behaviour of the tunnel. This decision goes in-line with the REFER strategy to automate as much as possible the structural health monitoring of its most relevant infrastructures. The Rossio fiber optic structural health monitoring system was developed and installed by the consortium FiberSensing/EPOS, according to REFER specifications. The MEMCOT method was used to determine the tunnel's convergence.

The structural prediction of the tunnel's future behavior, along with geology's analysis, was taken into account when determining which sections to monitor. The monitoring system is able to measure distances between points on the vault and abutments which allow the determination of displacements throughout time. Data should be collected once a day and programmable for higher frequencies. Alarms and notices are easily defined and messages sent to e-mail accounts and mobile phones.

System Architecture

For each of the 109 monitored sections, one channel of the system was used. Each section was monitored with seven strain and one temperature sensor.

An FS22 Industrial BraggMETER with 1 optical channel combined with an Optical Multiplexer Expansion Unit was used. The 872 sensors are acquired in a time switch sequence. Data is then processed and saved to a database.

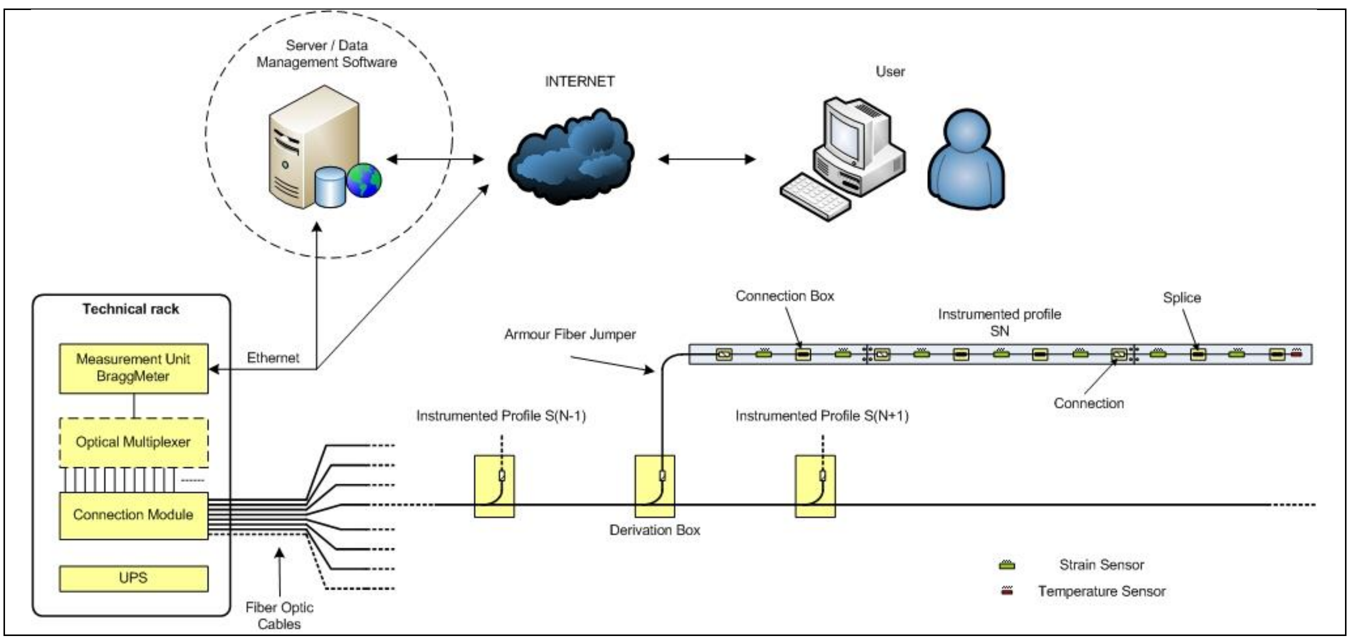

Fig. 19: Architecture of the system

A 19'' rack was installed in the technical room. This enclosure protects the interrogator, the Multiplexer and the UPS. The technical room is connected to the intranet of the Rossio tunnel.

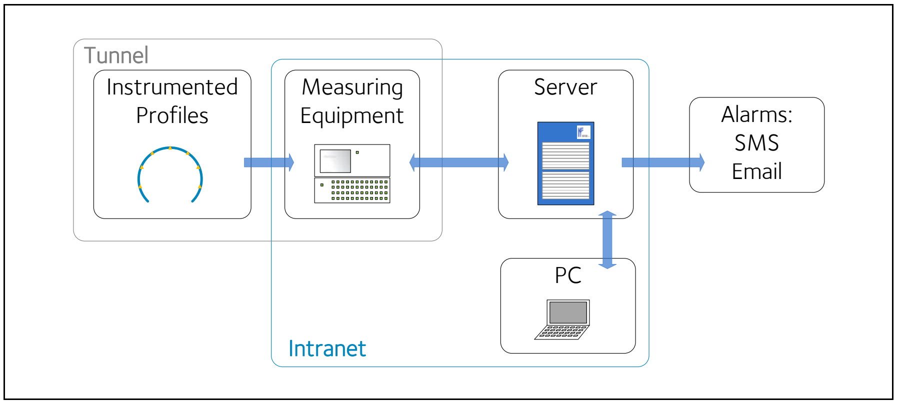

Fig. 20: SysTunnel Arquitecture

Web interface

All the information is presented to the user in a web browser. In Fig. 21, the dataflow of the system is schematically represented.

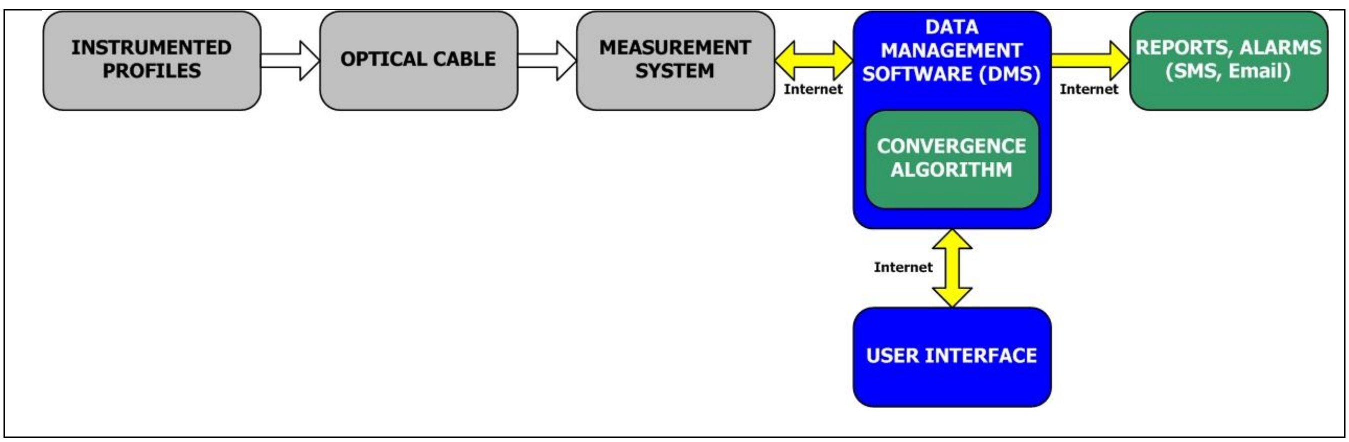

Fig. 21: System dataflow

A second software application is installed on the registered users' computer to remotely access data. Saved data is password protected. This is the interface for searching and visualizing data and for configuration of system parameters, measurement to perform and alarms.

The user can search data - that can be displayed in graphs or tables - and combine sensors in several ways. In Fig. 23, the results for convergences in a random section for the period of a month are presented.

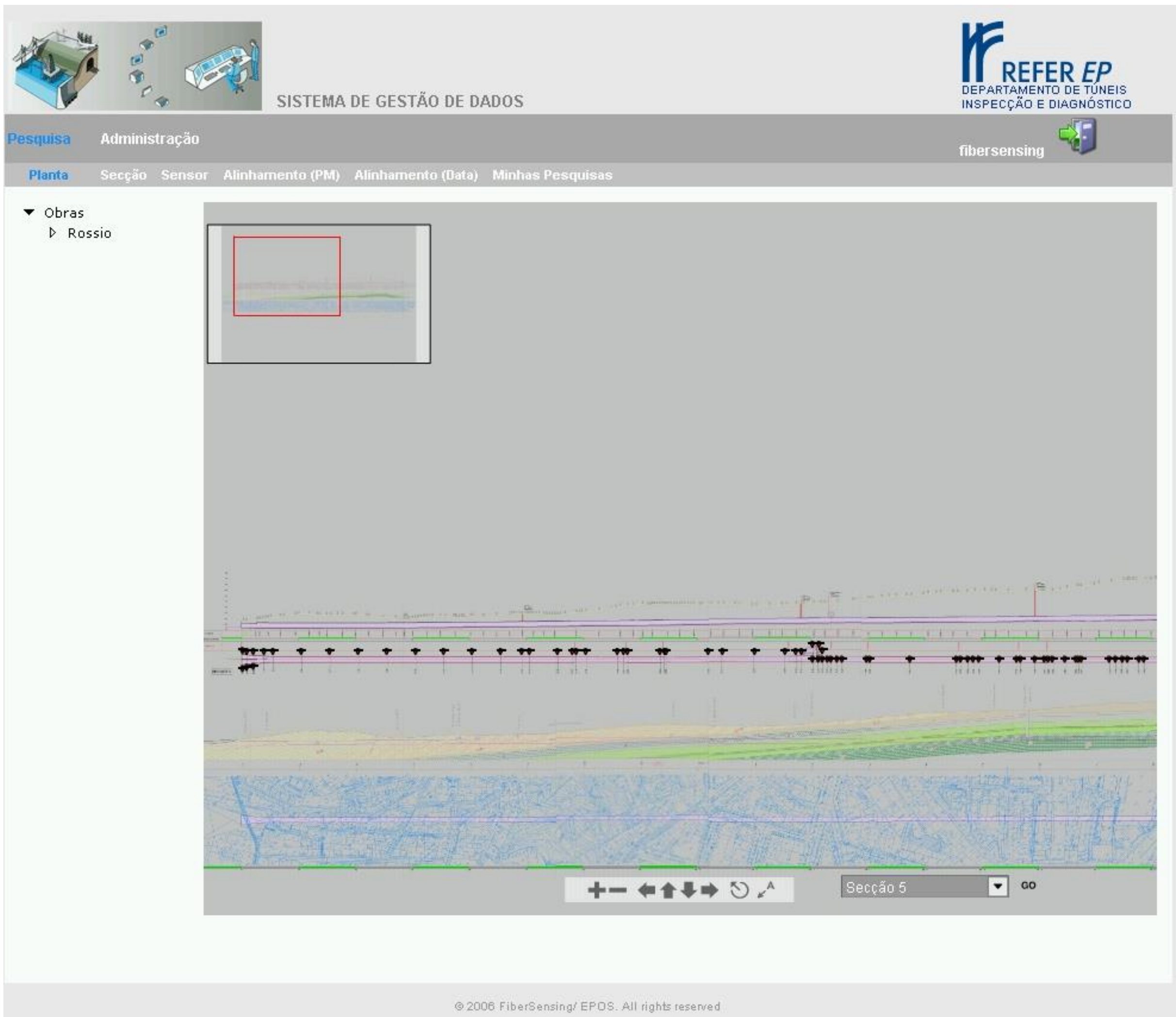

Fig. 22: Data Management system web interface

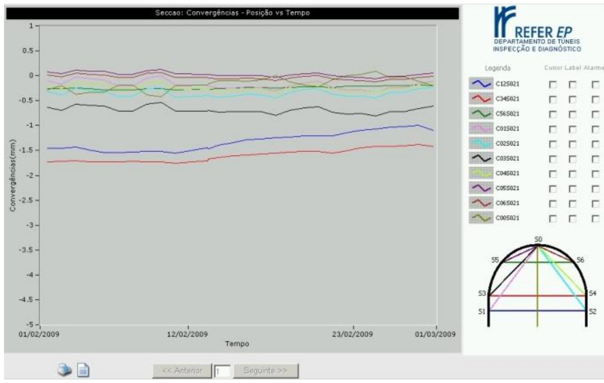

Fig. 23: Example of a search result on convergences over a month

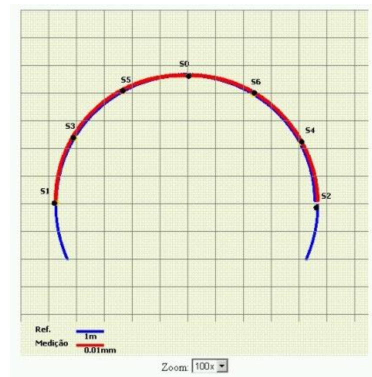

Fig. 24: Example of a search result on the section deformation between two specified dates

Installation

<u>Vertical Alignment</u>

The first task to perform on the sections to-be instrumented was the definition of the vertical alignment using a circular laser (Fig. 25) and the installation of pre-supports. The main purpose of these supports is to ensure the instrumented profile position. These also have the function of supporting the bars while being installed and helping during the resin curing (Fig. 26).

Fig. 25: Vertical alignment definition

Fig. 26: Pre-supports

Elevation of the Instrumented Bars

Each SysTunnel instrumented profile was divided in 3 bars for handling and transportation issues. The central bar was the first to be elevated (Fig. 27) and temporarily hanged on the pre-supports. Then the side bars were also elevated, hanged and mechanically connected to the central bar.

Fig. 27: Bar elevation

Fig. 28: Mechanical connection between bars

Optical Connection and Verification

All sensor connections between bars were made. The connection between bars was prepared with but-joined connectors so it would be easier and faster. This task had to be closely controlled with a FS42 Portable BraggMETER so signal losses could be identified. Whenever signal losses compromised the measurements, the butt-joint connection was replaced with a permanent connection. Connectors between two fibers have bigger losses than permanent connections - called the fusion splicing - and are more prone to degradation with time.

The success with butt-joint connections was of 92.2% in the Rossio Tunnel.

Fig. 29: Optical connection

Fig. 30: Optical connection verification

Profile Fixation to the Tunnel’s Wall

A two component epoxy was used for the fixation of the instrumented profiles. The resin selection was based on its mechanical properties as well as on its pot life. The used epoxy was MBrace Adesivo from Degussa has excellent tensile stress resistance and an adequate pot life. After the application of the epoxy on the back of the profile with the aid of a gun, the profile was pressed against the tunnel’s wall - initially by hand and then using two hydraulic jacks on the feet of the profile as in Fig. 34. The pre-supports were tightened (Fig. 35) to help maintain the profile in position while the glue cured. The profile installation ended when both extremities of the profile were anchored to the wall of the tunnel. The anchoring was placed so that the profile stays fixed to the structure where the settlement/displacement is considered null.

Fig. 31: Resin preparation

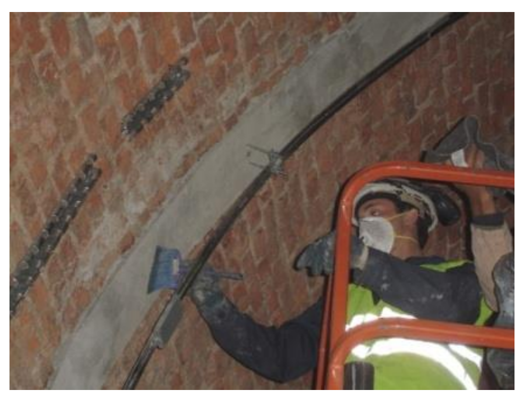

Fig. 32: Cleaning of the surface

Fig. 33: Epoxy application

Fig. 34: Hydraulic jacks

Fig. 35: Tightening of the pre-supports

Fig. 36: Grounding

Grounding

In the Rossio Tunnel there was the obligation to ground every mechanical part inside the tunnel, so every profile was connected to the existing ground cable according to the owner's standards.

Optical Cable Connection

To connect each instrumented section to the Interrogator, multi-fiber cables were used. Near each section, one of the fibers was pulled out of the cable and connected to a jumper that leads to the sensors in the profile (Fig. 37). The cables were deployed along the tunnel, protected and guided in a technical gutter.

Fig. 37: Optical cable connection box

Fig. 38: Jumper protection

Topographic Calibration

The extensometric method for measuring convergences requires a calibration to determine the sensor's initial position. Once the section was fixed to the tunnel, the topographic survey of the section was performed. Each sensor was mechanically protected in factory with a metallic cap that included a target on the center position of the sensor, as shown in Fig. 40, to allow topographic readings.

Simultaneously to the survey sensors, wavelength was measured for the "zero" definition.

Fig. 39: Optical cable connection to the rack

Fig. 40: Metallic protection cap with target

Technical Rack Connection

The technical rack with the Interrogator and other needed equipment should be preferably installed outside the tunnel for these reasons:

1. the installation and connection will not be restricted to working schedules inside the tunnel
2. a clean and ambient-controlled room may be selected for the rack installation
3. maintenance of the equipment may be performed without restrictions due to working authorizations inside the tunnel

In the Rossio Tunnel, however, the technical rack was installed inside the tunnel on the Campolide end. A specially designed closet was installed in the owner designated refuge hole. The structure was equipped with thermo-controlled ventilation to prevent overheating, dust filters to reduce the dust on the rack and a strong lock to prevent vandalism and theft.

System Usage Experience

The structural monitoring of a Tunnel in operation is different from the monitoring of a structure under construction. Here the movements are, in principle, greatly reduced, the loads are distributed, the structure is already adjusted to the requests and therefore, the deformations have a slow evolution.

In conventional monitoring the frequency of the readings is usually annual. If there are concerning developments in the structure, it can be quarterly or half-yearly. In extreme cases (accidents or adverse natural phenomena) it can even be performed daily. This means that data is analysed every time it is collected and actions are taken in accordance to the results.

When an automatic structural monitoring system comes into service the amount of information received on a daily basis makes it impossible to analyse the structure every time there is a new measurement. If there are no alarms that alert the system manager to a possible danger situation or for the evolution of the structure the amount of collected data is useless.

Created alarms for the measurements on the Rossio Tunnel can be divided into two groups.

The first group corresponded to alarms of danger. Here the association is made with the speed of convergence. With speeds above and below defined values of mm/day the system sends a message to check the respective alignment. Different levels of danger can be created.

The second group of created alarms system aims to support the Manager and avoid the individual check of monitoring values of all the sensors. For their configuration time and collected data is needed. The defined levels had to be adjusted with time and Tunnel regular behaviour analysis. The oscillatory evolutions of the deformations over time - the "breathing of the tunnel"- reflect the seasonal effects on the structure caused not only by temperature variations, but also and most importantly by the effect of the hydrostatic pressure related with the variations of the water table in the aquifers. For example, a normal oscillatory behaviour can be seen in Fig. 41. An alarm was created for a minimum value of 0.0 mm and a maximum value of 4.5 mm. If these values are overcome a message is sent with instructions to check the section is sent. Then the System Manager will check out what is happening and find the origin of the phenomenon.

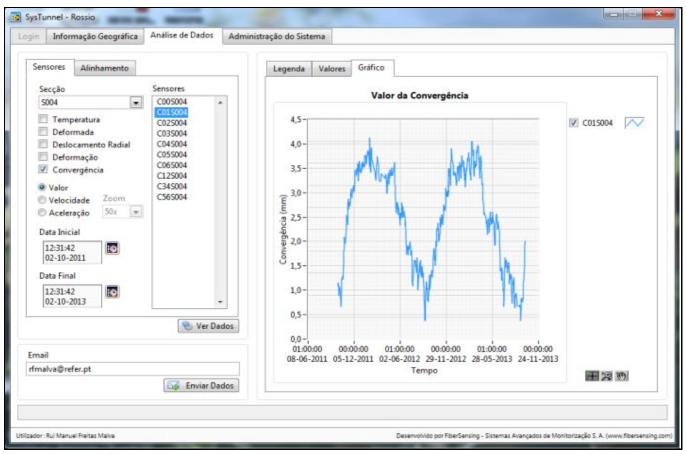

Fig. 41: Regular behaviour of the alignment C01S004

6 Application Example: São Paulo Metro Tunnel

Overview

Paulista Avenue in São Paulo, Brazil, is the most important financial centre of the city as well as one of its touristic attraction poles. Thousands of people move around this important axis that connects other important avenues of the city. It is served by São Paulo's Metro Green Line 2.

For the construction of Torre Matarazzo (Fig. 42), the monitoring of the Metro line was required.

This new skyscraper was erected in an ancient terrain in this avenue and was planned to hold a business centre, a shopping mall and car parking. The tower consists of 23 floors above ground and 7 excavated floors.

Fig. 42: Matarazzo Tower

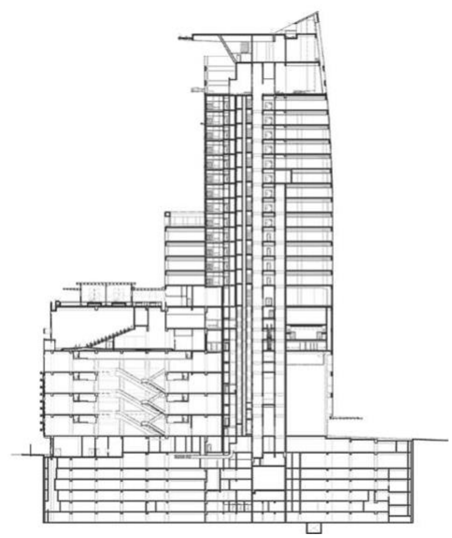

Fig. 43: Matarazzo Tower plan

The building contention substructure is an anchored diaphragm wall with 50 cm width. The green line from São Paulo Metro passes a few meters away from the excavation site. During the construction the tensional state of the soil around the subway tunnel suffered changes, so it was necessary to monitor the subway structure behaviour to offer a safer conceptual solution.

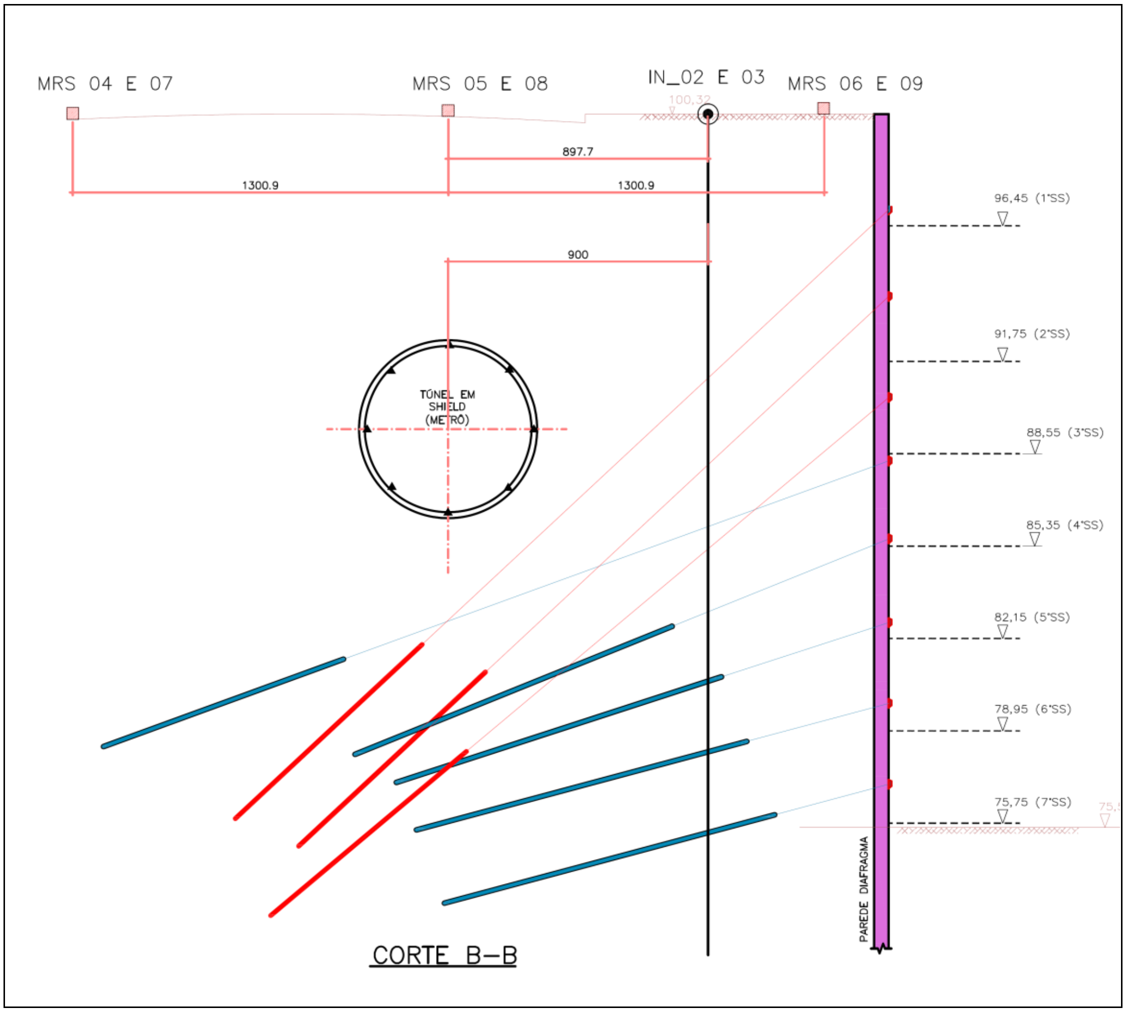

Fig. 44: Excavation and diaphragm wall anchoring plan

The Metro line consists of two circular tunnels with 6 m diameter at 8 m below street level. The most influenced tunnel is at 11,5 m from the diaphragm wall.

The Metro line was not supposed to be interrupted while the construction was taking place. A real-time monitoring system that would not interfere with the regular traffic had to be installed during the excavation and support wall construction. At the same time, the safety of the existing structure and mainly of the passengers using the public transportation system could not be disregarded.

The SysTunnel system was installed on the influence area of the excavation to continuously access the deformations and convergences of the tunnel.

System Architecture

In São Paulo Metro tunnel two sections were monitored with seven measuring points each. One strain and one temperature sensors were used for every measuring point.

To interrogate all sensors, a FS22 Industrial BraggMETER with 4 optical channels was used. The 28 sensors were acquired every minute. Data was processed and saved to a local database.

A 19'' rack was installed at a technical room at the Metro station. This enclosure protected the interrogator, the server PC, the UPS and an internet connection.

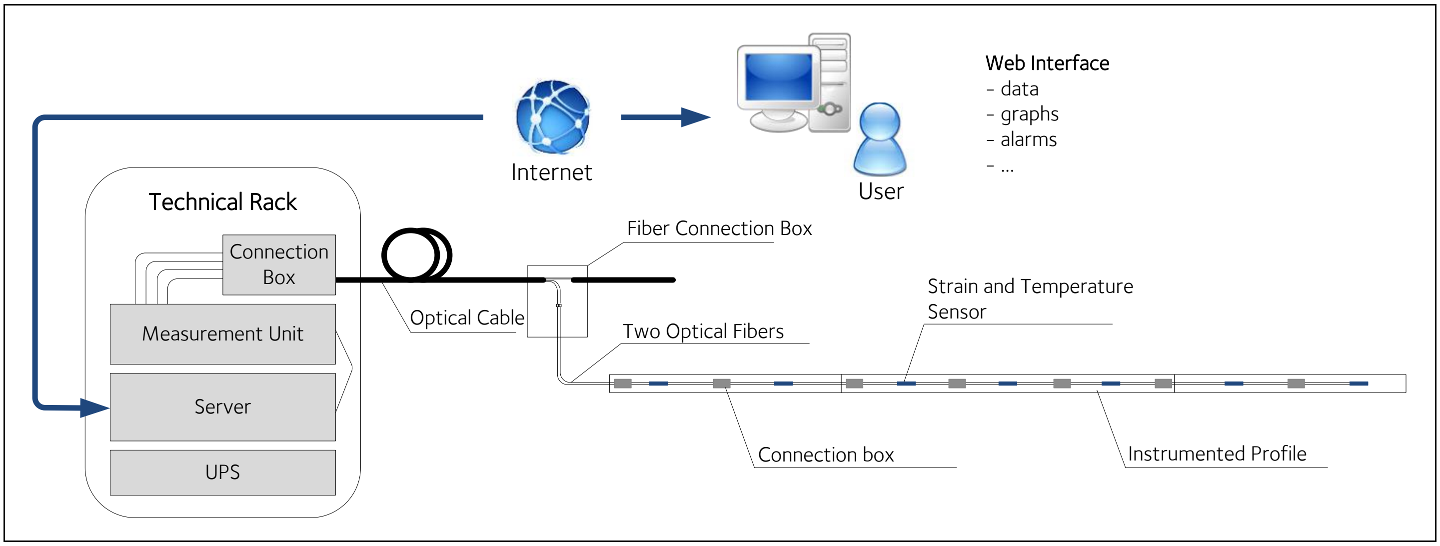

Fig. 45: System architecture on São Paulo Metro Tunnel application

Web interface

A specially designed web interface allowed data search, visualization and download from any other computer with internet connection. Alarms could be configured and e-mail messages were sent every time an alarm event occurred.

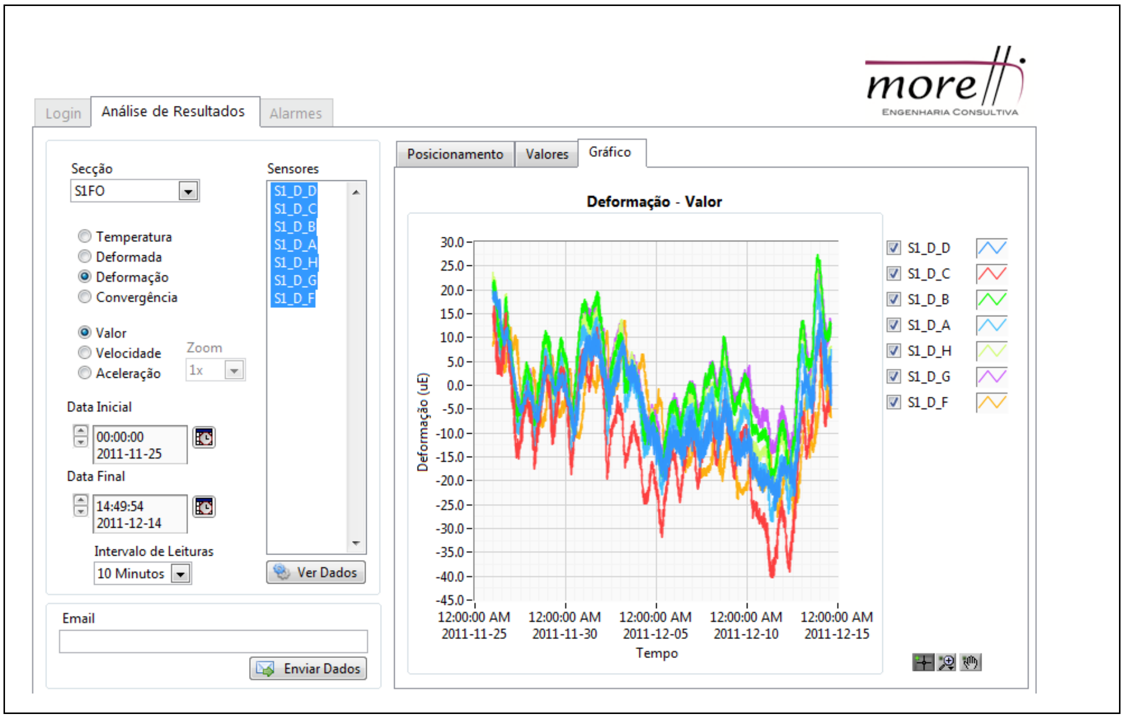

Fig. 46: Data search on the web interface

Stored data could be seen in the form of time graphs, xOy representations or numerical tables. In Table 1, the stored measurable values are presented.

Measured Values	Representation Units
Strain	Microstrain (µm/m)
Velocity of Strain Variation	Microstrain per day (µm/m/day)
Acceleration of Strain Variation	Microstrain per day^2 (µm/m/day^2)
Temperature	Degree Celsius (ºC)
Convergence	Millimetre (mm)
Velocity of Convergence	Millimetre per day (mm/day)

Acceleration of Convergence	Millimetre per day^2 (mm/day^2)
Coordinates	Meter (m)

Table 1: Measured values and units

All values, except for the coordinates, are represented throughout a time period set between two defined instants for the search.

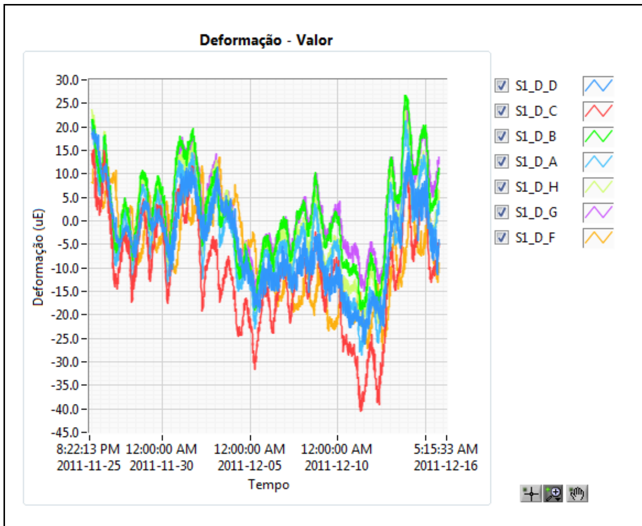

Fig. 47: Time horizontal axis

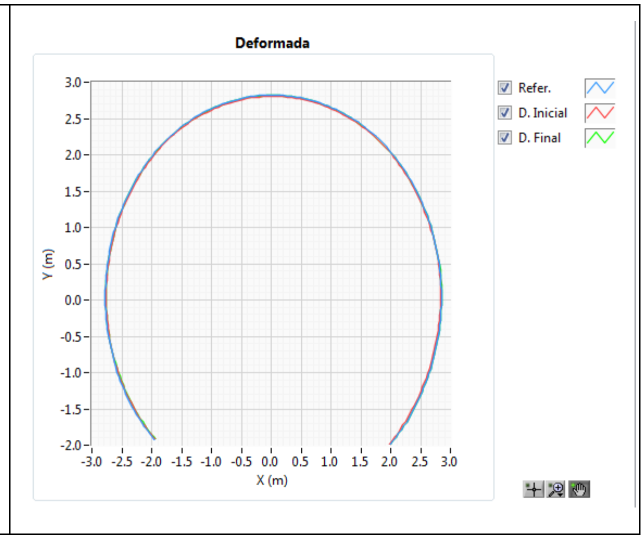

Fig. 48: xOy graph

Two types of alarms were generated. Non-configurable alarms, which correspond to a system malfunction, and Configurable alarms, which correspond to measured values. Administrator users can define alarm values for all positions of strain and convergence measurements, as well as for their velocity and acceleration.

Installation

The installation of the SysTunnel System on the Metro de S. Paulo was very similar to the one performed at the Rossio Tunnel in Portugal.

<u>Production</u>

Since the tunnel perimeter was around 12 m, it was necessary to divide the profile into smaller bars for transport, production and handling purposes.

Each instrumented section had seven weldable strain sensors for strain measurements and seven weldable temperature sensors for compensation of the temperature effect on the strain measurement.

The installation of the sensors on the bars was performed in industrial facilities in São Paulo, Brazil. The sensors were spot welded to the metallic bars and subsequently protected from moisture and mechanical impacts. One temperature sensor was installed next to the strain sensor. After the moisture protection tape application on top of the sensors, a protective stainless steel cap was directly welded to the structure by means of the same hand-probe spot welder. From this cap, input and output fibers enter and exit it, being already protected with 3 mm PVC buffer with internal stainless steel coil [7].

A connection box was placed between each sensor, and welded to the bar. Junctions that were performed during production were fusion spliced; those which were to be performed during the installation of the profile on the construction site were joined with connectors. This way, every bar was an array of sensors with only a few connectors to be joined together inside the tunnel.

Fig. 49: Welding of sensors

Fig. 50: Protected sensors

In Situ Installation

The system installation inside the tunnel was performed during the night, when the metro line was not operational. This meant an opening of four working hours. The main challenge of this installation was the planning in order to have all tasks completely performed at the end of each intervention, assuring total security conditions for a normal metro line operation.

Since the instrumented profiles were glued to the surface, the surface at the section locations had to be cleaned to remove dust and grease from the tunnel wall.

Afterwards, the vertical positioning of the section was marked and provisional supports were installed. The instrumented bars were lifted and hanged on the supports. Screwed connections were used to join the three instrumented parts. Optical interconnections between bars were performed and verified for wavelength and signal power using a FS42 Portable BraggMETER.

Fig. 51: Profile transportation

Fig. 52: Profile connection

Fig. 53: Fiber connections

Fig. 54: Optical cable box

The different tasks were organized per day as follows:

- Surface cleaning and installation of the provisional supports;

- Profile physical connections and sensor optical connections;
- Profile gluing and optical connection to the multi-fiber optical cable.

The acquisition equipment was installed outside the tunnel, meaning that work could be performed during the day. A technical rack was installed in a room at the metro station.

Fig. 55: Technical room

Fig. 56: 19" rack

The interrogator was connected to a Server PC where the application was running to control it, process acquired data and store it in database. A second software application granted the remote access to the saved data. This web interface represented data in graphics and values for user defined time intervals and allowed their exportation via e-mail.

System Usage Experience

During the most critical stages of the building construction, the system was kept online and measuring continuously. The SysTunnel was only a parcel of a complete monitoring system that included conventional surveying methods to access other effects of the construction, such as settlements, inclinations,…

On the first months - since Nov/2011 to Mar/2012 - corresponding to the execution of the first five levels of anchors, the recorded values ranged from 0 to ± 1 mm and very low levels of deformation were registered as well [8]. However, the advance to deeper levels with higher loads was reflected in the state of deformation of the tunnel's surrounding soil.

Data	Hour	Strain Values (με)	Excavation Level
22-Mar	10:00	-13,08	6th
25-Mar	23:00	-79	6th
27-Mar	09:00	-179	6th

05-Apr	22:00	-216	6th
11-Apr	13:00	-273	6th
11-Apr	14:00	-305	6th
11-Apr	15:00	-599	6th
11-Apr	16:00	-735	6th
13-Apr	14:00	-746	7th
13-Apr	15:00	-821	7th
24-Apr	14:00	-840	8th
05-May	19:00	-1000,79	8th
30-Sep	16:00	-894	8th

Table 2: Deformation state evolution of sensor G from "string" 4 (Horizontal) of SFO2 (2012)

Table 2 presents the strain values for the strain sensor from the horizontal convergence direction (represented in green in). SFO2 is one of the two monitored sections, and corresponds to the one that is closest to the construction.

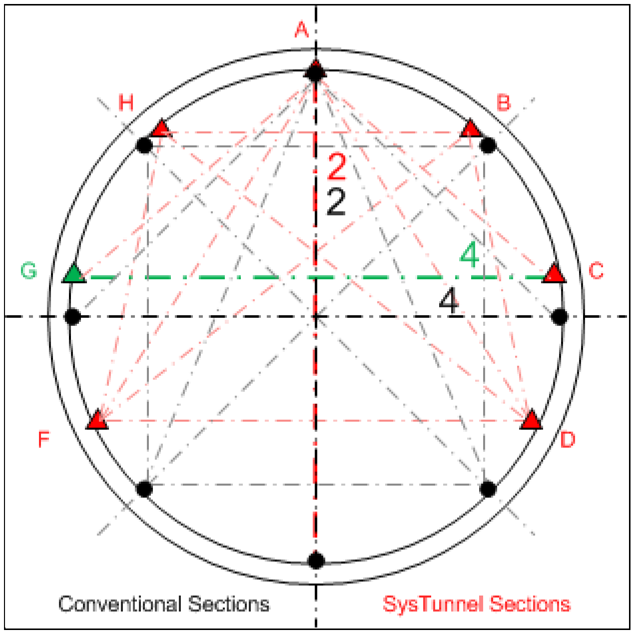

Fig. 57: Sensor positioning on SFO2 (2012)

On April 11th 2012, the strain rate reached significant values by tripling its value in only 3 hours. In addition to this strain analysis, it was verified that the conventional values exceeded the alert limit of 12 mm on 4 sections, with the greatest incidence in string 4 (horizontal) and 2 (vertical) of the tunnel. With this, there was a widening of the horizontal section and a narrowing of the vertical section. All the other measurements were in line with the measured behaviour.

The comparison of the horizontal and vertical convergences between the conventional (CC3 and CC6) and the fiber optic (SF01 and SF02) showed the same trend but with different convergence values (see

Table 3 and Fig. 57).

	Section 1		Section 2	
	SF01	CC3	SF02	CC6
String 4 (H) (mm)	1,6	8,14	4,38	14,33
String 2 (V) (mm)	-0,33	-3,92	-0,25	-12,51

SF: fiber optic

CC: conventional

Table 3: Comparison of convergence values of conventional and remote monitoring.

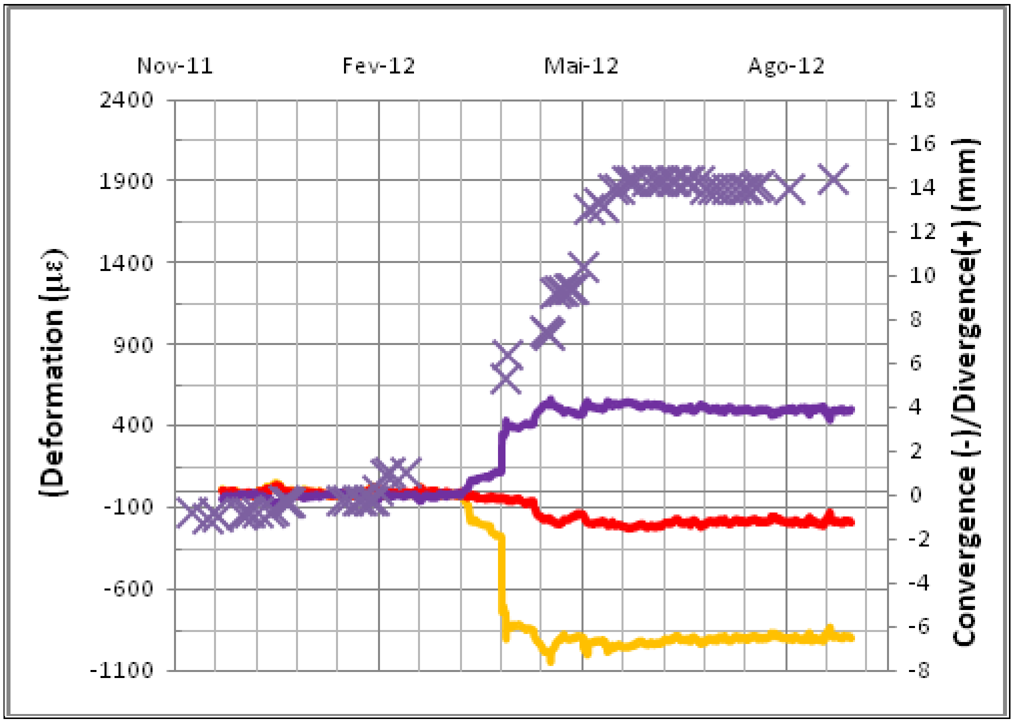

Fig. 58: Evolution of deformation on sensor (C,G) from string 4 and convergence of the "string" 4 of SFO2 and CC6

The differences found between conventional convergence measurements and the estimated by the SysTunnel, as shown in Table 2 and in Fig. 58, can be explained by several factors:

- Human error
- Accuracy of equipment
- Method for temperature compensation in both instruments
- Location of sensors in concrete rings
- Empirical component on the SysTunnel algorithm for calculating the radial displacements.

Despite the significant differences in the values of convergence it should be noted that these are obtained from data recorded punctually. Moreover, it was the sudden evolution of values that allowed the team of engineers to set off the alarm prior to what was scheduled, which resulted in a temporary stop of the excavation and anchoring to ascertain the implications of this change in the deformation state.

7 Conclusions

The use of the SysTunnel has been proven successful for different application scenarios:

It is appropriate for long term monitoring as well as for usage during short periods when monitoring is required. One of the main characteristics that make the system well suited for the presented applications is the fact that measurements can be taken during regular traffic inside the tunnel.

On the two presented application examples, important lessons were learned:

1. A normal behavior of a structure during its long term operation corresponds to the seasonal evolutions of the deformations over time. The main concern appears when there are variations that fall out of this pattern.

2. For a flexible structure under operation, where major changes on the surrounding area were happening, the use of an automated system with alarm generation was decisive into procedure.

3. The remote system allows the measurement control to be made during regular operation of the structure meaning that alarms values can be detected at any time.

4. The system can only estimate convergence values. Nevertheless, it determines strictly the structures movement in terms of relative magnitude and variations which are found to be the most important information for alarm generation.

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