MONITORING SYSTEM OF THE LANDFALL MICROTUNNEL BY BRAGG TECHNOLOGY

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ABSTRACT

The scope of the present paper is to describe an innovative system and methodology for the monitoring of the **structural integrity of a Microtunnel (MT)**, built for the Trans Adriatic Pipeline (TAP) at Italian sealine landfall.

TAP is the last portion of the gas pipeline that brings gas from new sources in the Caspian region to Western and South-Eastern Europe.

The offshore pipeline system consists of an approximately 105 km long offshore pipeline, with landfalls in both Albania and Italy. The Italian pipeline landfall is on the coast of Apulia Region in the municipality of Melendugno.

The Italian landfall has been realized through the **MT technology**, which allows the installation of the pipe without "**open pit" trenching**, thus minimizing the impact on the coastal environment.

The tunnel laying is performed by an innovative Tunnel Boring Machine (TBM), namely a guided remote-controlled milling shield.

The **TBM** is pushed into the ground and is completed with several hydraulically sealed cylindrical pipes (made of pre-compressed reinforced concrete) of 2400/3000 mm of internal/external diameter. All the single segments merge in a unique continuous tunnel, which houses the gas pipeline. After completion the pipeline remains flooded in seawater in the MT.

According to requirements of maintenance plan and **firefighting measure**, a proper periodic check of the MT was required to prove the MT integrity and avoid any obstruction to the gas venting. It was therefore proposed an innovative methodology for monitoring the structural integrity of the MT based on a network of **optical fiber cables** (defined "**sensing cable**") in which both strain and temperature sensors are embedded. These sensors have been realized through **Bragg technology**.

The measurements are based on the monitoring of the axial extension to which a series of strain sensors, embedded in the optical fiber cables, should be subjected in case of MT collapse.

Such chain of sensors is properly constrained on the MT internal surface, between specific fixed points realized on the concrete cylindrical segments.

The details on the design, the materials selection, the installation and the monitoring methodology are reported in the paper.

INTRODUCTION

TAP is the last portion of the gas corridor connecting the Caspian region to Western and South Eastern Europe. The pipeline system comes ashore in Southern Italy, where it is buried in a Microtunnel, 1540 meters long, below the coastal surface of San Foca (Lecce). TAP Microtunnel is composed by several cylindrical pipes made of pre-compressed reinforced concrete, merged in a unique continuous tunnel, which houses the gas pipeline and is flooded in seawater. This underground infrastructure requires the monitoring of structural integrity and early warning of anomalous conditions, as indicated by the Local Authorities' prescriptions, that request the adoption of proper methods to perform the periodic check of Microtunnel tensional state. However, sensors traditionally used for structural changes detection, such as vibrating strain gauges or resistance gauges, present strong limitations for this specific application, mainly due to electric isolation issues in an underground, flooded environment. Moreover, electrical sensing is more subject to deterioration over time due to usury and corrosion phenomena.

FBG (Fiber Bragg Grating) is an innovative, on rise technology, whose operating principle is totally different from conventional electrical sensing. In fact, since reflected light is used as signal carrier, it is not affected by electromagnetic and radio frequency interference. It is intrinsically safe in case of hazardous and severe environments and is not subject to corrosion. Moreover, FBG is characterized by inherent multiplexing capacity and long-distance transmission and it is able to provide absolute measures, with no need for reference signals or calibration procedures. All these advantages make this technology very suitable for long-term monitoring of TAP Microtunnel structural integrity.

FBG TECHNOLOGY FUNDAMENTALS

A Fiber Bragg Grating is a microstructure, photo inscribed in the core of a single mode optical fiber. This microstructure changes the physical characteristics of the core and generates a spatial periodic modulation of its refractive index. The effect is that when a broadband light passes through the grating, FBG behaves like a selective band filter: a very narrow range of wavelength is back-reflected, while remaining light spectrum continues to propagate down the fiber.

The maximum reflectivity occurs in correspondence of the *Bragg wavelength* λ_B, obtained by the following mathematical relationship:

$$\lambda_B = 2n_e\Lambda \qquad (1)$$

where n_e is the effective refractive index of fiber transmission mode and Λ is the grating period.

The Equation (1) implies that wavelength λ_B is affected by physical and mechanical modifications of FBG region. As an example, strain can cause a variation of Λ and n_e via a displacement of the grating period and the stress-optic effect; the same is for temperature change, that leads to variation of n_e and Λ through thermo-optic effect and thermal expansion.

The relation between *Bragg wavelength* λ_B and variation in temperature and strain is expressed by Equation (2):

$$\Delta\lambda_B = \lambda_B\,(1-\rho_\alpha)\varepsilon + \lambda_B\,(\alpha_f+\xi)\Delta T \quad (2)$$

where $\Delta\lambda_B$, ε and ΔT are respectively the change in *Bragg wavelength*, strain and temperature; ρ_α is the elasto-optical coefficient of the fibre material; α_f and ξ are the thermal expansion and thermo-optic coefficients of the fibre.

As a result, if an FBG is subject to thermal or mechanical variations, this information can be measured by acquiring the changes in back-reflected spectrum of the FBG sensors in order to obtain ε and ΔT.

FBG APPLICATIONS

Since the FBG technology was developed [1][2], the potential and benefits it could bring to numerous engineering fields were immediately clear, as for example structural and civil engineering, geotechnical engineering, control system and maintenance. In fact, Bragg technology has inherent peculiarities making it effective in solving different measurements problems: immunity to electromagnetic interference, corrosion and humidity resistance, long-distance transmission, minimum thermal drifts and high life cycles, no need for calibration procedures and power supply (except for the interrogation unit), multiplexing capability.

For these reasons, FBGs have been extensively used in many application fields.

In 1990, Mendez et al. [3], firstly applied this technology to monitoring of concrete structures and since then the employment of FBG for strain, stress, temperature analysis of bridges, tanks, dams has increased [4][5], considering that this technology overcomes some difficulties associated with embedment and installation and meets successfully the necessity to have several measurement points over very long distances.

FBG sensing also counts several geotechnical applications: *Lin et al.* [6] set up a real-time FBG system for local scour monitoring; moreover, this technology was employed to detect the position of landslides slip surface and monitor landslides internal deformation [7].

Bragg technology also is very suitable for deepwater applications: in Oil & Gas sector *Brower et al.* [8] have designed a real time monitoring system for subsea pipelines and facilities based on FBGs for early problems detection and proactive intervention. This technology was chosen because of its electromagnetic interference immunity, corrosion resistance, ease of use and handling, and minimum attenuation over long distances.

It is therefore clear that Bragg technology is well suited for permanent monitoring applications over several years and that semi-distributed strain sensor of Bragg gratings (henceforth referred to as "sensing" cable) is the ideal solution for any application where a large number of measuring points over long distances is required.

DESIGN OF STRAIN MONITORING SYSTEM

Components and Materials

In order to verify the structural integrity of TAP Microtunnel and, consequently, the absence of yielding that could cause obstructions of Microtunnel venting devices, the technical approach adopted is based on the monitoring of the axial extension of strain gauge embedded in a fiber optic cable, suitably bound on the inner surface of the Microtunnel between specific fixed points (support clamps) integral with the concrete cylindrical blocks.

The monitoring system is composed by optical cables, properly pre-tensioned between two fixed points (henceforth referred to as support clamps), arranged every 18 meters along the MT length. A single optical fiber can be accompanied by tens of sensors connected in series, significantly reducing weight and size compared to similar sensors based on electrical technology, each requiring dedicated wiring. This peculiarity allows to structure even hundreds of meters measuring chains.

The configuration of a single pre-strained optical cable is reported in Fig. 1.

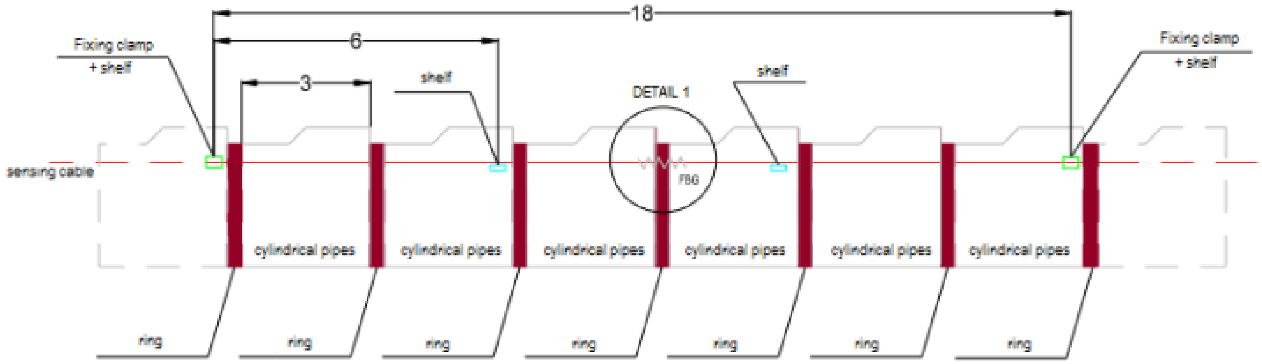

Fig 1: Sensing cable configuration

The optical cable is fixed to the inner surface of Microtunnel by using tensioning clamps integral with concrete blocks every 18 meters and is supported every 6 meters by proper support shelves. Both the tensioning clamps and the support shelves are designed for marine application (Fig. 2): several tests have been performed on the prototypes in order to prove the installation time and the final adhesion resistance on a similar wall to Microtunnel inner surface on wet conditions (Minimum test temperature of 14 °C; maximum test temperature of 20 °C; average humidity 69 %).

Therefore, after market survey to find materials suitable for the structure and relevant installation supports, having excluded the use of Inox 316L steel either coated or protected by small sacrificial anodes, ABS (Acrylonitrile-Butadiene-Styrene) plastic structures have been selected to be installed on the MT wall by use of bi-component Marine Epoxy Resins as stable glue. Since market survey results have not identified a suitable solution, it has been decided to manufacture clamps and supports by 3D printer.
Tensioning clamps and shelves are shown in Fig. 2.

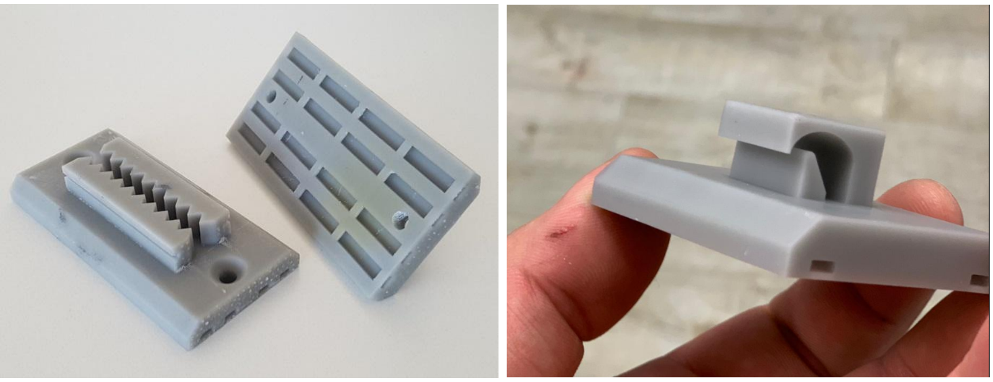

Fig 2: Tensioning clamps (on the left) and support shelf (on the right)

Fig 3: Application of two-component resin on the support shelf

Installation

The installation layout consists of nos. 4 sensing cables installed along the entire length of the MT and an interrogation unit, to be installed in a 220 V powered monitoring cabinet.

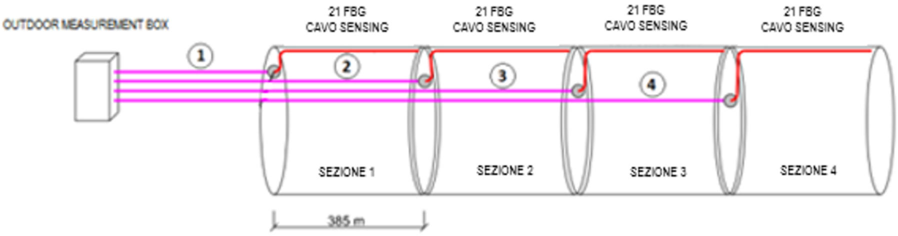

Fig 4: Microtunnel monitoring system layout

Therefore, clamps and shelves (14.00 clock orientation, watching towards sea) are placed within the MT structure by use of an electric tractor (Fig. 5).

Fig 5: Electric tractor preparation for clamps and support shelves positioning

Fig 6: **Sensing cables Reel for unrolling fiber optic cables (on the left) and sensing cables installation completed (on the right)**

As depicted in Fig. 4, each cable consists of a 21 Fiber Bragg Grating (FBG) sensors array spaced every 18 meters and written in the core. The outer layer of cables is made of Glass Fiber Reinforced Polymer (GFRP) coat which protects the gratings and ruggedizes the structure to increase its integrity and stability. Technical specifications of sensing cables are reported in Tab. 1.

Tab. 1: Sensing cable specifications

Parameter	Specifications
GFRP Cable Diameter	2 mm
Strain Sensing Sensitivity	~0.7 pm/με
Temperature Calibration Constant for -20C to 120C	~17 pm/°C

Material	GFRP
Weight	7,8 g/m
Tensile strength for OD=1 mm	>1100 MPa
Young Modulus	>50 GPa

Each cable covers approximately 385 meters of the Microtunnel length and is pre-tensioned every 18 meters and fixed to its inner surface through the clamps and support shelves.

Monitoring methodology

Optical cables are connected to the acquisition channels of the interrogation unit, located outside the Microtunnel, in a 220 V powered measurement cabinet (Fig. 7).
The interrogation unit is a swept wavelength fiber laser, capable of scanning a wide range of wavelengths at a configurable cycle time, up to 1 Khz.
By considering that each strain sensor is uniquely identifiable through its characteristic wavelength, and that it is associated with a progressive position along the Microtunnel length, it is then possible to correlate reflected wavelength peak shift to the specific position of the grating.

Fig 7: Microtunnel strain monitoring cabinet

In Fig. 8 spectra peaks of a sensing cable FBGs acquired during start-up of monitoring system are shown.
Raw data acquired by the interrogation unit are converted in strain and temperature measurements, that can be recorded, analyzed and correlated with displacement, hence highlighting the MT internal state. In particular, considering that the upper bound of each FBG sensor is + 10000 με and that strain sensors are arranged and constrained between fixed points (support clamps) every 18 meters along the MT length, the maximum detectable deformation is + 18 cm.

Data Interleave: 10

CH 1: 0.25 nm Peak (128)
CH 2: 0.25 nm Peak (128)
CH 3: 0.25 nm Peak (128)
CH 4: 0.25 nm Peak (128)

Peaks: 21
Peaks: 0
Peaks: 0
Peaks: 0

Total Output Rate (kb/sec): 0,00 (0 / 0 Active)
Total File Count: 0
Remaining: ----- days (78,67 / 237 GB)

Fig 8: Spectra peaks of FBG sensors Bragg Wavelength

Fig 9: Monitoring system tests during installation

During strain monitoring activity, foreseen every six months, strain data values will be archived and compared to baseline values, i.e. strain measurements acquired at the completion of construction and commissioning activities (Fig. 10).

For evaluation of MT integrity, strain changes will be analyzed in order to discriminate between variations attributable to anomalous changes in infrastructure stability and negligible variations introduced by changes in Microtunnel environmental temperature and normal relaxation phenomena occurring between Microtunnel concrete cylindrical blocks.

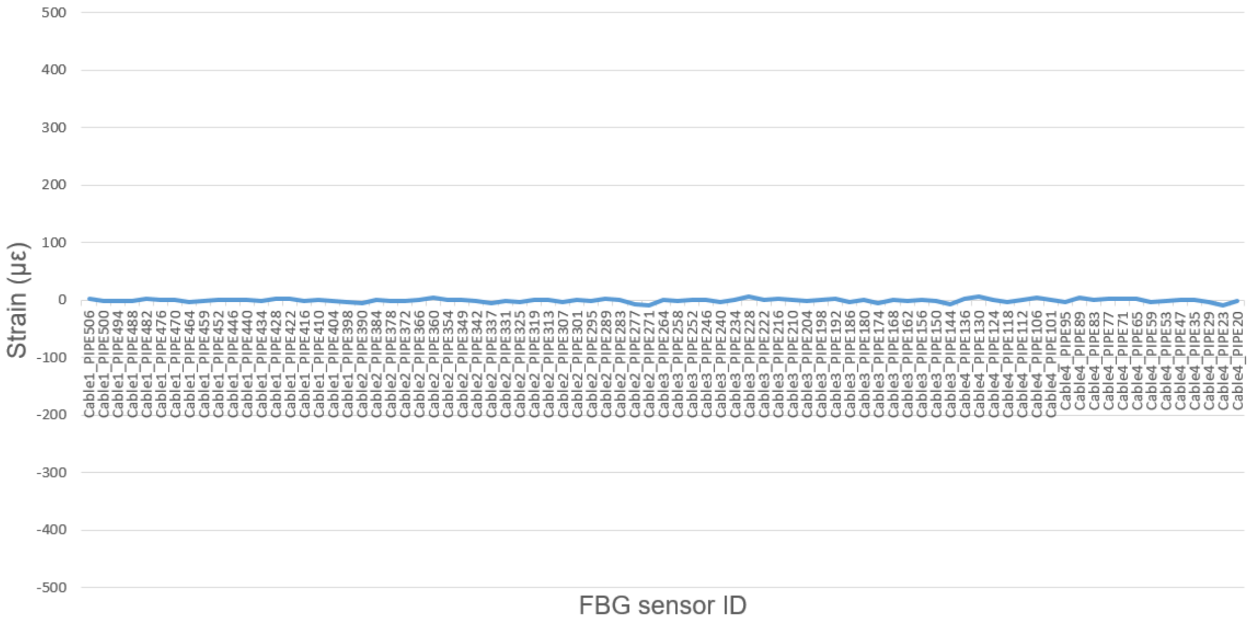

Fig 10: Microtunnel baseline values

CONCLUSIONS

Fiber Bragg Gratings (FBG) technology was used to design and install an innovative sensor network aimed to monitor the structural integrity of the underground tunnel construction (Microtunnel), built at the landfall of the Trans Adriatic Pipeline (TAP), sited in Melendugno (Lecce), along the Apulian coastline in Italy.

The measurements of the Microtunnel tensional state are conveyed from field sensors to the remote-based acquisition unit, thus allowing a reliable, periodic check of dataset values, in accordance with the maintenance plan and the firefighting measures to be adopted.

Compared to conventional electrical sensing, FBGs is particularly suitable for this specific field application. In fact, no electronic component is installed underground, thus avoiding issues associated with electrical isolation, interference immunity and signal attenuation. Another benefit of FBGs is their long-term tolerance in harsh environments because of fatigue durability and resilience to moisture. Moreover, sensing cables installed embed several gratings on the same optical fibre, which reduces the complexity of the monitoring system architecture since the acquisition unit, located outside, can simultaneously interrogate sensors with multiplexing capability.

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