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Line C in Rome: Strain measurements in precast TBM lining segments using embedded Smart Wireless Monitoring System

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ABSTRACT: Line C is the third line of the Rome underground system. The T3 stretch is presently under construction: it runs for a length of about 2.8 km right underneath the historic city center of Rome. Two EPB TBMs with a 6.70 m cut diameter are being used to excavate the tunnels at a depth between 30 and 60 m below the ground level. Strain and temperature measurements have been acquired to collect data in continuous mode, starting from the early curing stages. Wireless and low power consumption data-loggers and vibrating wire strain gauges, both embedded in each segment of the instrumented ring, allow remote monitoring of all the main events in the TBM lining, without any interference with the ordinary underground activities. In order to check the strain behavior of the lining, single instrumented precast segments were tested through special full-scale loading tests.

1 INTRODUCTION

1.1 *Line C – Rome Underground*

Rome's Line C subway, under construction by General Contractor Metro C S.c.p.A. since 2007, is a fully automated underground railway line characterized by an automatic train control system. The line, with its 30 stations, crosses the Capital from the south-east side to the north-west area stretching over a distance of 25,6 km. The construction of Line C will almost double the area covered by the current underground network and it represents one of the most important works ever built in an urban context. The first part to the city center, in operation and under construction, develops for 21 km, 8.5 above ground and 12.5 underground, with a total amount of 24 Stations. The underground part has been excavated by EPB TBMs with a 6.70 m cut diameter, at a depth between 20 and 60 m from ground level.

1.2 *The under construction T3 Stretch*

The T3 Stretch, presently under construction, runs for 2.8 km from San Giovanni Place to Venezia Place in a heavily urbanized area and below extremely important historical monuments (it is an UNESCO World Heritage Site; Figure 1). Twin tunnels are located at a depth between 30 and 60 m below the ground level.

The monitoring system has been designed to provide all the elements necessary to perform an analysis of the interaction between works in progress, the surrounding soil volumes and the anthropic preexistences, in the most complete and quick way.

Instrumentation is organized in monitoring sections distributed along the metro line. The distribution criteria, typology and geometry of monitoring sections is function of the specific contour conditions along the stretch: geotechnical features of the soils, preexisting buildings and monuments, tunnels depth etc. The following Figures 2, 3 and Table 1 show a typical full

Figure 1. An example of interaction between Line C and historical monuments.

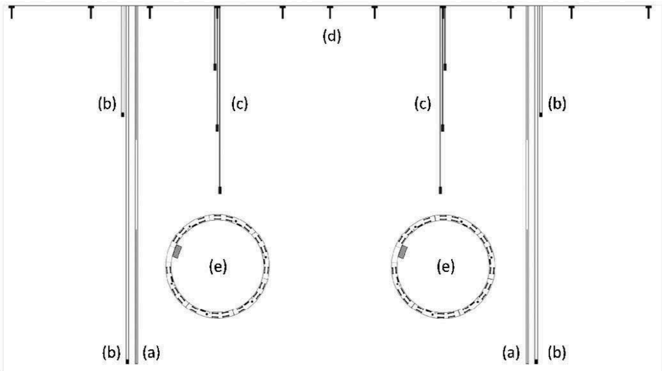

Figure 2. Tunnel line - Typical full monitoring section. Inclinometer (a); Piezometer (b); rod extensometer (c); leveling pin (d); instrumented ring (f).

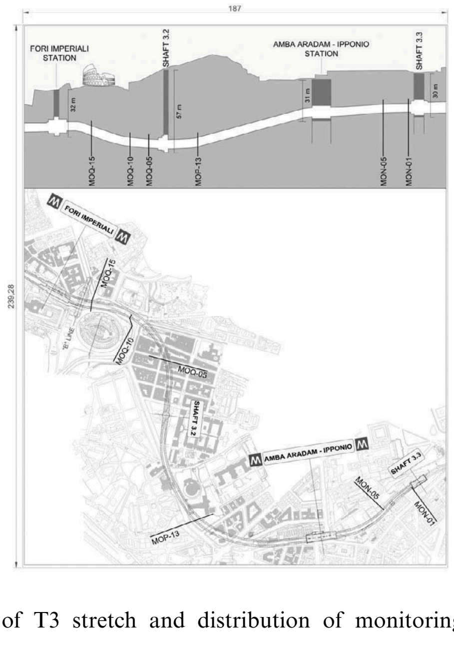

Figure 3. General layout of T3 stretch and distribution of monitoring rings in the tunnel lining (Table 1).

Table 1. T3 Stretch – Monitoring rings of TBM tunnel lining.

Monitoring section	Even Track	Odd Track	Head
Name	km	km	m
MON-01*	0+209,916		23,97
MON-05*		0+350,367	26,32
MOP-13	1+168,100	1+126,680	44,86
MOQ-05	1+855,363	1+804,772	42,00
MOQ-10	2+069,557		33,19
MOQ-15	2+230,238	2+214,201	27,15

* Monitoring rings installed at the date of this paper.

monitoring section of TBM line with a couple of instrumented rings inside the tunnel lining, and its distribution along the T3 Stretch of the Line C.

2 MONITORING OF TBM LINING

The past experiences gained during the construction of the Line C tunnels, with the installation of over 60 segmental lining rings instrumented with vibrating wire strain gauges, and the current integration with the most modern technologies of communication and data transmission, has allowed to refine the methodology of structural monitoring for the TBM tunnel linings of the T3 Stretch. At the same time, this new monitoring system provide important information to the project design, making possible the acquisition of the deformation history of the structures continuously: from the preliminary phases of concrete casting and maturation up to the operation phase of the metro line.

2.1 *The Smart Wireless Monitoring System (SWMS)*

The Smart Wireless Monitoring System (SWMS) is a structural monitoring system applied to the deformation control of TBM tunnel linings, specially designed and realized to achieve the following goals:

- Eliminate any operational interference with ordinary underground operations, during the installation phases. All the workings have been completed in the precast segment factory,
- Record and transfer monitoring data (ε and T °C) during all the main phases of the structure: from the early construction stages and the curing stage at the manufacturer stock place till the assembly in the tunnel during ring erection, advance of the TBM and tail grouting. The system has been designed also to analyze long-term behavior of the tunnel lining,
- measurement certainty through redundant systems to ensure data access.

The SWMS experimental system, applied for the first time in Metro C to the instrumented rings of the T3 Stretch, consists of (Figure 4):

- Monitoring devices embedded in each segment (radial and longitudinal strain gauges),
- WDG – peripheral wireless data-loggers installed in the inner face of each segment,
- GTW – gateway. Data gathering, storage and export base-station for each instrumented ring.

The peripheral data-loggers acquire physical data by sensors, that are recorded in the integrated memory, and transmitted to the base-station in wireless mode. Data-loggers continue to sample also without radio coverage; indeed they are able to store up and transmit the data packets when the coverage becomes available again.

The gateway can be equipped with different communication solutions, which allow remote visualization and download data from the tunnels. (e.g. radio network, cable, fiber optic etc.).

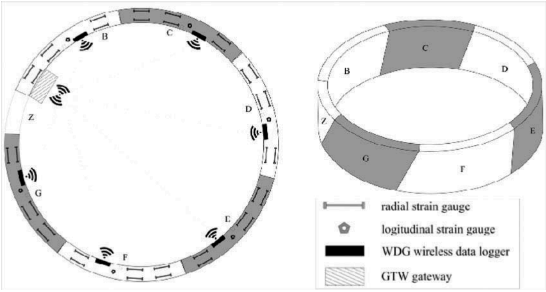

Figure 4. Instrumented ring with Smart Wireless Monitoring System (SWMS).

2.2 *Instrumentation layout*

The deformation measurement in the segments of the tunnel is performed by vibrating wire strain gauges anchored to the steel reinforcement of the monitored structure. These instruments allow to monitor the strain state in the lining rings and their interaction with the surrounding soil.

Each strain gauge has a built-in thermistor to provide temperature information for thermal corrections and at the same time to follow the thermal behavior after the casting phase of the segmental tunnel lining.

Each lining ring (5.80 m internal diameter and 30 cm thickness), is made up of n. 6 segments beyond the key element (Figure 4). In the instrumented rings, each segment, excluding the key, is instrumented with n. 6 radial vibrating wire strain gauges. Another one is positioned longitudinally, to check the thrust cylinders effect during the installation phases of the ring, for a total of n. 42 strain gauges.

The automatic data acquisition system consist of peripheral wireless data-loggers (WDG), installed in the inner face of each segment and deputy to acquire physical data by sensors (Figure 6). The WDG unit is designed to be customizable for different projects, in terms of number and type of sensor signals.

The data acquisition unit is contained in a plastic box with a high protection degree. The cap of the box, equipped with screws and O-ring closing, can be opened by the inner side of the segment (detail a in Figures 5, 6). The box shape is compatible with geometric gaps of the segment reinforcement. The box is equipped with only one input, connected to a junction box by multicore cable. The junction box is IP68 and contains multiplexer where all the signal cables of the embedded instruments are connected (detail b in Figure 5).

The WDG system is equipped with a waterproof safety box directly connected to the junction box (detail c in Figures 5, 6). This secondary access allows to communicate via cable between data-logger/gateway when the wireless connection does not work (e.g. underwater segment). At the same time, the gateway via this cable is able to power the peripheral data-logger inside the segments (e.g. over battery life). Both the accesses in the inner side of the segment are closed with quick-setting cement, to allow the right working of the suction plate of the erector during the installation phases of instrumented ring (Figure 7).

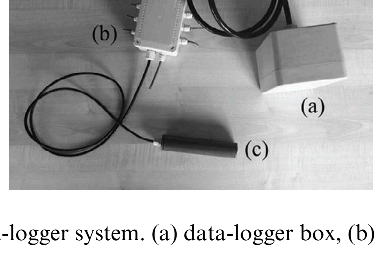

Figure 5. WDG - Wireless data-logger system. (a) data-logger box, (b) junction box, (c) safety box.

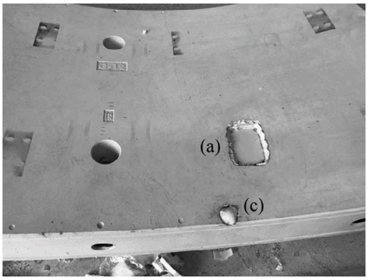

Figure 6. Inner side of instrumented segment. (a) access to data-logger box, (c) access to safety box.

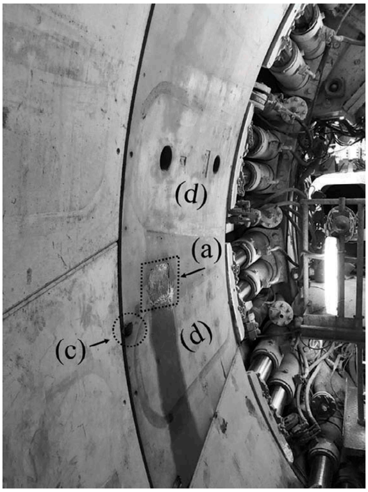

Figure 7. Installation of instrumented ring. (a) datalogger box, (c) safety box, (d) suction plate footprints of erector. Dotted areas indicate the cementation of monitoring boxes access.

The receiving unit (GTW - gateway), one for each instrumented ring, will manage all the peripheral wireless data-loggers embedded in the segments (Figure 4). The gateway is a datalogger equipped with a radio in coordinator configuration and an embedded Linux computer with a solid state hard disk, to provide customizable advanced network services and connectivity such as FTP server, modem, fiber optic or cable, according to the site needs. The gateway can be directly powered when is in continuous configuration, or equipped with a battery and a timer to temporarily acquire data (e.g. 1 hour a day) by the site.

2.3 *Monitoring data*

The first part of TBM twin tunnel excavation in T3 Stretch, about 400 meters long from 3.3 Shaft to Amba Aradam – Ipponio Station (Figure 3), has been completed in the begin of August 2018 after two months of advancement for each of the two tunnel. In this area the first two experimental instrumented rings have been installed (Table 1), using the new Smart Wireless Monitoring System. These rings have been pre-cast in the factory in March 2018. Since then the WSMS System is recording in real time, continuously and in wireless mode deformations and temperatures of the TBM segmented lining, during the main phases of its work.

A full set of monitoring data is shown in Figure 8, where is collected the main strain behavior of the segmented ring MON-01, installed in the even track of the T3 stretch and with 24 m depth from ground level (Tab. 1, Figure 3).

For simplicity, only C, E and G segments data are presented, split up in longitudinal (b), intrados (c) and extrados (d) strain gauges (Figure 8). For each instrument group the average temperature is shown as well (dotted line). The main working phases are readable in the graph (a): TBM advance vs time, dates of concrete casting and assembly of instrumented ring.

Conventionally the strain is either positive (tensile), or negative (compressive). It is assumed that zero reading of strain gauges is the value recorded at the time of ring installation. All monitoring data are already corrected by temperature effects.

The first critical stage is recorded during the concrete casting (indicated by the dot line in Figure 8a), where the mechanical action of the concrete on instruments and its thermal release clearly influence all the measurements. More than three months elapse between the casting phase and the lining ring installation. In the first two months all the instruments register a general trend of compressive strain, around 200 με, probably related to the curing stage at the manufacturer stock place. In the last month and before installation, a general stabilization of the readings has been observed.

The example in Figure 9 highlight in a weekly window the main effects of the concrete casting on extrados strain gauges of the segments. At the beginning the measurements suffer an important offset caused by mechanical actions on instruments (casting, formwork vibrations), then they tend to stabilize after that concrete thermal effects ran out.

The second critical stage is related to the assembly of the segments in the tunnel during ring erection (indicated by the dash line in Figure 8a), advance of the TBM and tail grouting. In these steps and during the TBM advance, the segmented lining ring start to work recording a permanent strain until stabilization, that is function of the TBM face distance. After stabilization it is possible to analyze also long-term behavior of the tunnel lining.

The example in Figure 10 emphasize the strain behavior of the ring during and after the assembly stage in the tunnel. Data are focused on longitudinal strain gauges oriented towards the thrust direction of the TBM. The data show the cyclical noise of the TBM thrust, registered by strain

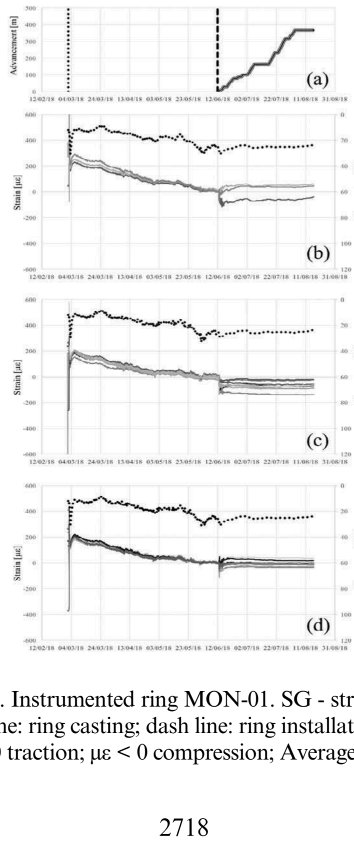

Figure 8. T3 stretch – even track. Instrumented ring MON-01. SG - strain gauges data of segments C, E, G (Figure 4). (a) Tbm advance, dot line: ring casting; dash line: ring installation. (b) longitudinal SG; (c) intrados SG; (d) extrados SG. Strain: με > 0 traction; με < 0 compression; Average temperature in dot line.

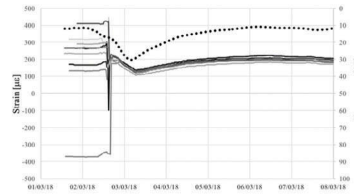

Figure 9. Extrados strain gauges. Zoom on the concrete casting phase and the beginning of curing stage. Average temperature in dot line.

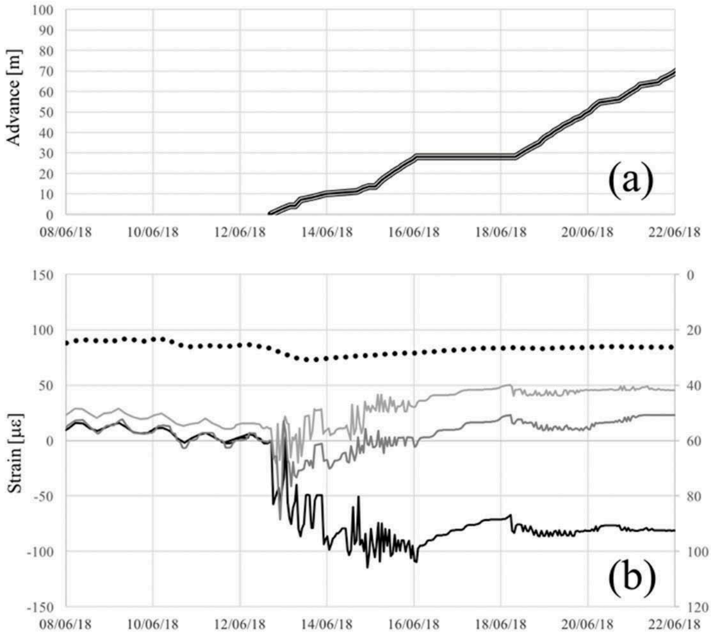

Figure 10. Longitudinal strain gauges. (a) Tbm advance; (b) emphasis during and after the assembly stage of the instrumented ring in the tunnel. Average temperature in dot line.

gauges with a sampling every 30 min. The thrust effects on lining rings tends to decrease with the distance, to become negligible over 30 m the TBM face (5 diameters).

The main stress is recorded after the early stages of the assembly, when the TBM face is less than 12 m to the lining ring (2 diameters). Beyond this distance, and until the completion of the first excavation phase, a general stabilization of the data on all the instruments is observed (Figure 8). With the last TBM breakthrough of Amba Aradam – Ipponio Station occurred on 03 August 2018, starts the long-term behavior analysis of the tunnel lining, currently under observation.

2.4 *Loading test on precast segments – preliminary results*

The behavior of precast tunnel segments, and the relations between load and first crack formation and the evolution of the crack opening, have been observed through special full-scale load tests. The experimental tests were carried out in the Material and Structure Laboratory of the Civil Engineering Department of the University of Rome "Tor Vergata", and affect any reinforcement class of the precast segments.

In order to check the behavior of the strain gauges under external stresses, a sample segment has been tested through a bending test (Figure 11).

The monitoring layout and the steel reinforcement class of the tested segment are the same of the instrumented ring installed in the tunnel lining (Figure 12). The bending test was performed by applying a normal force on the convex surface of the segment by hydraulic jack. The segment was placed on cylindrical supports and the load, applied at mid-span, was transversally distributed adopting a steel beam.

Loads were applied with increasing steps up to a maximum of 750 kN. During the load test all the development of cracking patterns has been studied (number, size, geometry, cracks opening vs load, etc.). The vertical displacements of the segment were measured with three potentiometer wire transducers (WDT), while two LVDTs (MDT) were adopted for measuring the cracks opening at mid-span in the inner side of the segment (Figure 11).

At the time of writing, laboratory results are not available yet, while the preliminary results of embedded strain gauges are plotted in Figure 13 (strain vs load) and Figure 14 (strain vs time).

The higher response is registered in the intrados side with the strain gauge SG36, located in the central part of the segment. The tensile strain increase with the stress until to about 2400 με for 750 kN (maximum load), and recording of 750 με of residual strain after the load is removed (Figure 14). A similar behavior is followed by SG40, but with a lower magnitude, recording the higher value around 900 με and about 400 με of residual strain (Figure 14).

The other instruments do not seem to react to the load increasing steps, particularly for those located on the extrados side of the segment. These instruments reply only after the maximum load, with a residual tensile strain probably related to the final cracking pattern (Figure 14).

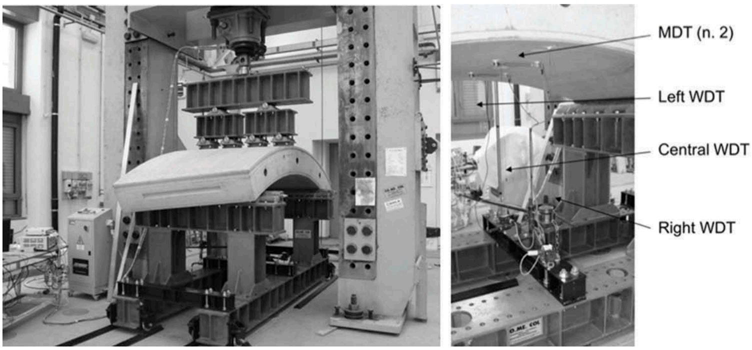

Figure 11. Full scale bending test on segments. Laboratory instruments: MDT – Mechanical displacement transducer (n. 2), WDT - Wire displacement transducer (n. 3)

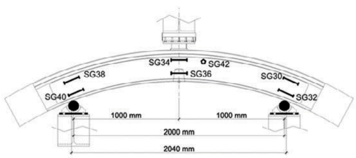

Figure 12. Instrumented test segment. Monitoring layout.

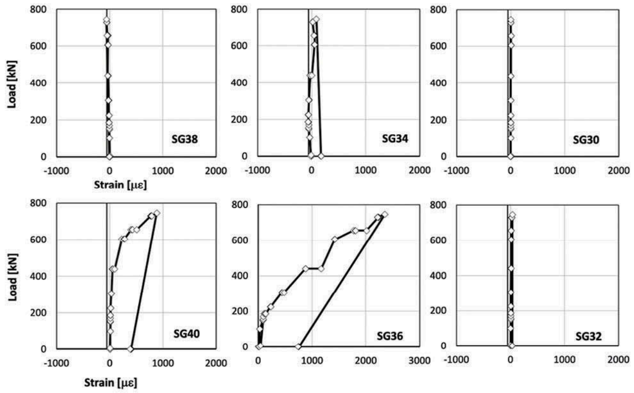

Figure 13. Bending test. Strain vs load diagrams.

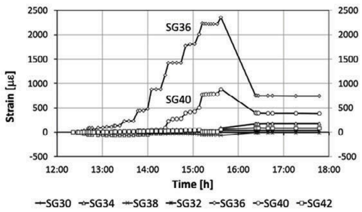

Figure 14. Bending test. Strain vs time diagram.

3 CONCLUSIONS

The current tunneling works for the T3 stretch of Line C of Rome Underground have provided the chance to test the strain behavior of the segmental pre-cast lining using the experimental embedded Smart Wireless Monitoring System (SWMS).

The SWMS is a structural monitoring system with low energy consumption, specially designed and realized to achieve the following goals:

- Eliminate any operational interference with ordinary underground operations, during the installation phases of the lining. All the workings have been completed in the precast segment factory,
- Record and transfer monitoring data (ε and T °C) in continuous mode during all the main phases of the structure: starting from the curing stage at the manufacturer stock place and followed by the main events until the instrumented ring was set in place in the tunnel, performing also long-term behavior analysis of the tunnel lining,
- measurement certainty through redundant systems to ensure data access.

Referring to the last tip, the SWMS System introduce new solutions designed to guarantee data access in any environmental conditions: a) wireless mode, b) via cable through the safety box (direct access to embedded data-logger), c) via multicore cable behind the data-logger box (direct access to embedded instruments).

Data analysis show that every action could have a substantial influence on the segmental loading that cannot be neglected in the structural design. During the concrete casting of the segments, strain and temperature measurements have been acquired to collect data in continuous mode from the early construction stages and the curing stage at the manufacturer stock place until the assembly in the tunnel during ring erection, advance of the TBM and tail grouting, performing also long-term behavior analysis.

Finally, in order to check the behavior of the monitoring strain gauges under external stresses, a sample segment has been tested through a bending test and the preliminary results have been shared.

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