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Fiber Sensors Based System for Tunnel Linings' Structural Health Monitoring

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ABSTRACT: Structural engineering is a field of engineering dealing with the analysis and design of structures supporting or resisting various loads. Studies of structural engineering requirements, specifically for densely populated areas, have indicated the need for high safety standards particularly in structural monitoring having in mind latest shifts from construction costs to life cycle costs and lifetime performance including safety and use. Structural monitoring is now being supported by various emerging technologies especially in areas of high seismicity where structural monitoring can be regarded of particularly high importance. Optical sensing technologies have a lot to offer in the field of structural monitoring providing the basis for condition assessment before, during or after any event. Structural monitoring based on fiber-optic technologies provide real-time, wireless and remote deformation sensing capabilities making them ideal regarding safety of vulnerable tunnel cross-sections or sections where very high standards of safety are required. Quick and reliable structural assessment can be enhanced with integrated software that collects and processes the data and assesses the structural reliability of the lining. Optical sensing technologies are most of the times supported by the above algorithms and are technologically progressing day by day. However it is quite important that the already existing and emerging deformation technologies are evaluated and optimised so that they alone, or in combination, can provide optimal performance in the structural sensing of structures and particularly tunnels. The MONICO EC Project has developed a prototype system consisting of an optimized fibre optics based deformation-sensing system for real-time measurement of deformations of reinforced concrete linings in tunnels and a Decision-Support-System (including user interface and decision suitable algorithms) that can drive proactive maintenance and earthquake risk management and can assess the structural reliability of the monitored lining under operating and seismic loads. Through this paper, the technologies, algorithms and supporting software components will be presented together with the results of the final large-scale tests of the MONICO project.

1 INTRODUCTION

Tunneling activity is on the increase around the world, and it is not just the volume of work which is rising. The demands of modern transport networks mean that tunnels are longer and wider than ever before and being driven through increasingly difficult ground conditions. Moreover, several planned tunnels are in countries of high seismicity and a good part of the tunnel lengths will be under densely populated areas and require very high standards of safety.

When talking about Structural Health Monitoring (SHM), we usually include any process involving damage identification in engineering sectors such as constructions. Any deviation or change to the material or the geometric-properties/boundary-conditions of the structure can be regarded as damage (responsible for altering the system proper operation or performance).

In this work, two different fiber optic deformation monitoring systems are combined with advanced algorithms in order to assess the condition and evaluate the safety of tunnel linings under operating and seismic loadings.

2 REQUIREMENTS AND TECHNOLOGIES

2.1 Tunnel Monitoring Requirements

Baring in mind the rising demands of modern transport networks and the increasing awareness of the sensitivity of tunnels to seismic activity it is obvious to understand the high need for advanced monitoring technologies to assess tunnels (especially in the aftermath of a seismic shock). Recently, tunnels have experienced significant damages in large earthquakes including the 1999 Kocacli, Turkey earthquake, the 1999 Chi-Chi, Taiwan earthquake and the 1995 Kobe, Japan, earthquake – Wang W. L. et al (2001). Moreover, the damage to the tunnel structure is difficult to assess and a damaged tunnel that has survived the major earthquake might not have the capacity to survive consecutive seismic aftershocks. Having at hand a real-time, effective and precise monitoring system, will additionally (in the aftermath of a damaging earthquake) aid transportation officers in making critical decisions regarding shutdown of damaged tunnels.

Under the framework of civil structure health monitoring, there are currently no quantifiable methods in determining the status of a structure after a major earthquake or other event that could cause damages to the structure itself – Loupos K. et al (2011), Loupos K. et al (2010), MONICO Tech. Annex, Hashash Y.M.A.(2001). SHM methodologies can be used to determine the status of the structure and thus minimize uncertainties regarding post-event damage assessment and have thus a lot to offer in structures undergoing ageing effects.

2.2 Fiber Optic Sensing Technologies

Following the above and the related bibliographic references – Bairaktaris D. et al (1999), Farrar C.R. et al, Aktan et al - it proves that SHM can be evaluated through the measurement of deformations in various positions (strain). This can be achieved using strain gauges, usually being used. Such sensors can prove bulky in terms of sensitivity or noise that would require signal conditioning (filtering, amplification, excitation etc). On the other hand, fiber-optics-based technologies can prove the ideal replacement of standard monitoring technologies, offering low cost, high precision and real-time solutions, resulting thus into a highly competitive growing field of fiber-optic structural sensing in constructions. Moreover, following the structures' characteristics and behavior, deformations under the effects of loads or changes in the constituent materials can contain a lot of information about their health condition. Hence by following these deformations and after their proper analysis we are able to analyze the loading and ageing behavior of the structures and assess their safety.

2.3 The MONICO EC Project

MONICO is an EC co-funded "Specific Targeted Research Project" (STREP) operating under the capacity area “FP7 - Research for the benefit of SMEs”. Emerging fiber optic deformation monitoring systems have been combined with advanced algorithms to assess the condition and evaluate the safety of tunnel linings under operating and seismic loadings. MONICO has provided an integrated package that includes fiber optics sensors providing real-time tunnel deformation measurements under operating and seismic loads. The system package also includes a Decision Support System (DSS) that processes the gathered real-time measurements and assesses (a) the loading acting on the lining and the lining’s factor of safety under operating loads and (b) the lining’s ability to survive expected after-shocks after an earthquake.

The scientific and technical objectives of MONICO – MONICO Tech. annex - can be summarised below:

- To evaluate and possibly combine, two promising fibre optics technologies (i) Bragg grating, (ii) BOTDR principle for continuous tunnel monitoring;
- To develop a methodology for the assessment of the local structural condition of the reinforced concrete monitored sections in the tunnel lining cross-section under operating loads based on measurements of deformation;
- To extend the deterministic energy-based theory of local seismic failure for reinforced concrete structures to a probability-based assessment of local seismic structural reliability;
- To develop a methodology for the assessment of the global structural condition of the reinforced concrete lining cross-section based on the local, probabilistically defined, conditions in the monitored lining sections;
- To provide both deterministic and probability-based assessment of the seismic structural reliability and the structural reliability under operating loads for both local and global failures in tunnel linings;
- To experimentally evaluate the sensing and data acquisition system and the predictive ability of the methodology for the seismic failure.

In MONICO, an energy-based theory of seismic failure for reinforced concrete tunnel lining cross-sections has been developed that is based on the history of deformations during the earthquake derived from fiber optic measurements. This theory is used to evaluate the remaining dissipative energy capacity of the cross-section before the limit state is being reached. Accordingly, a probability-based assessment of the seismic structural reliability and a probability-based assessment of the structural reliability under operating loads are also provided in MONICO for both local and global failures in reinforced concrete tunnel linings - Loupos K. et al (2010, 2011).

3 TECHNOLOGICAL IMPLEMENTATIONS

During MONICO, two different types of fiber optic monitoring technologies were used and applied in simulated tunnel situations. They were calibrated, tested and evaluated at structural lab level and also through a test case tunnel ring as follows.

3.1 Fiber Bragg Grating (FBG) Monitoring System

Fiber Bragg Grating (FBG) technologies can be used in a series of monitoring applications for civil structures including roads, bridges, tunnels etc. Apart from the temperature and strain sensing capabilities, the non-destructiveness, remote sensing and precision capabilities have a lot to offer in such applications. Furthermore, FBG technologies offer some advantages compared to conventional strain gauges such as: they are totally passive, have smaller size, they are non-conductive, they are more environmentally stable and have quite strong potential due to their low cost.

MONICO has employed two types of FBG configurations:

- FBG sensors embedded on concrete and attached to the reinforcement steel
- FBG sensors externally mounted in metal holders wielded on the reinforcement bars

The embedded FBG sensors for the test consist of a rebar with one or more FBG(s) were glued into a groove. These sensors were used to measure compression and expansion of the concrete. To prevent bonding of a part of the sensor to the surrounding concrete, the sensors were wrapped. Regarding the externally mounted sensors, they were fixed to anchors that are welded to the reinforcement cage before casting of the concrete. Using this technology a pre-straining of the fiber with the FBG was necessary in order to measure negative strains (compression).

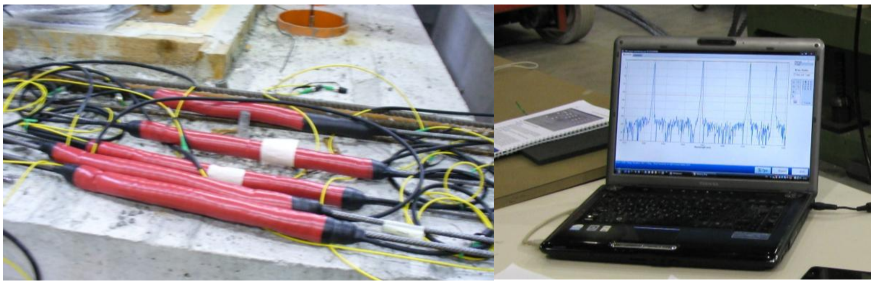

Figure 1, 2- FBG Sensors and Interrogation Software Running

3.2 Brillouin Monitoring System

Brillouin optical time domain (BOTDR) technologies provide fiber-based temperature and strain capabilities as distributed sensing systems. Briefly, the main advantage of Brillouin technique is the capability of continuous strain and temperature measurements along a simple and inexpensive commercial fiber cable that runs along the entire structure to be monitored (MONICO Tech. Annex).

Brillouin scattering, is occurring when light in a medium (air, water or crystal) interacts with time dependent optical density variations and changes its frequency and path. The variations in density can exist due to acoustic modes, magnetic modes or temperature components. When the optical fiber is compressed its index of refraction changes, and a component of the traveling light wave, interacting with the periodic refraction index variations, is deflected (as in three-dimensional diffraction grating). In this way the light is subject to a Doppler shift, so its frequency changes. The interrogator unit of the Brillouin sensing system is able to measure frequencies arising from the detuning between the incident and backscattered light. The frequency shift shows the magnitude of strain/temperature, while the location of the strain incident can be calculated from round-trip time. Typical operational characteristics of Brillouin technology are ~km range, ~1Hz sampling rate and >1m spatial resolution - Merzbacher C.I. et al (1996), Imai M (2003). For the MONICO purposes a dynamic operation of >10Hz with spatial resolution of less than 40 cm was required and a custom coiled fiber setup was adopted to achieve these specifications.

MONICO developed a novel Brillouin sensor setup in order to match the Brillouin technology inherent specifications with the specific MONICO requirements. A coiled-fiber configuration was adopted to fit the spatial resolution requirement. Two appropriately arranged metal hinges were anchored on the points of interest to behave as the pulleys around which the fiber coils. As the points of interest are elongated (stressed), the metal hinges are displaced and optical fiber coils are "sensing" this stress. Metal hinges exhibit a cylindrical profile with radius of 3cm, to assure that optical fiber properties are not altered (no power loss), while they exhibit v-groove holders on the side for properly handing the fiber coils (side view)– MONICO deliverable D1.3.

3.3 Decision Support System (DSS)

The DSS consists of the Expert System and the Data Base. The former is an interface between the user and the results (system measurements) and coordinates the rest of the developed modules. The user is able to estimate the present structural condition at the monitored sections in the tunnel cross-sections as well as the overall structural condition of the cross-section through the integrated DSS and monitoring system. Moreover, the user is able to examine the history of strains during an earthquake, and what is the structural condition of the monitored sections and the whole cross-section after an earthquake.

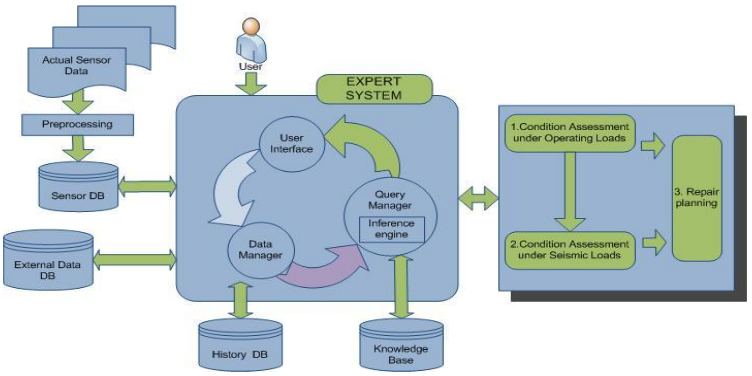

Figure 3- Decision Support System Architecture – Loupos K. et al (2011)

3.4 Deterministic and probabilistic Assessment Algorithms

The monitoring system has a back-bone mechanism developed, responsible for the deterministic and probabilistic assessment of the structural condition of monitored tunnel reinforced concrete cross- sections. The system estimates internal forces, external loads and actual values of the safety factors or damage indices, based on the recorded strains of sensors installed on the transversal reinforcing bars at 8 critical points (Figure 4- Decision Support System – Tunnel Cross Sections) - Loupos K. et al (2010, 2011).

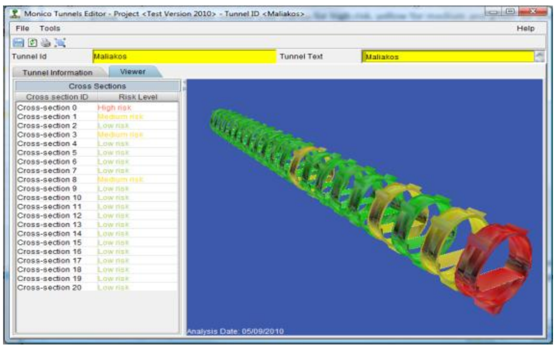

Figure 4- Decision Support System – Tunnel Cross Sections - Loupos K. et al (2011)

The structural assessment concerns the long term behavior under normal operating conditions and the behavior under seismic forces. Regarding the long term behavior, the internal forces developed at the positions of the strain sensors and the corresponding to them safety factors are initially estimated (Local condition). In Global level, the values of those parameters and the values of the external soil and water pressures are estimated for the total points along the perimeter of the cross section (Global condition). For the seismic behavior from a big number of strain records received during an earthquake event the hysteresis loops pattern in terms of bending moments and curvatures at each one of the eight points on the perimeter is registered. From the area of the hysteresis loops the energy dissipated during the earthquake is estimated. The damage index is derived being the ratio of the dissipated energy to the total available internal bound energy represented by the area of the hysteretic envelope (Local condition). This condition is obtained by a procedure similar to that applied for the long term behavior - Loupos K. et al (2010, 2011), MONICO Tech. Annex.

4 MONICO FINAL TESTS AND EVALUATION

In order to perform the evaluation, validation, calibration and final tuning of the monitoring technologies as well as the analysis algorithms and methodologies, one final large scale test was performed including the installation of both sensorial technologies into a large tunnel ring. A tunnel circular cross section with an outer diameter of 483 cm, inner diameter of 443 cm, width of 100 cm and thickness of 20 cm was conceived to simulate a tunnel section. Two large actuators, placed vertical to each other were placed inside and outside the ring circumference, were used to apply displacements in order to reproduce reaction forces of a standard earthquake. The final test set-up is shown in Figure 5 - The eight monitored sections of the Tunnel Ring. With regard to the tests on substructures, the conventional displacement δy was calculated following the procedure outlined in the SAC guidelines – Clark P (1977). It was composed of two contributions: δy beam and δy frame to take into account the limited deformation of the reaction frame. For the cyclic test of the ring, the standard ECCS cycling loading procedure was selected – ECCS recommended testing procedures. In detail, the loading protocol was proportional to a conventional displacement δy which represented the elastic-plastic transition of the cross section. Cycles with maximum displacement of δy/4 to 4δy were imposed. Both optical technologies, (FBG and BRILLOUIN) were installed in 8 points of interest at the tunnel circumference. A total of 48 fiber sensors were installed (32 FBG and 16 Brillouin sensors).

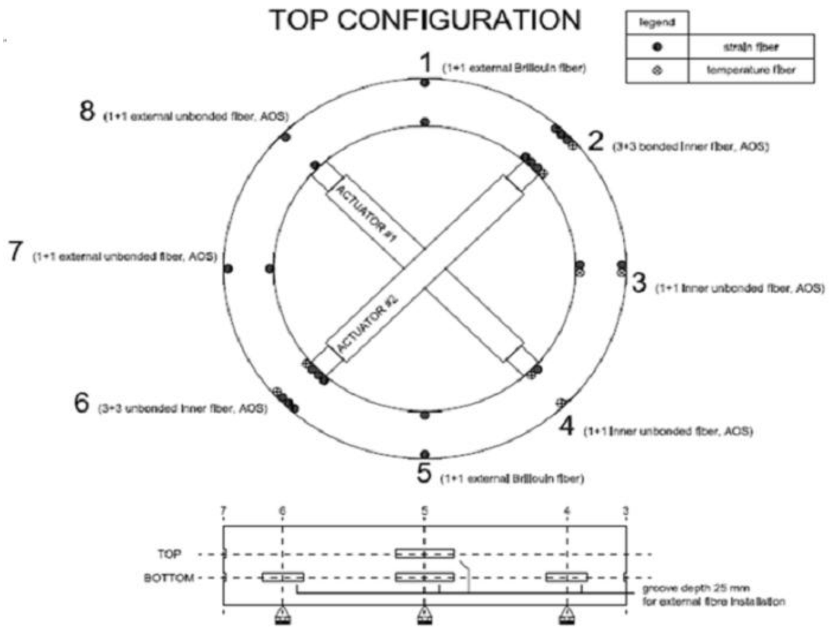

Figure 5 - The eight monitored sections of the Tunnel Ring

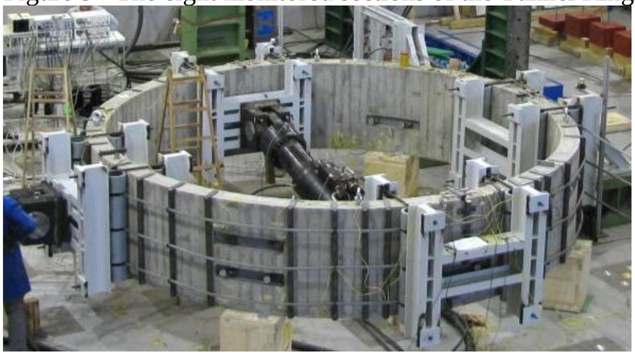

Figure 6 - Final Tests' Tunnel Ring

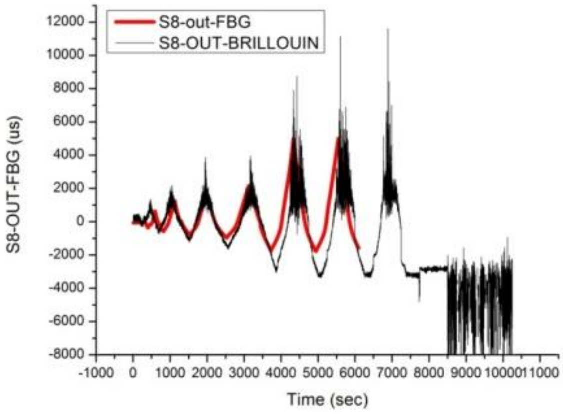

Figure 7 – FBG vs BRILLOUIN Measuremens for whole experiment (Section 8)

Section-8 measurements have been included as a representation of the two technologies measurements. We have not selected sectios 1 or 3 since these diagonal sections remained intact and did not provide and strain changes throughout the experiment. In the diagram above we can see the 6 cycles of the dynamic loading in the section-8 of the tunnel ring. At time 7500sec we can observe the concrete failure. As we can see above, there is a very good correlation of both technologies results, monitoring the tunnel ring behavior. The Brillouin technology can directly be compared to the FBG but provides high noise levels at high strains.

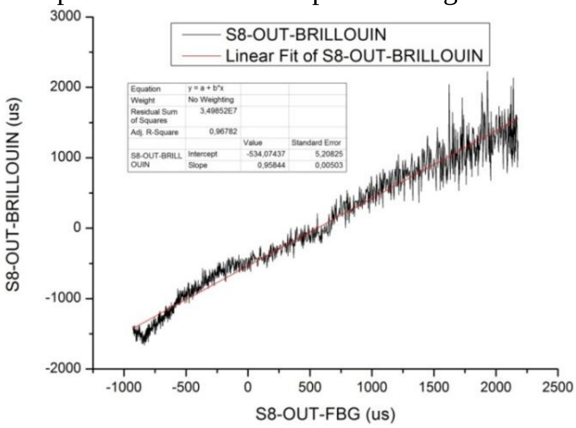

Figure 8 – Linear Fitting for Brillouin vs FBG sensors (Section 8)

Further analysis in Figure 8 (above) that depicts the strain measured with FBG versus the strain measured with Brillouin sensors shows that the linear fitting slope for the dynamic range from -

1000μs to 2500μs is close to 1 (0,96). However, high levels of noise for the Brillouin sensors are evident for high strain values.

5 CONCLUSIONS

The high applicability of the technologies and methodologies developed in MONICO project can be realized by its overall high applicability a robust, precise, quick, easy to use and at the same time reliable SHM system. MONICO developed an optimized version of deformation monitoring system able to monitor the structural health of large structures and particularly tunnels over dynamic and static loading.

Two different optical technologies were identified, calibrated, fine-tuned and evaluated to fit technical specifications in order to correctly feed the Expert System for the static and dynamic evaluation of the results: the FBG technology and the Brillouin technology. Both monitoring technologies were successfully tested providing high accuracy and good matching between them. The FBG sensors proved to have increased accuracy and lower noise. The Brillouin technology showed increased noise for high strain values and limited number of succeeding sensors. Both monitoring technologies were evaluated and the methodologies and algorithms developed were validated through a series of preliminary (small-scale) tests but also based on the results of the final tunnel test-ring constructed to simulate real-life tunnel conditions.

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