Journal of Instrumentation

PAPER • OPEN ACCESS

Use of FBG sensors in advanced civil engineering applications

To cite this article: M.A. Caponero 2023 *JINST* **18** C07020

Published by IOP Publishing for Sissa Medialab

Received: *January 28, 2023*
Revised: *February 26, 2023*
Accepted: *March 7, 2023*
Published: *July 28, 2023*

6th International Conference Frontiers in Diagnostics Technologies
ENEA Frascati Research Centre, Frascati, Italy
19–21 October 2022

2023 JINST 18 C07020

Use of FBG sensors in advanced civil engineering applications

M.A. Caponero

Frascati Research Centre, ENEA,
via Enrico Fermi 44, Frascati RM, Italy

E-mail: michele.caponero@enea.it

Abstract: Structural health monitoring (SHM) in civil engineering structures has gained a key role to provide early warning for the occurrence of conditions leading to potential damage and unsafe service. Among the various available technologies, fiber optic ones have proved to be reliable and convenient to perform permanent monitoring in both static and dynamic regimes. Fiber optic sensing solutions based on the fiber Bragg grating (FBG) technology are very versatile and they can be effectively used to provide multipoint sensing systems distributed on large structures. FBG sensors have a point-like form factor, but they can be easily packaged in solid housings in order to fit the necessary measuring gauge and sensitivity, shape and size, mechanical and environmental requirements. As key advantages over electric technologies, FBG sensors offer immunity to electromagnetic interference, in-series cabling of sensors for different physical parameters, stable response to both quasi-static phenomena and fast response transitory phenomena. This paper presents some monitoring solutions developed in ENEA with FBG sensors for civil engineering applications.

Keywords: Optics; Overall mechanics design (support structures and materials, vibration analysis etc)

https://doi.org/10.1088/1748-0221/18/07/C07020

Contents

1 Introduction

Among the sensors based on various fiber optic sensor (FOS) technologies, fiber Bragg grating (FBG) sensors have reached full reliability for industrial applications and are experiencing an increasing diffusion thank to their versatility and cost scalability [1]. Versatility is related to their many peculiar features, such as: immunity from electromagnetic interference; possible measurement of many parameters, ranging from acceleration to humidity; in series cabling to produce chain-of-sensors for both mono- and multi-parameter measurements; small dimension suitable for punctual sensing, and easy mounting in transducers to enlarge the measurement gauge; possible embedding in composite materials and structures. Cost scalability is mainly related to a low cost of the single FBG sensing component, and to the availability of modular cost-effective datalogger (usually referred to as FBG-interrogation systems) which are based on a main central unit and multiplexing expansion units. As an additional benefit, for the cabling of an FBG sensing system it is possible to adopt the many products and solutions developed for the telecommunication fiber optic networks, thus relaying on durable and adaptable solutions. An effective limit of the FBG technology is the high locality in the measurement: quasi-continuous sensing systems can be developed with many close sensors, but no proper continuous sensing can be accomplished (for instance, to detect the occurrence of a fracture at any location along a beam).

Civil engineering has become an important field of application for the FBG technology [2, 3]. FBG monitoring systems provide an effective solution to accomplish permanent monitoring in both static and dynamic regime, allowing the application of the various well-assessed structural health monitoring (SHM) techniques and procedures for on-call maintenance, and early warning of fatigue excess and potential damage. For instance: i) the electromagnetic immunity feature greatly facilitates SHM of electrified railway tunnels and bridges, avoiding the complex countermeasures that shall be adopted with electric sensors; ii) cabling long highway viaducts with hundreds of sensors, can be done using the same efficient procedures and reliable materials (armoured backbone cables, fanout enclosures, outdoor breakout cables, . . .) developed for passive data/internet networks. Specific interest in the FBG technology arises from the possibility to manage with one datalogger the different necessary sensors, typically a bucket of strain gauges, crack meters, accelerometers and tilt meters. Specific interest also arises from the long-term durability of the FBG sensors which operate in passive mode with no need for electricity, and to the easy long-length cabling and easy embedding in cement materials.

After a short recall of the principles of the FBG technology, this paper presents solutions developed in ENEA and applied for three different aims: i) monitoring the cure of large masses of concrete; monitoring special reinforcement rebars of retainment walls; iii) structural monitoring within the retrofitting works for the seismic improvement of an existing bridge.

1.1 Principle of operation of the FBG technology

The principle of operation of the FBG sensors is recalled here with the limited intent to highlight the intrinsic character of the FBG technology, which neither necessitates to alter the size and structure of the optical fiber, nor necessitates power supply at the sensing location. A comprehensive presentation of the FBG technology is given in [4].

FBG gratings are produced as diffraction gratings in a short segment of an optical fiber. The production occurs by a periodic variation of the refractive index of the core of the optical fiber, with no evident alteration of its dimension and appearance. The rest of the fiber stays pristine and operates for the transmission of sensor's signal. Il broadband light propagates along the fiber, a specific narrowband back-propagating signal originates at the FBG grating by diffraction. The central wavelength of the signal is linearly dependent on the strain and temperature of the FBG grating. Thus, if the FBG grating is put in structural or thermal contact with a component, it can be operated as an FBG strain or temperature sensor, with the value of the parameter of interest being encoded in the spectroscopic analysis of the FBG signal.

To measure parameters different from strain and temperature, the FBG grating can be functionalized (i.e., made indirectly sensitive to the wanted parameter) by use of a proper transducer. For instance: embedding the FBG grating in a hygroscopic material, humidity can be monitored via the strain of the FBG grating resulting by the swelling of that material. Commercial FBG sensors have been developed for a variety of mechanical, environment and biochemical parameters, with full coverage of all common requirements for any application in the civil engineering field.

Since the signal of the FBG grating is sensitive to both temperature and strain, to perform strain measurement a thermal compensation is necessary. In fact, structural contact usually implicates thermal contact, so that the total signal is the sum of a strain signal and a thermal signal. Thermal compensation can be easily done by use of two companion FBG gratings, one in structural contact (e.g., by glue) and the other one in thermal contact only (e.g., by thermal fluid paste), by subtracting the signal of the latter from the signal of the former.

Many FBG gratings can stay along the same optical fiber and can be operated in wavelength division multiplexing (WDM). In fact, the signal of an FBG grating can be considered a narrowband selective reflection of the broadband light launched into the fiber. Thus, the light wavelengths not reflected by an FBG grating keeps propagating along the fiber and can be used for other FBG gratings. To apply WDM, two basic constraints apply: i) absence of overlapping of the different signals, also considering the wavelength shifts that occur during the measurement; ii) allocation of all the signals within the broadband launched into the fiber. As a basic reference: i) FBG-interrogation systems have a broadband of 80 nm, and a wavelength shift resolution of 1 pm; ii) FBG gratings have an intrinsic sensitivity of 1 pm per 0.1°C and 1 pm per microStrain.

2023 JINST 18 C07020

2 Monitoring the cure of concrete manufacts

A distributed monitoring system was developed for a critical structure of the sports complex 'Città dello Sport' in Rome, designed by architect Santiago Calatrava. The complex includes two pavilions that have an exceptionally large fan-shaped roof, made by a half-dome netting structure closed with glass tiles. The overall architectural design makes the curved central beam of the half-dome be supported by a pillar which in turn is supported by a top-level mezzanine slab. To meet the necessary severe structural requirements, the mezzanine thickness is about two meters. The monitoring system was mainly intended to control the construction of both the mezzanine and the pillar, their structural assessment at the mounting of the many heavy glass tiles, and their structural condition in the long term. Figure 1 shows the sports complex under construction. Construction works had a long-lasting stop, and glass tiles are not mounted to date.

The monitoring system consists of 36 FBG strain sensors and seven FBG temperature sensors. The sensors are cabled as seven chain-of-sensors, each chain consisting of one FBG temperature sensor and a variable number of FBG strain sensors, ranging from four to seven. The sensors of each chain are operated in WDM. The FBG strain gauges stay on selected reinforcement rebars of the mezzanine slab and stay on the steel H-beam of the pillar. As glass tiles are not mounted to date, no significant strain monitoring was done yet, while the FBG temperature sensors were used to monitor the cure of the poured concrete.

Figure 2 shows the location and the naming of the FBG temperature sensors. The evolution of the cure is critical to the final performance of the concrete manufacts. In fact, during the cure the temperature of the concrete varies significantly due to the heat released in the hydration reaction of the cement. In the case of thick castings, this heat is not easily dissipated and the thermal gradients, together with the hyperstatic nature of the structure, can cause shrinkage cracking patterns which can affect the quality and durability of the manufact [5]. For this construction, special products and pouring techniques were adopted. The FBG temperature sensors were used to monitor the time history of the temperature. The monitoring provides a significant parameter for the evaluation of the correct execution of the work.

Figure 1. The sports complex during the construction works with the fan-shaped roof without glass tiles in position (left). Construction works at the location of the mezzanine and pillar (centre and right). Arrows provide reference to locate the components in figure 2.

The chains were produced and tested in the ENEA laboratory. The FBG gratings were from provisions of individual components, each staying at the centre of a fiber segment two meters long. The FBG gratings of each chain are connected in series by splicing, with interposed segments of fiber as long as necessary to have each FBG at the planned position. To produce the engineered

2023 JINST 18 C07020

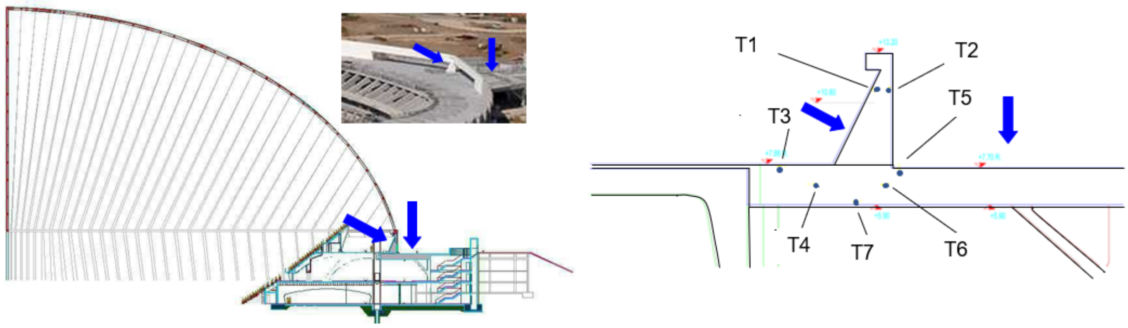

Figure 2. Sections of the sports complex plan, and aerial picture of the part of the complex before the installation of the dome. Arrows point at the mezzanine and the pillar where the sensors were installed. The section on the left-hand side shows the naming of the temperature FBG sensors.

chain, the fiber is inserted in a flexible metallic tube, with openings at the positions planned for the strain sensors. The fiber rises the opening and the FBG grating is embedded in an epoxy ingot moulded in place on the opening. The mould seals the opening and is shaped to fit the reinforcement rebar, thus it can be glued on the rebar and can work as an engineered FBG strain sensor. The FBG grating to be used for temperature monitoring stays in a metallic box at the far end of the chain. The FBG grating is loosely stuck with thermal paste on the rigid surface of the box, thus not subject to strain. For each chain, the FBG temperature sensor is also used for temperature compensation of the FBG strain sensors. Although the FBG temperature sensor is at some distance from the FBG strain sensors of its chain, the deep embedding in the large concrete mass justifies the assumption of thermal equilibrium and its use for thermal compensation.

The sensors of each chain are operated in WDM. The chains have various lengths, ranging from 10 to 20 meters. The near ends of the chains are wired to a fiber optic backbone, terminated in a technical service room of the pavilion. The installation of the chains followed the progress of the assembly operations of the metal reinforcement rebars whose density would have prevented access to the lower layers after full assembling. Data acquisition was done with an FBG-interrogation system by Micron Optics (model sm125, 1 Hz sampling frequency), with 0.1°C temperature resolution.

Figure 3 shows the monitoring of the concrete pouring and curing of the mezzanine slab Time is given as elapsed time since shortly earlier the beginning of the pouring operations. Given the amount of concrete, pouring was carried out simultaneously from several points and lasted several hours. At the end of the pouring operation, to counteract the rapid cooling and drying expected at the top surface, insulating blankets were laid on. The bottom and lateral surfaces are adequately insulated by the wooden formwork. The plot shows that all sensors measure a sharp increase in temperature when they are submerged in the concrete. In fact, the temperature of the fresh concrete (18°C) was significantly higher than the ambient temperature (winter, 3°C at the beginning of the operations). The temperature increase continues with the cure of the concrete, reaching a maximum value after about 58 hours. Later, the temperature begins to cool down toward the ambient temperature, thus providing experimental evidence of the cure's full accomplishment. At about time 168 h the T03 and T05 sensors, both close to the upper surface of the slab, record an abrupt cooling corresponding to the removal of the insulating blankets. Later, the two sensors follow the variation of the ambient

2023 JINST 18 C07020

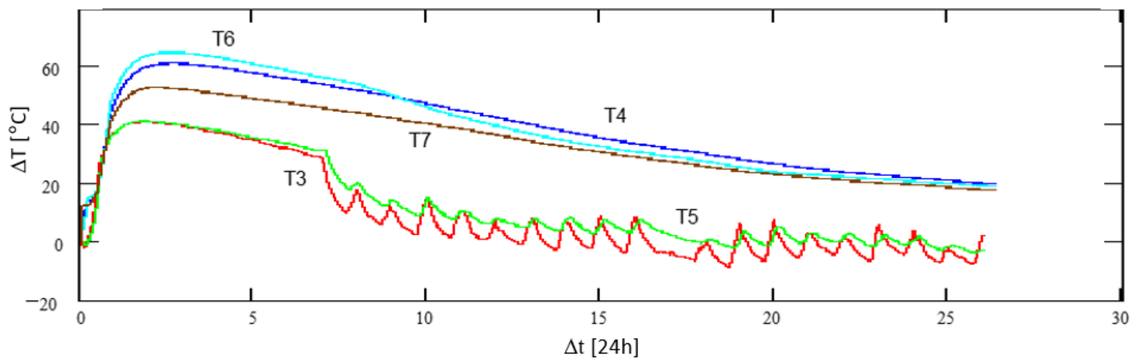

Figure 3. Time history of data from the temperature sensors embedded in the concrete at the mezzanine.

temperature according to the day/night cycle, with a drift due to the cooling towards the ambient temperature. The other sensors do not feel the temperature day/night cycle, because deep in the concrete. The T06 sensor also shows to be late affected by the removal of the thermal covers, showing at about time 194 h an increase in the cooling speed. That can be justified by its location close to the slightly thinner part of the slab.

Figure 4 shows the monitoring of the concrete pouring and curing of the pillar. Monitoring started about 54 hours before the pouring operations, a period in which the ambient temperature in the day/night cycle is evident. After pouring, the initial rapid heating and the following slow cooling provide evidence of the evolution of the hydration of the cement. Since day 21, after the removal of the wooden formwork, there is an increasing sensitivity to the ambient temperature. Despite the two sensors are near the surface as sensors T3 and T5 are, a faster initial cooling and a different tending final value can be noted. The final tending value finds justification in the varied environmental conditions, being the production of the pillar subsequent the production of the mezzanine. The faster initial cooling finds justification in the lower thermal insulation of the wooden formwork with respect to the insulating blankets laid in the mezzanine; ii) the smaller thickness of the inner mass of concrete and consequent lower heating.

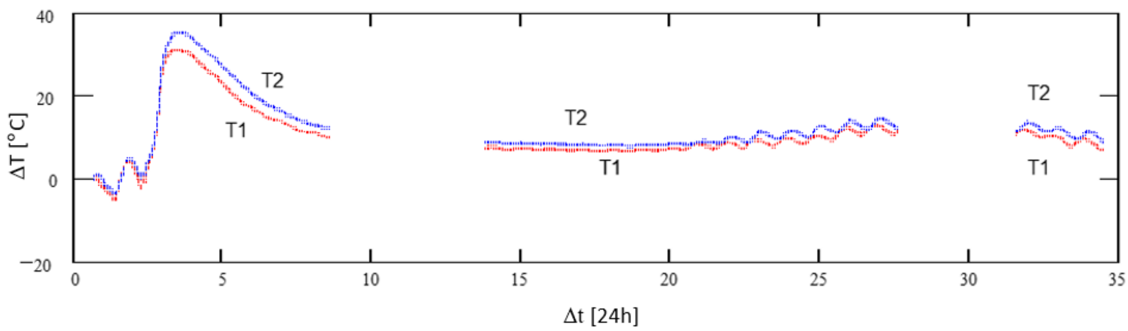

Figure 4. Time history of data from the temperature sensors embedded in the concrete at the pillar.

2023 JINST 18 C07020

3 Structural monitoring of special retainment works

A distributed structural monitoring system was developed for special sections of a retainment wall made for the construction of the Rome ‘line C’ underground route. The construction works are still in progress to date, with part of the route completed and in service. The excavation of pits is necessary for various technical services related to the underground tunnelling. Among the pits excavated and later covered, a large one was the pit in the square ‘O. Marucchi’. The perimeter of the pit was very close to the buildings. Thus, the pit was excavated with the production of a containment wall along the full perimeter of the excavation works.

Use of containment walls is a well assessed technique in excavation works [6]. The technique basically considers the construction of a buried fence to prevent soil collapsing inward the pit. The wall is made directly into the ground, by many adjacent panels of large vertical size and small cross section. Each panel is made by reinforced concrete, produced in a dig with the necessary cross section. Digging is done by machineryes with mordant bucket or other tools mounted on telescopic harms. Usually, bentonite is injected in the ground to avoid the collapse of the dig. Once the dig is ready, the reinforcing cage is laid in and concrete is poured.

For the pit in the square O. Marucchi a few special cages in glass fiber reinforced polimer (GFRP) were used. Those cages were planned to stay in the wall in correspondence of the intersection of the tunnel and the pit, with the intent to facilitate the advance of the tunnel boring machine (TBM). A TBM is a machine used to excavate tunnels with a circular cross section, in principle through any kind of variety of soil, from sand to rocks. The TBM is a truck mounted advancing machinery that excavates the tunnel by means of a rotating disk with crushing tools. The excavated soil is automatically backward transported by the TBM’s conveyor belt system. To have the TBM pass through a concrete wall reinforced with steel rebars, needs time consuming preparation work. In fact, the steel bars bent and get stuck, and possibly damage, the crushing tools of the rotating disk and the openings of the conveyor belt system. On the contrary, GFRP rebars are well crushed by the TBM [7].

Figure 5 (left) shows the principle of operation for the panel of the retainment wall at the intersection with the tunnel. Because of the large height of the panel, the full reinforcing cage was made by three sections. The central section is with GFRP rebars, the other two sections are with steel rebars. The activity took place in 2007. Figure 5 (centre) shows the layout of the sensors. Figure 5 (right) shows the work yard. International codes and guidelines for concrete structure reinforced with GFRP have been developed mainly from 2000 to 2010, thus the interest for monitoring the application was high.

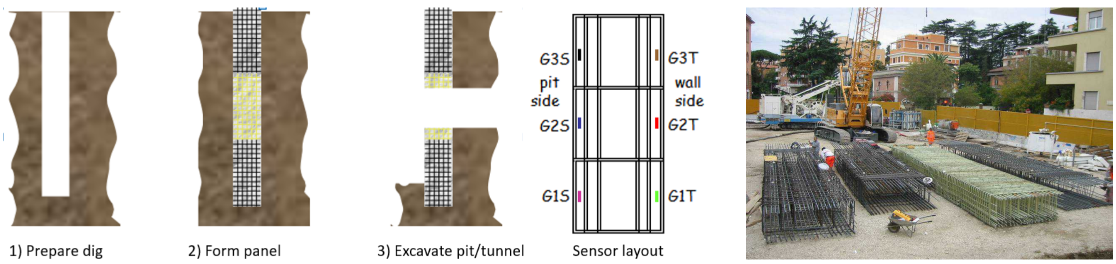

Figure 5. Sketch of panel production process, and sensor layout (left). View of the work yard (right).

FBG strain sensors were prepared to monitor the three sections of the panel's cage. Sensors were produced and tested in the ENEA laboratory, cabled as chain-of-sensors and prepared in a housing shell developed custom for the application. Figure 6 shows the housing shell, its working principle and the installation procedure. The housing shell is in GFRP tissue, and it is a hollow half-cylinder about 20 cm long. Its inner diameter is equal to the diameter of the GFRP rebar, to fit as a saddle on it. On its surface, the housing shell has a longitudinal cut, as shown in figure 6 (left). The FBG grating is aligned over the cut and stretch clamped by glue at the two sides of the cut. The two ends of the optical fiber are inserted in a flexible tubing which in turn are clamped by glue on the housing shell, as shown in figure 6 (centre). For the installation, a thick layer of structural glue shall be spread on the rebar, and the housing shell shall be put in place, as shown in figure 6 (right). As the shell is pressed against the bar, the glue (not shown in figure 6) goes through the cut and performs the structural bonding with the FBG grating. Multiple sensors were cabled as chain-of-sensors by splicing after preparing each sensor on the housing shell.

The aim of the installation was to record the variation of the strain condition of the reinforcing cages, from the production of the panel, during the excavation of the pit, and until the tunnelling (when sensors on the GFRP cage are destroyed). For each cage, there are two sensors, one at the side facing the pit, one at the opposite site.

Figure 6. The housing shell (left), and its working (centre) and installation principle (right).

The cages were inserted in the dig and the concrete was poured on October 8th 2007. Figure 7 shows data at different times after the pouring. Data were recorded with a portable datalogger for a few hours. The reference strain condition (zero strain) was acquired soon before the start of the concrete pouring work. The first monitoring recording occurred 10 days after the pouring, a time gap sufficient for a good cure of the used type of concrete, with the significant exothermic and shrinkage processes ended. In the figure three acquisition campaign are shown. On October 18th all sensors record a similar strain condition, thus providing evidence that the cure of the concrete affects the different sections with similar compression, as expected by homogenous concrete shrinkage. After the beginning of the excavation of the pit, differential deformations are recorded by the sensors, with a major variation sensor G2S on the GFRP cage, side facing the pit. The opposite sign of the deformation of the sensors at the same level but on opposite sides, allow to infer that a global slight bending of the panel occurs. On January 11th a large variation of strain occurs for sensor G2S, which does not find correspondence in the data of the other sensors. At that time, the pit's bottom level approached the level of sensor 2GS, which can explain a relaxing of the GFRP rebars facing the pit. The same relaxing was not recorded by sensor G3T, which can be explained by the different bending behaviour of the steel rebar. The absence of large strain variation for sensor G2S anyway shows a correct containment of the terrain by the section of the panel with the GFRP cage. Figure 8 (left)

2023 JINST 18 C07020

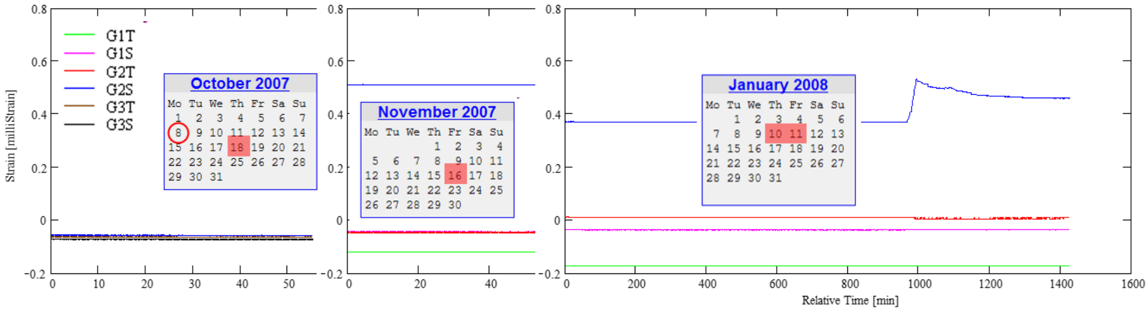

Figure 7. Data recorded at different times after the construction, with evidence of one major deformation.

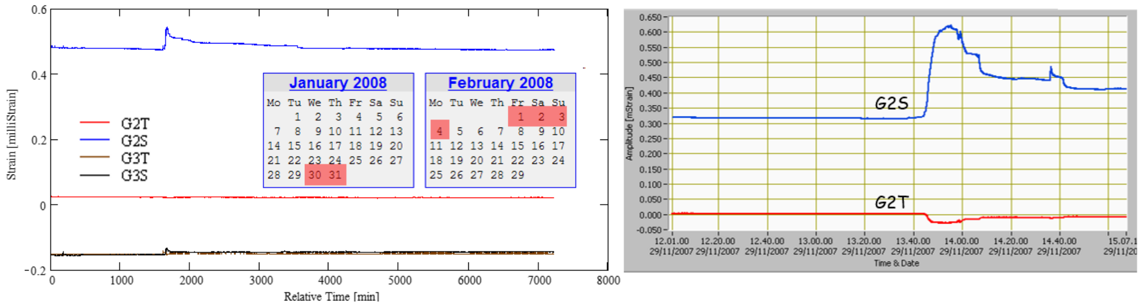

Figure 8. Data recorded for six consecutive days (left). Expanded time scale view of a signature of bending deflection (right).

shows a longer and late data recording, again with evidence of recurrent major strain variation for sensor G2S. Figure 8 (right) shows a transitory event experienced by the GFRP cage, with opposite variations at the two sides as expected by an overall bending deformation.

Structural monitoring of retrofitted structures. A system with FBG strain and temperature sensors was developed for monitoring the bridge 'Torrente Casale' in the south of Italy, on highway A2. The bridge was interested by strengthening interventions, to improve its seismic performances. The intervention was based on the use of carbon fiber reinforced polymer (CFRP) material [8]. Two types of strengthening components were used: prefabricated pultruded bars, and on-site production of patches and wrappings. Figure 9 (left) shows a section of the bridge transverse to the highway axis, with evidence of the position of bars, patches and wrappings.

The wrappings were made at the tip and foot of selected columns, and the patches were made at critical locations of selected beams. In both cases, multiple layers of tissue were applied to meet the required structural performance. The tissue was impregnated with high-strength epoxy adhesive. FBG sensors were prepared as chain-of-sensors on a thin optical fibre cable (0.9 mm diameter) to allow easy embedding between two layers of the stacked tissues. Figure 9 (centre) shows one beam with one of the patches, and the box and flexible tube used for the cabling of the long tails of the chain-of-sensors. Figure 9 (right) shows the wrapping at the foot of one of the pillars, and the long tails of the chains-of-sensors prior to be cabled.

2023 JINST 18 C07020

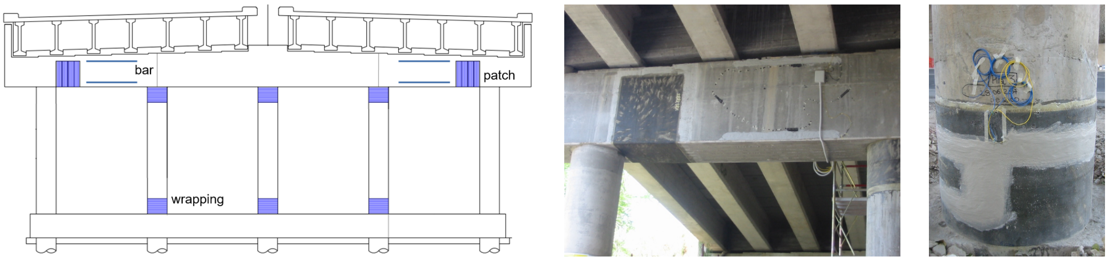

Figure 9. Cross section plan showing the installation locations, and pictures of one patch and one wrapping.

Figure 10 (top) shows a pultruded bar instrumented with FBG strain sensors. Bars were inserted in grooves machined in the beams, as deep as necessary to reach the most external existing steel rebars. The installed bars were then buried with structural epoxy cement, as shown in figure 10 (bottom).

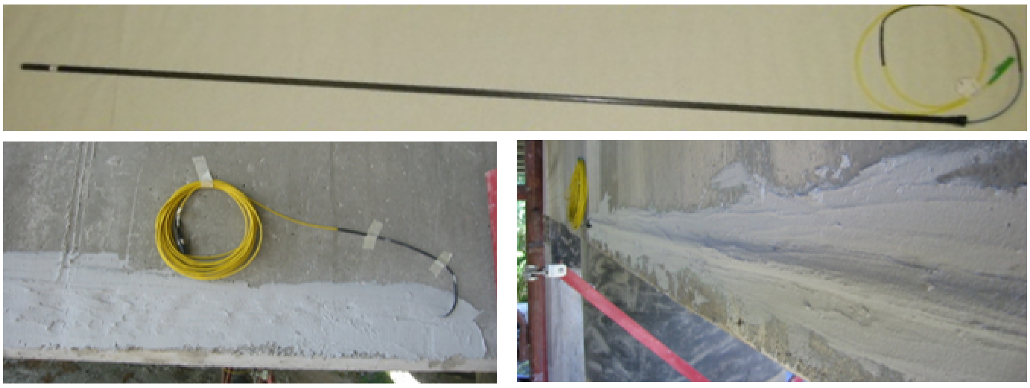

Figure 10. An instrumented bar prior the installation (top). Pictures of two installed bars.

Data were acquired with a programmable scheduled program, based on one short period in continuous acquisition and one long period in standby. Data acquisition was done with an FBG-interrogation system by Micron Optics (model si425, 250 Hz sampling frequency) with 1 μStrain resolution.

Figure 11 shows an acquisition sample of eight hours, with a 1 min continuous acquisition every 10 min. Data are from one of the sensors at the foot of one of the pillars. In the long term, the quasi-static thermal deformation of the structure due to the environment temperature can be seen in the left-hand side plot (time 4 h corresponding to about 14:00). In the short term, the dynamic time history of the deformation due to the vehicular traffic can be seen in the right-hand side plot.

Figure 12 shows an acquisition sample from one of the instrumented bars. In the left-hand side plot, deeps correspond to the transit of the vehicles which make the beam experience bending deformation. The smooth increasing trend of the plot is due to the thermal deformation induced by the environment temperature change. In the right-hand side plot, the expanded time scale allows to clearly show the time evolution of the elastic deformation of the beam at the transit of the vehicles. The amplitude and width of the deeps are related to the weight and speed of the vehicles, respectively.

A comparison between the plots in figure 11 and figure 12 points out the different structural behavior of the foots of the pillars and the beams. As expected: i) the formers, clamped in the

2023 JINST 18 C07020

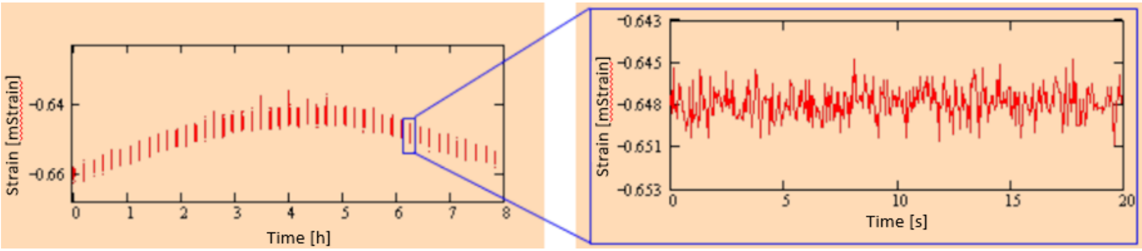

Figure 11. A sample of discontinuously acquired data from a sensor embedded in the wrapping at the foot of one of the pillars, with evidence of vibrations in expanded time scale.

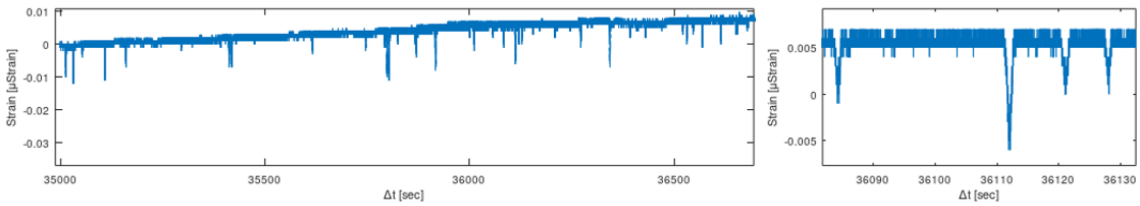

Figure 12. A sample of data from an instrumented bar at one of the beams, with evidence of bending in expanded time scale.

underlaying basement and subject to axial compression, are subject to volumetric vibrations with long damping time and show a continuous vibration due to the intense traffic; ii) the latter, with relatively slim form factor and subject to bending, show a relevant deformation strictly correlated with the dynamic of the transit.

Concluding remarks. This paper presents solutions developed in ENEA and applied for different monitoring aims in the civil engineering field. Sensors were prepared, assembled and tested in the FOS laboratory of the ENEA Research Centre of Frascati. The developed solutions proved to be efficient for practical use. In fact, installations were done in complex construction yards, by standard-skilled construction workers and in standard operating conditions with no critical interferences with the standard construction procedures. The success of the installation with no damaged sensors, the distinct signal of the installed sensors, and the overall good performance of the monitoring campaigns, proves the high industrial readiness of the solutions which can be adopted. The applications provide evidence of one of the most peculiar features of the FBG sensors, namely the capability of both long-term stability for quasi-static measurements and fast response to transitory events. That feature allows to implement structural monitoring procedures based on different parameters, such as: i) quasi-static thermal deformations due to circadian and seasonal cycles; ii) long term structural settling due to ground movements; iii) amplitude of the deformation due to the transit of heavy vehicles; iv) variation of the operational frequencies and dumping.

References

[1] K.T.V. Grattan et al., *Fiber optic sensor technology: an overview*, *Sens. Actuators A* **83** (2000) 40.

[2] P. Moyo, J.M.W. Brownjohn, R. Suresh and S.C. Tjin, *Development of fiber Bragg grating sensors for monitoring civil infrastructure*, *Eng. Struct.* **27** (2005) 1828.

[3] M. Majumder, *Fibre Bragg gratings in structural health monitoring — Present status and applications*, *Sens. Actuators A* **147** (2008) 150.

[4] A. Othonos, *Fiber Bragg gratings*, *Rev. Sci. Instrum.* **68** (1997) 4309.

[5] P.C Aıtcin, *The durability characteristics of high performance concrete: a review*, *Cem. Concr. Compos.* **25** (2003) 409.

[6] M.I. Ramadan et al., *Cantilever Contiguous Pile Wall for Supporting Excavation in Clay*, *Geotech. Geol. Eng.* **36** (2018) 1545.

[7] S. Reichenbach et al., *A review on embedded fibre-reinforced polymer reinforcement in structural concrete in Europe*, *Constr. Build. Mater.* **307** (2021) 124946.

[8] W.K.M. Frhaan et al., *CFRP for strengthening and repairing reinforced concrete: a review*, *Innov. Infrastruct. Solut.* **6** (2021) 49.

2023 JINST 18 C07020