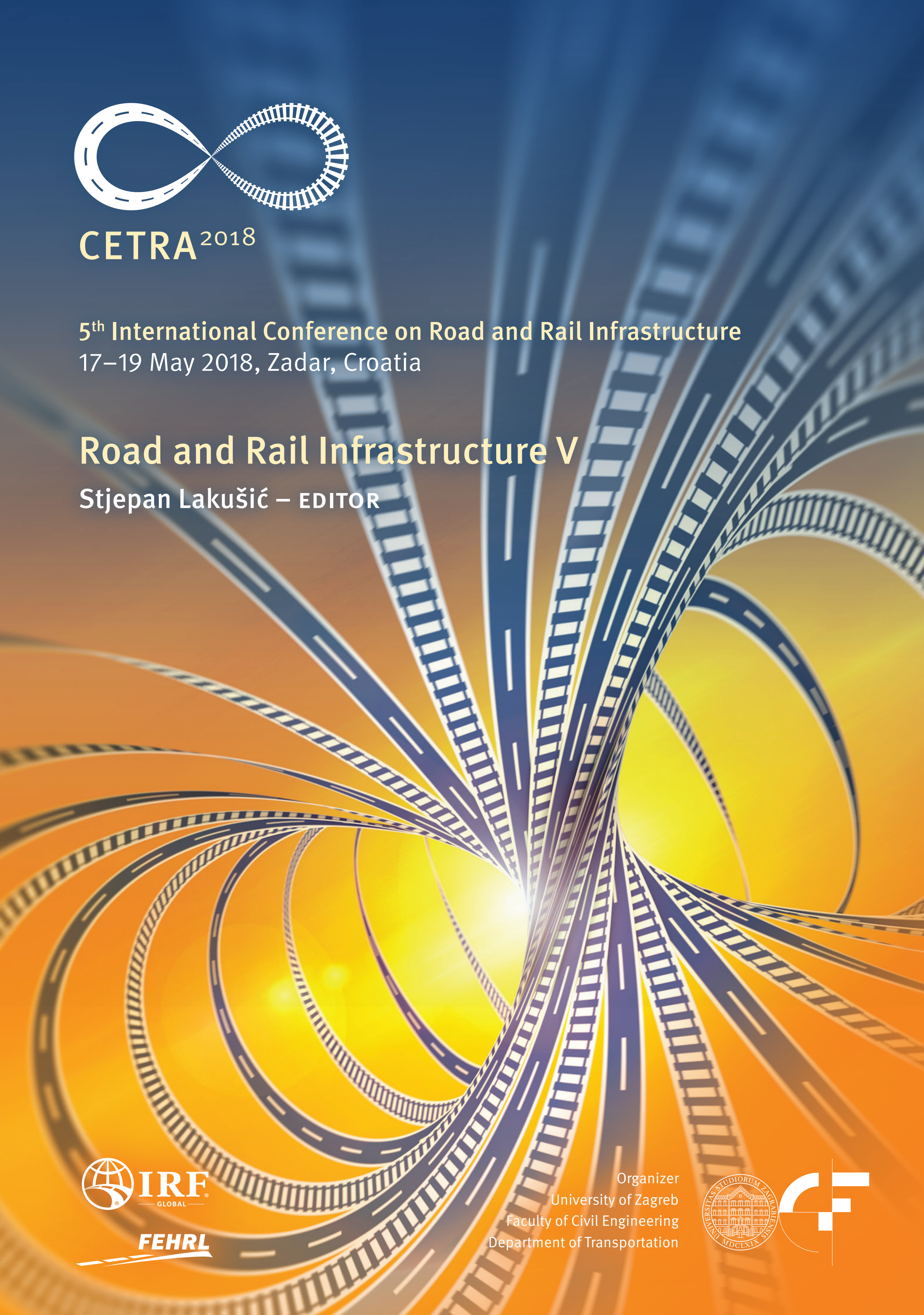

CETRA 2018

5th International Conference on Road and Rail Infrastructure
17–19 May 2018, Zadar, Croatia

Road and Rail Infrastructure V

Stjepan Lakušić – EDITOR

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FIELD TESTING OF FBG BASED DEFORMATION SENSORS EMBEDDED IN CONCRETE BRIDGE STRUCTURE

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Abstract

As far as the road network is concerned, bridge and tunnel structures are considered to be its most important and complicated elements. Bridges are completely exposed to environmental impacts; therefore, it is necessary to predict the actual structural health. The prediction can be based on monitoring of mechanical stresses which can be used to determine any resulting deterioration of load bearing structure. The main objective of bridge monitoring during construction phase is an observation of a structural behaviour in individual construction stages, particularly the actual mechanical stresses (or deformations) in critical cross sections. Based on the measured data it is possible to verify the designed parameters or to modify the design in following construction stages (load bearing structure dimensions' adjustment, pre-stressing, loading of the bridge suspensions, etc.). After the construction completion, it is possible to observe the traffic intensity as well as deformations due to temperature changes, in addition to mechanical stress monitoring. This paper presents the initial phase of a field test dealing with the utilization of embedded fibre optic sensors (custom design) for monitoring the bridge structure. The load bearing structure of the bridge is pre-stressed continuous beam structure with three individual spans; this structure is replacing the old stone four-arch bridge, which was already in poor technical condition. The sensors are integrated directly into the load bearing elements; two different types of sensors were embedded into the concrete structure. The paper describes sensor design, installation, monitoring of the pre-stressing process and monitoring of stresses in several weeks after putting the bridge into operation. The two different types of Fibre Bragg Grating sensors were tested in laboratory conditions prior bridge installation. Testing is described and results are evaluated in the paper as well.

Keywords: mechanical strain monitoring, FBG sensors, bridge structure, testing

1 Field conditions

The bridge structure is situated outside of the built-up area on the II/152 road next to Stare Hobzi in the southern part of the Czech Republic. The bridge transfers the traffic across Moravska Dyje river. The original bridge was an old stone four-arch bridge in poor technical condition. The old bridge had to be demolished and replaced by a new structure. The river flows in the second span, all the other spans are designed for inundation.

The foundation of a new bridge structure consists of 36 drilled large diameter piles (each 900 mm in diameter and 5.0 m / 6.0 m deep) fixed to the weathered bedrock and connected to bridge supports. The load-bearing structure of the bridge is pre-stressed continuous beam structure with three individual spans (23 + 30 + 23 m) made of concrete C35/45 – XF2. The pre-stressing reinforcement (tendons) is designed as Y1860-S7-15.7 and concrete reinforcement (rebars) is made of structural steel B500B. The total length of the load bearing structure (LBS)

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is 77.8 m, the length of bridging 74.5 m, the width of LBS is 8.5 m and the total width of the bridge is 9.0 m. The beam cantilevers length is 2.5 m. The depth of LBS is pitching from 1.0 m in the middle to 1.6 m above the supports. On both ends of the LBS, there are crossbeams with 1.65 m depth. The bridge is equipped with cornices with stone curbs. The safety of both traffic and pedestrians is ensured by vertical steel handrail crash barrier. The construction contractor is Metrostav a.s. and the structure was designed by Projekční kancelář PRIS spol. s r.o. [1]. The site was handed over to the contractor in May 2017; the construction started with preparatory works, followed by demolitions, earthworks, foundations, and substructure. The works concerning the LBS started in August 2017. The formwork of bridge beam structure was installed, the reinforcement was placed and on October 21 the bridge was concreted. The prestressing of the structure took place on October 30 and on November 1 the formwork started to be removed. Then the road surface was completed, the bridge equipment placed and the whole construction process was completed by finishing works at the beginning of December 2017. The bridge has been put into operation on December 12, 2017. Afterward, the earthworks under the bridge structure started. Due to unpleasant weather conditions (snow melting, raining), the site under the bridge was very muddy and therefore inaccessible, neither for people nor for machinery, until the last week of February 2018.

2 Embedded FBG sensors

During the field test, two different types of optical sensors were used: FOS array for point measurement of elongation and single FOS inside a special mechanical package working as extensometer. In the laboratory, FOS inside the special mechanical package and FOS inside a 3D printed structure were tested and compared to a reference, commercially available, fibre optic sensor. All the types use Fibre Bragg Grating (FBG) measurement principle.

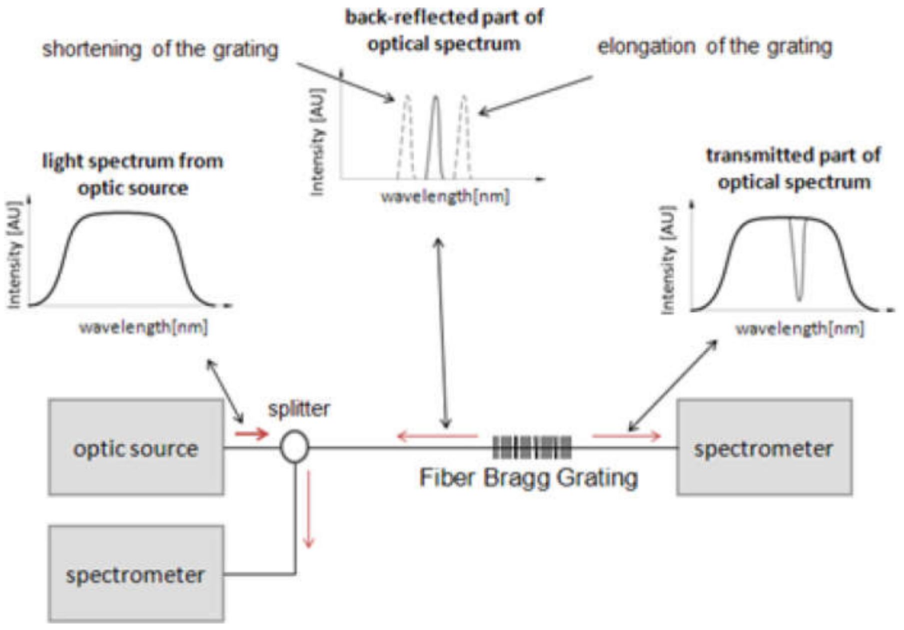

Figure 1 Experimental configuration for measurement with the FBG sensor, [2]

FBG sensor is an intrinsic spectrometric type of sensor, based on a periodic variation in the refractive index of the fibre core, which reflects particular wavelengths of light and transmits all the rest. Typical measurement configuration for the FBG sensor is pictured in Figure 1. The broadband light spectrum from optic source is guided by the optic fibre into the FBG sensor.

Part of the light is reflected by the grating (in a form of narrow Gaussian peak), the rest is transmitted. For sensing purposes, the reflected peak is commonly measured using a spectrometer. FBG sensor working principle is based on a sensitivity of grating period and refractive index to changes in strain and temperature. Each Bragg grating is characterized by so-called Bragg wavelength. Central (Bragg) wavelength is shifting according to the deformation of the grating. Elongation causes a positive shift, shortening causes a negative shift. The FBG principle is described in more details in [3-5].

Sensor for point measurement (GFRP, see Figure 2a) consists of so-called Draw Tower Grating (DTG) sensor array with protective Glass Fibre Reinforced Polymer (GFRP) sleeve (outer diameter – 1 mm, number of FBGs – 4). Longitudinal glass fibres in combination with Vinyl Ester resin provide sufficient mechanical protection for optical fibres in the temperature range from -40 °C to 120 °C.

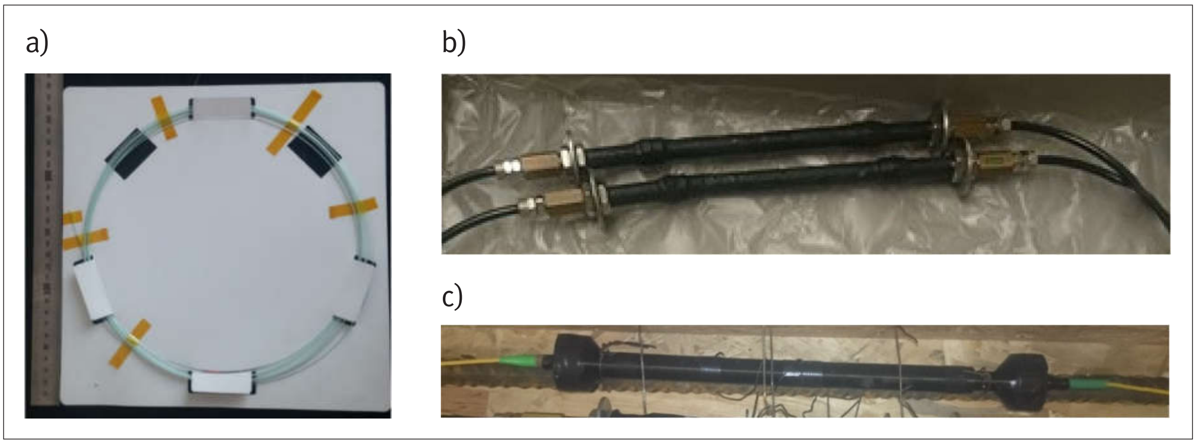

Figure 2 FBG sensors used for the field and laboratory testing. a) FOS array in GFRP protection sleeve; b) FOS inside special mechanical package; c) FOS inside 3D printed structure.

Sensor for extension measurement (SAF, see Figure 2b) is based on a newly modified Safibra FBGS-01 strain sensor. Sensor construction was changed to withstand high moisture and pressure load during the concrete manufacturing process. The additional reinforcing tube was used to cover FBG and to provide positive pre-strain of roughly 2000 μm/m. Working principle is based on FBG sensor measuring extension between two anchoring points (circular steel plates) with optional base length.

3D printed sensor (see Figure 2c) is designed as an embedded element for mechanical strain monitoring in concrete structures. The sensor is able to monitor the behaviour of complex concrete structures, such as bridges, footbridges, tunnels and long-span floor structures; it can be used for example for their overload detection. The sensor is made from two mutually sliding cylinders made of ABS-M30 thermoplastic. Inside the sensor, there is an optical fibre equipped with fibre Bragg grating (FBG). By applying the mechanical stress, the wavelength varies and is reflected by the Bragg grating; the reflected wavelength detection is then performed by spectral analysis.

3 Testing prior to field deployment

The embedded FBG sensors were tested in laboratory conditions prior to the field deployment. Three types of sensors were placed into the reinforced concrete beam with dimensions 150 x 200 x 1800 mm. There were two SAF sensors (described in the previous chapter), one reference sensor (commercially available product) and one sensor in 3D printed structure (described in the previous chapter). The concrete used for the beam was C30/37 and the reinforcement was two steel rebars with the diameter 20 mm. The schematic longitudinal section is presented in Figure 3.

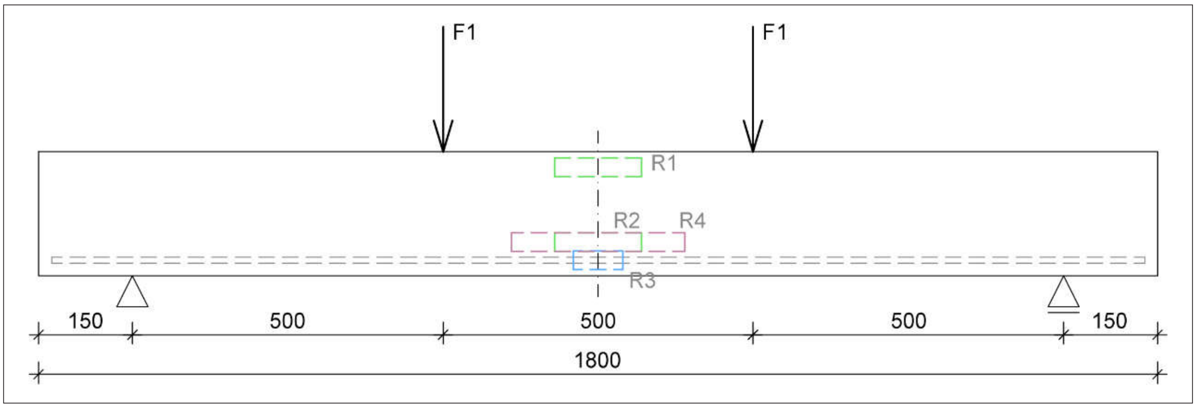

Figure 3 Schematic longitudinal section of a testing concrete beam. R1, R2 – tested sensors SAF, R3 – reference sensor, R4 – 3D printed sensor

In the first stage, the sensors embedded in the beam were subjected to long-term stability testing. During the test, good response of sensors to temperature changes with no mechanical loading of the structure was observed. Tested and reference sensors demonstrated very similar behaviour, 3D printed sensor showed slightly bigger values of measured strain. The reason is the higher value of the thermal expansion of the case of the 3D printed sensor. The testing proved overall stability in time and good response of the sensors to temperature changes.

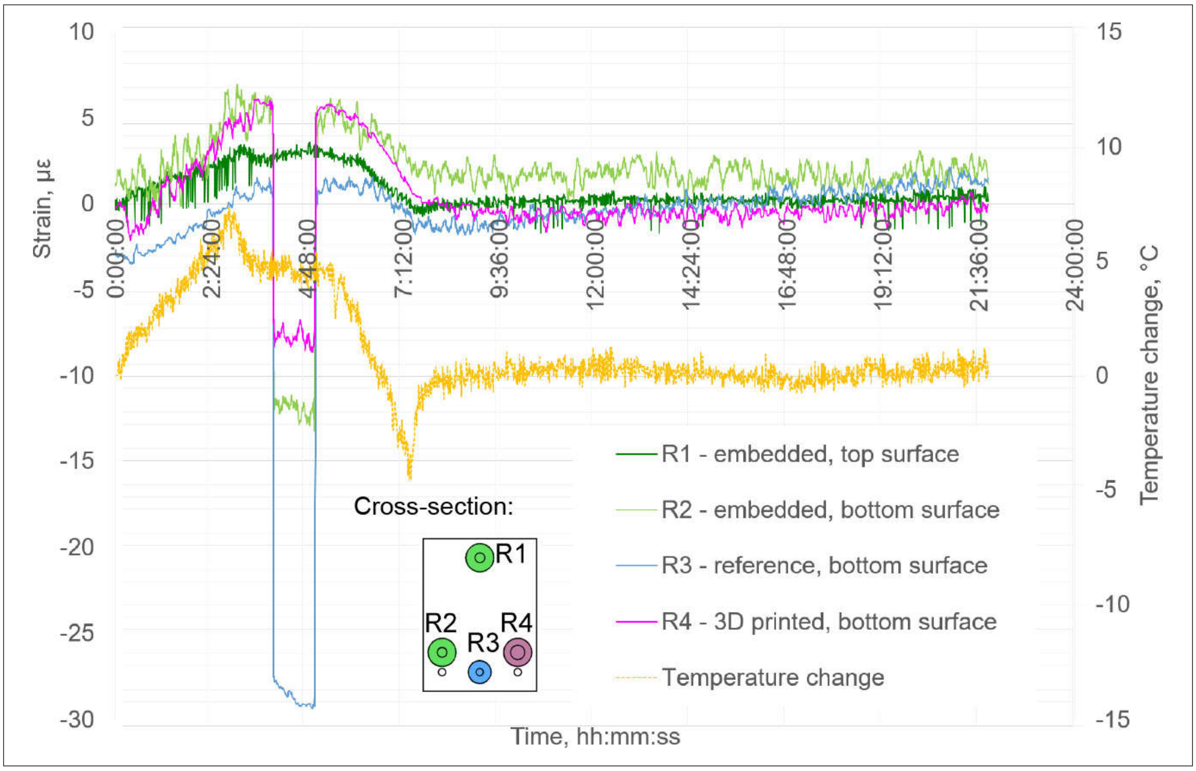

Figure 4 The response of the sensors to mechanical loading and unloading. Schematic cross-section of a testing beam with position of sensors

The second stage of laboratory testing was a short-term stability test. The beam was left unloaded for almost four hours; the temperature changes were observed all the time. Then the beam was loaded simulating the four-point bending test (as shown in Figure 3). The I-shaped 460 kg steel beam has been used as a weight inducing the single force F1 to be 2.25 kN. Due to the very low level of the maximal stress (no cracks developed yet, maximal stress equals to 1.13 MPa), the elastic behaviour of the beam is considered; therefore, the maximal calculated mechanical strain in the middle of the beam equals to 35 μm/m. The loading has been kept stable for an hour, then the test beam has been unloaded again. The response and overall stability have been observed for another almost seventeen hours. Considering the fact, that the test was performed in a test hall with higher temperature variation, the temperature changes were monitored for the whole duration of the test.

The plot in Figure 4 shows the temperature variation (dashed yellow curve) at the beginning of the test together with the response of all the sensors (strain variations correspond to temperature changes). The response of all the relevant sensors to the mechanical loading and unloading of the beam is clearly visible as well; nevertheless, the values of the measured strains slightly varies.

The reference sensor R3 is placed very close to the lower surface of the beam; the value of the measured strain is the biggest of all the tested sensors and also is almost the same as the maximal calculated strain in the cross-section. Values of strain measured by sensors R1 (SAF) and R4 (3D printed) are almost the same and concurrently lower than the value obtained by reference sensor R3; they are placed closer to the neutral axis of the cross-section. The sensor R1 (SAF) was placed close to the top surface of the beam and measured almost no change in strain. The stability of sensors after the unloading was proven very good; the strain measured by all the sensors is close to zero.

4 Field measurements

The area surrounding the bridge is a Special area of conservation (SAC) and therefore was not affected except the demolition and necessary construction works. The site was restored to its original state after the bridge reconstruction. There were no works concerning the riverbed, except for the reinforcement of the banks of the river bed on the outline of the bridge by a stone casting with a concrete footing. The site is an inundation area; it is regularly flooded. The slopes around the bridge are reinforced by stone embedded in concrete. There is an inspection staircase in the vicinity of one of the bridge supports. All the other areas surrounding the bridge structure have been grassed over.

Due to the construction works, the sensors were mounted to the bridge reinforcement in October 2017. There were two types of sensors used – two pieces of FOS inside the special mechanical package (SAF sensors) and one FOS array for point measurement (GFRP sensor) with four FBGs. The position of sensors is shown in Figure 5.

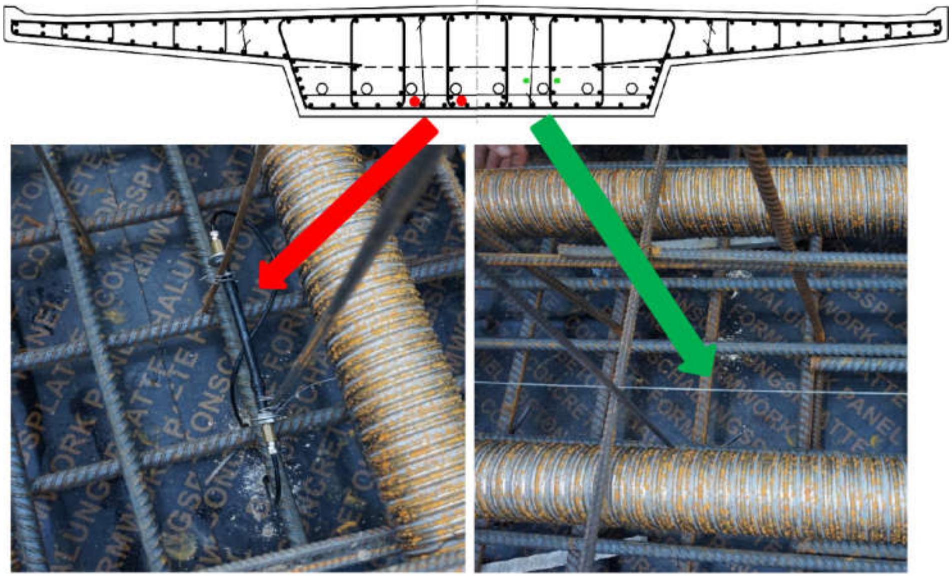

Figure 5 Schematic cross section of the bridge with position of sensors, photographs from the installation. Red (left) – the position of two SAF sensors. Green (right) – position GFRP sensor

After the installation, the bridge was immediately concreted. The first stage of measurement started on October 27, 2017, and lasted until November 1, 2017, when the formwork started to be removed. In the measuring period, the structure has been pre-stressed. The pre-stressing process has been monitored and is presented in Figure 6. The plot shows, that the effect of pre-stressing is bigger regarding the SAF sensors. That is presumably due to the fact, that they are placed near to the bottom surface of the cross-section; on the other hand, the GFRP FOS array is placed closer to the neutral axis; therefore, the values of measured strain are smaller. All the sensors show two main phases of pre-stressing as well as the individual pre-stressing steps.

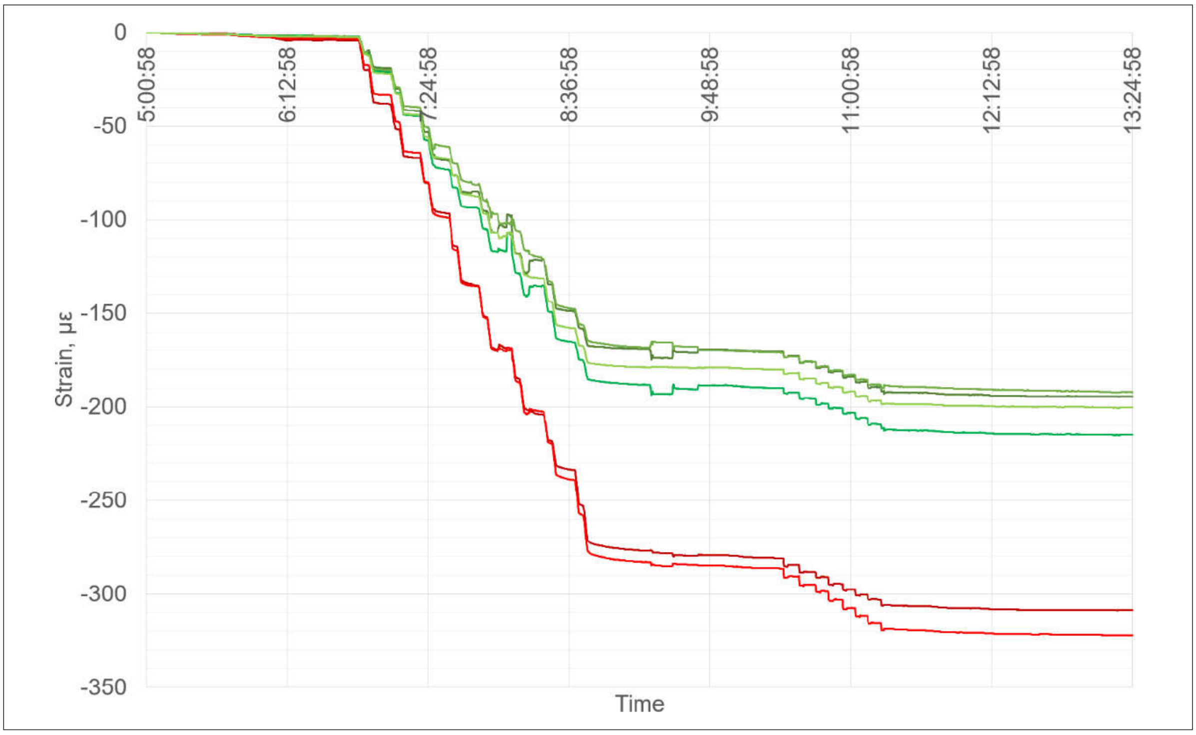

Figure 6 Pre-stressing of the bridge structure, October 31, 2017. Shades of red – sensors in steel case. Shades of green – GFRP FOS array

Figure 7 Pictures from the checking of the sensors. Left – measured spectrum of four FBGs in GFRP sensor. Right – damaged connectors of SAF sensors

The next stage of measurement was planned for February and March 2018, after completion of the construction works. Nevertheless, the unfavourable weather conditions (heavy freezing and snowing) allowed only the quick check of the sensors. The connectors of the GFRP sensor were functional, the measured spectrum of all the four FBGs is presented in Figure 7 (left). The connectors of both SAF sensors were unfortunately damaged during the construction works (formwork removing, earthworks made by heavy machinery) and need to be reconnected, see Figure 7 (right); that will happen as soon as the weather allows for (fibre splicing is not possible at temperatures below 0°C).

5 Conclusion

Three different types of fibre optic sensors working on the FBG principle were tested during the field and laboratory measurements: FOS array in GFRP sleeve, FOS inside a special mechanical package and FOS inside a 3D printed plastic structure. Besides their response to mechanical loading, the temperature stability in time was observed.

The laboratory testing proved the overall stability of all the tested sensors in time and good response of sensors to temperature changes. Considering the response to the mechanical loading, the measurement showed the sufficiently good response of sensors; the measured values corresponded to the position of individual sensors along the cross-section of the test beam. When unloaded, all the sensors proved elastic behaviour without any permanent deformation of their structures.

During the field test, fibre optic sensors were embedded into the load-bearing structure of the road bridge (pre-stressed continuous beam structure with three individual spans). After the installation, the pre-stressing process of the bridge structure was monitored; all the sensors proved very good response to individual pre-stressing steps. The construction works after the pre-stressing caused damage of several connectors, which need to be repaired; that was due to unfavourable weather conditions not possible yet. Therefore, the reconnection and long-term measurements had to be rescheduled to start in spring 2018.

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References

[1] Otevřel, R., Řehulka, M.: Technical report – Bridge no. 152-007 in front of Staré Hobzí. Brno, 2015.

[2] Růžička, M., Dvořák, M., Doubrava, K.: Strain measurement with the Fiber Bragg Grating optical sensors, Proceedings of the 50th Annual Conference on Experimental Stress Analysis, pp. 385-392, Tábor, Czech Republic, 2012, ISBN 978-80-01-05060-6.

[3] Othonos, A., Kyriacos, K.: Fiber Bragg gratings: fundamentals and applications in telecommunications and sensing, Artech House, Inc., 1999, ISBN 0-89006-344-3

[4] Záleský, J., Čápová, K., Záleský, M.: Concept of fibre optics geotechnical deformation monitoring and in-situ deployment in open cast mine, Geoconference on Science and Technologies in Geology, Exploration and Mining, SGEM 2014, vol. II, pp. 179-186, Albena, Bulgaria, 2014, ISSN 1314-2704.

[5] Zelený, R., Velebil, L., Včelák, J.: Fiber Bragg gratings embedded inside glued laminated timbers: an overview and evaluation, Proceedings of SPIE: Optical Sensing and Detection IV, vol. 9899, Brussels, Belgium, 2016, ISSN 0277-786X, doi 10.1117/12.2227902.