Structural health monitoring of a “Stary most” bridge in Bratislava with novel FBG technology

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ABSTRACT: Nowadays, engineering structures including bridges and buildings suffer from cyclic stress including changes to the boundary conditions, environment changes and constant load more than ever before. The increase in stress is likely to differ from the projected values and even though is still acceptable, it decreases the projected lifetime and increases the risk of failure. The aim of this paper is to describe the implemented FBG based monitoring system, present the measured values in context of the theoretically expected values, challenges during installation, commissioning and data evaluation, real-life in-site experience and benefits for the owners of the bridge. This will be demonstrated on the bridge “Stary most” located in Bratislava, Slovakia. The construction of the new bridge went from 2014 until 2016. During the projecting phase, it was decided to equip the bridge with intelligent structural health monitoring system to determine the current state of health and retrieve long term information about the integrity of the structure.

1 INTRODUCTION

The “Stary most” located in the capital of Slovakia, Bratislava, was commissioned in the beginning of 1946. From that time until 2013 the bridge underwent multiple reconstructions and at the end of 2013 it was decided to replace the bridge with a completely new one due to its bad conditions and age. More than 400mtr long bridge was constructed during 2014-2016 over the Danube River. It carries the name of the original bridge called “Stary Most” and it serves as important and integral part of the Bratislava’s public transportation system connecting both parts of the city for pedestrians and trams.

The incremental launching method (ILM) was chosen as the way of construction, due to space restrictions and the location of the bridge. During this construction method the bridge main structures are assembled on one shore and afterwards launched longitudinally towards the other shore. This is performed in a series of subsequent launches until the bridge reach the opposite shore.

The main or supporting steel structure of the bridge is technically and operationally the most challenging construction. It was therefore decided that it’s necessary to monitor the technical condition (state of stress, deformation, temperature) during operations. Such system should allow to be used in two phases: Firstly, during the construction process to verify the stresses in the construction during the launch phases and verify them against simulated and calculated theoretical values. Secondly, during the usage of the bridge to assess and monitor the structural health of the construction from the long term perspective. The improvement of safety is a strong motivation considering some accidents reported from similar structures around the world.

It was proposed to use a monitoring system based on fiber optic technology – FBG system mainly because the nature of the construction and the strict requirements for the EMI immunity due to the trams, because of its electrical passivity but mainly due to its modularity that allowed continuous increasing number of measured points integrated in the same system together as the bridge continuously grew. All critical and warning values were implemented into cloud based data management software.

2 REQURIMENTS AND TECHNOLOGY

2.1 Fiber Bragg Grating Technology

Sensing systems based on Fiber Bragg Grating (FBG) technology are nowadays more and more deployed for SHM applications and carrying numerous advantages comparing to conventional electrical sensors. A fiber optic sensor acts in the sensing network as a passive component and allows deployment even inside explosive environments where any electrical signal is prohibited. While comparing the fundamental principle of both technologies the fiber optic sensor use light as the signal carrier, rather than electric current as in conventional sensors, which makes them immune to interference from electrostatic, electromagnetic and radio sources. Among these advantages the combination of fiber optic technology for data transfer and FBG technology for creating the sensing element provides wide broadband, low loss and the ability to carry the signal over long distances without needing an amplifier.

Fiber Bragg Grating is basically a spatial variation of the refractive index inside the core of an optical fiber. The wavelength where the maximum reflection occurs is called the Bragg wavelength λ_B and meets the Bragg condition (1):

$$\lambda_B = 2n_{eff}\Lambda \qquad (1)$$

Where n_{eff} is the effective index over the exposed region, Λ is the grating period. From the equation is obvious that changing either the effective index or the grating period will affect the reflected Bragg wavelength and therefore generating a strain change around the grating would result into wavelength shift and can be described by the following equation (2):

$$\frac{\Delta\lambda_B(\varepsilon,T)}{\lambda_B} = (1 - p_\varepsilon)\varepsilon + (\alpha + \xi)\Delta\mathrm{T} \tag{2}$$

Where p_ε is effective photo-elastic constant, Ɛ is the induced strain, α is the thermal expansion coefficient and ξ is the thermo-optical coefficient. The equation is also pointing out two effects affecting temperature affected grating. One of these effects is so called thermo-optical effect and has to be compensated by any meanings. The second effect is coming from the temperature expansion of the monitored object and doesn’t have to be excluded from the final readings.

2.2 Requirements for the monitoring system

The main objective from the end customer was to know the in-service integrity of the bridge and monitor the repeated mechanical stress. Secondly, the total stress acting on the structure and measured by the system should be possible to transform to pure mechanical stress which means to exclude the temperature induced stress. Both objectives are doable using the system however; one of the requirements prohibited the usage of any covering or enclosure system. The restriction of using a coverage system exposed the sensors to ambient temperature and set a challenge for the monitoring system in order to qualitatively remove this effect from the readings.

a) The monitoring system must inform about the state of stress of selected elements of the construction that is close to the limit values as well as on the state of stress which exceeds the limit.

b) The monitoring system must be weather resistant and its operation must not affect the millennial factors such as water, direct lightning strikes or hurricanes.

c) The system must be resistant to electromagnetic radiation generated by either the very high-voltage electric rail vehicles or their operation. It must be prepared for the impending expansion of electric vehicles is still a growing network of wireless technologies.

d) The system itself may not pose a security risk for the transmission of hazardous materials and neither could cause an explosion due to electric spark.

e) Monitoring must be continuous and real-time in order to evaluate the static effects on the construction. A cloud based system accessible from any computer is preferable.

2.3 Proposed monitoring system

Sylex´s monitoring systems are entirely based on the FBG technology using the optical fiber for carrying the information and also as the sensing element. The advantage of this system is the absolute electrical passivity of the network and the only element in the system with power drainage is the evaluation unit called interrogator.

Sylex´s SC-01 strain sensor was chosen for this monitoring project. The SC-01 (Figure 1) is a long gauge strain sensor with variable gauge length starting from 30cm to several meters with the option to carry intrinsic temperature compensation directly in-built inside the sensor body.

The housing of the sensor is made from high grade stainless steel creating a rugged and environment resistive package. The output of the sensor is expressed in strains and was lately processed to extract the mechanical stress and compared with the theoretical values. The evaluation of the mechanical stress was post-processed with the help of Hook's law (3) and knowing the material properties of the bridge.

$$\sigma = E\varepsilon \tag{3}$$

Where σ is the mechanical stress, E is the Young modulus of elasticity of the material and ε measured relative elongation expressed in strain.

A brief performance of the sensor is summarized in Table 1. SC-01 with a gauge length of 0,35m and with intrinsic temperature compensation was manufactured.

Figure 1: Illustration picture of the SC-01 sensor.

Performance properties	
Strain range	±5000με
Accuracy (guaranteed)	<0.35% FS
Precision (guaranteed)	<0.15% FS
Temperature compensation	Integrated
Temperature accuracy	<1°C
Temperature precision	±0.3°C
Temperature range	-20°C to +60°C
Ingress Protection rating	IP 67

Table 1: Brief summary of SC-01 performance

The built-in temperature probe was used for compensating the internal effects of the sensor and also for excluding the temperature induced strain from the total strain to be able to extract only the mechanical induced strain on the bridge.

The entire sensing network was connected using a 3mm armored cable with G657/A1 optical fiber and brought to the location of the interrogation unit. For this, a single S-line Scan 816 unit with 16x optical port was chosen to acquire all measuring locations.

3 INSTALLATION AND CHALLENGES

3.1 Sensor installation and challenges

In total, 49x SC-01 sensors together with couple of surface temperature sensors were installed across the construction at each junction box and afterwards connected using fiber optic distribution cable to the collector with the interrogator unit. Positions of all measuring points for both short and long term monitoring were determined according to FEA (finite element analysis) by the projecting company. Figure 2 shows the positions chosen for long term monitoring.

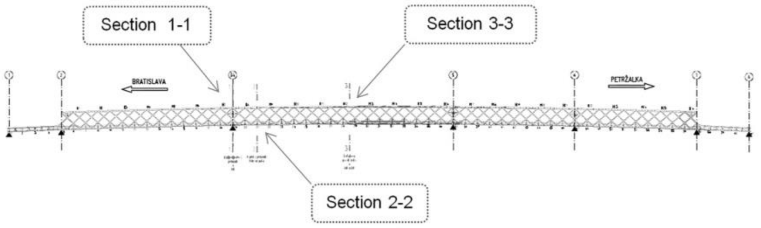


Figure 2: Schematic view of the bridge with highlighted locations for long term monitoring.

The installation on a bridge of such dimensions and moreover during the construction of the bridge itself is a challenge for both the engineers providing the installation but also for the sensors and equipment. The conditions were extreme and rapidly changing due to the continuous work of several other teams working on the construction. The lack of space while moving from one location to another, working at heights (Figure 3) required continuous vigilance above the land or river required continuous vigilance by the installation team which corresponded with the necessary time for the whole installation process.

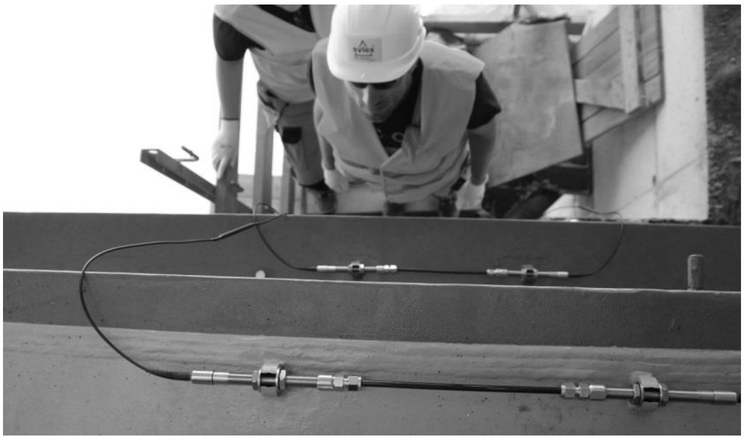


Figure 3: Installation team posing next to two SC-01 already installed and secured in place.

The SC-01 is mounted into stainless steel brackets which are holding the sensor securely in place and in the same time allowing to set-up the initial pre-strain on the gauge. All brackets were weld down on the structure during the manufacturing phase by the construction manufacturer. This solution has several advantages like shortening the time of installation but brought also several risks with it. Every pair of brackets had to be in a certain distance perpendicular to the surface and in one axis with each other. Any misalignment could jeopardize the readings. During the installation work and partial measurement it was discovered that at certain places the in-built temperature compensation of SC-01 wasn’t sufficient to reliable compensate the sensor and therefore it was decided to place at certain location a surface temperature sensor of type STS-01. The STS-01 has isolated temperature area from ambient temperature and served as an addition and correction element in the whole network.

3.2 Network topology

The whole monitoring system should fit into the visual conditions of the bridge and shouldn’t disrupt the esthetical appearance after the installation. The sensors were mostly positioned below the street level making them invisible for the eye of any spectator. However, the connection cables had to be run on the surface of the steel structure with the restriction of using any protective ducting. The optical network was therefore divided into two cabling categories. The primary cabling is managed inside a tray and connecting the junction boxes and the interrogator together. The secondary cabling is arraying the sensors between each other at particular locations using special Dyneema reinforced 3mm optical cable carrying G657/A1 optical fiber. Connectors were protected with IP 67 watertight connector protection and small dimensions minimizing the disruption of visual appearance. The junction boxes gathered several sensors at one location reducing the need of used cables to only one fiber to carry the signal from all sensors at one location. Afterwards, by using a 7mm fiber optic distribution cable with 24 fibers (primary cabling) all junction boxes were connected together and with the interrogation unit. In total, 6x junction boxes are distributed along the bridge gathering all sensors into one distribution cable with a total length of 600m. Figure 4 is showing the positions of all collector joints distributed across the bridge.

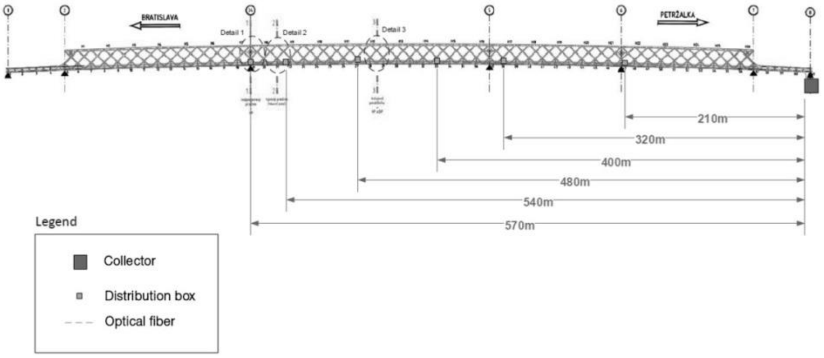


Figure 4: Schematic view of the bridge with highlighted locations of collector joints.

The interrogation unit was located inside the main collector positioned on one shore. Only one 7mm cable was necessary to be run to the main collector to bring the signal from 49 sensors positioned across the bridge.

3.3 Local and cloud based user interface

The S-line Scan series is a modular system allowing either the usage of only the interrogator or upgrading its capacity and functionality with computer and optical switch by simply stacking the modules on each other. The S-line Scan 816 used for this project was equipped with a 16 port optical switch and Windows based computer locally running the data logging software called Sentinel 1.0. It was necessary to provide only one standard power plug to power the whole monitoring system (Figure 5).

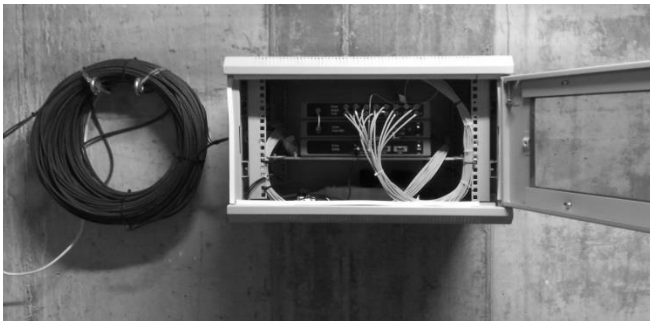
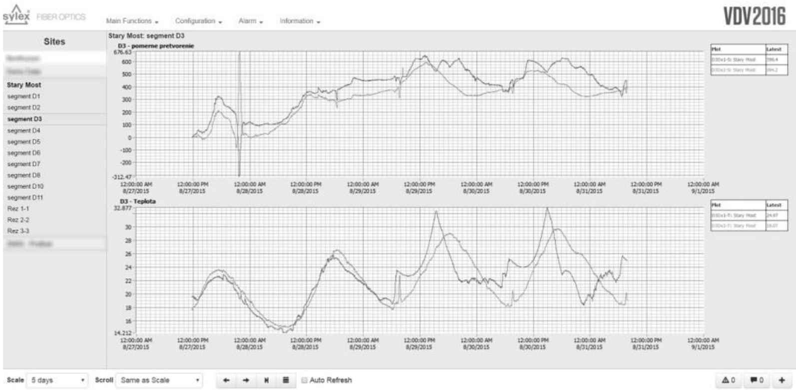


Figure 5: Final position of the system inside the main collector.

Sentinel 1.0 provides logging the data remotely though an FTP connection. Sylex established a cloud based solution running the VDV software called S-line View (Figure 6) simplifying the user interface and data preview to a simple click through the user web browser.



Scale 5 days

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Figure 6: Preview of historical data available through S-line View.

4 THEORETICAL AND EXPERIMENTAL DATA

4.1 Comparison of theoretical and experimental data by launching the bridge

Sylex´s role during the short-term monitoring was to collect data during the series of subsequent launching and afterwards compare them against the simulated data from the projecting company. These measurements were performed in real time during every launch was with the presence of Sylex engineers. The aim of this measurement was to compare and confirm model created using FEA (finite element analysis) by company SHP and like that verify the model.

This happened during 11 launches and compared against the values from simulation, Figure 7. The readings from strain sensors were interpreted by the strain equation (4) and afterwards post-processed using Hook’s law (3) in order to get stress.

$$\Delta\varepsilon = \frac{\frac{\lambda_{act,strain} - \lambda_{0,strain}}{\lambda_{0,strain}} - B\left(T_{act} - T_{0,inst}\right)}{A} - \alpha_{bridge}\left(T_{act} - T_{0,inst}\right) \tag{4}$$

where $\Delta\varepsilon$ is the relative elongation in strain, $\lambda_{act,strain}$ is the actual wavelength from the strain FBG, $\lambda_{0,strain}$ is the installation wavelength from the strain FBG, T_{act} is the actual temperature,

$T_{0,inst}$ is the installation temperature, α_{bridge} is the coefficient of thermal expansion of the bridge, B is the value of thermo-optical effect and A the strain gauge coefficient.

During every launch a high correlation was seen between the measured and theoretical data confirming not only the correctness of the experimental data but also the reliability of the monitoring system installed by Sylex.

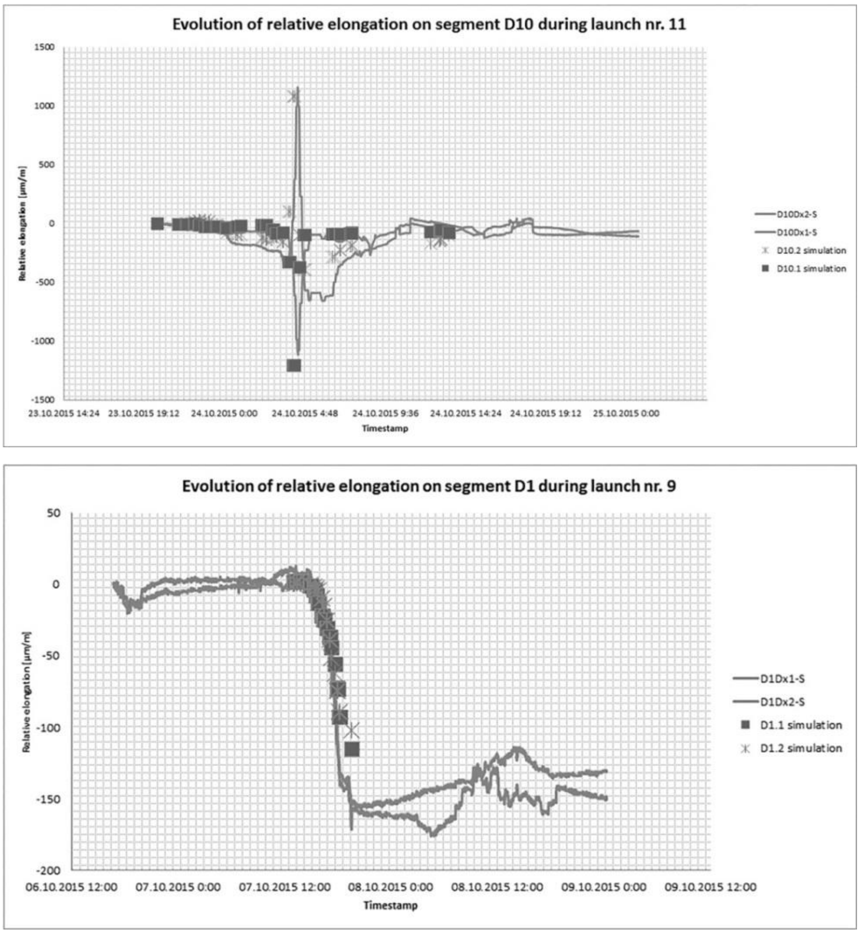

Figure 7: Evolution of relative elongation during launch nr. 9 and 11.

4.2 Long-term data

Long-term data should serve as a direct method for evaluating the technical condition (state of stress, deformation, temperature) of the bridge during his life-time and assess the structural health of the construction from the long term perspective. Data collection takes place in two steps; all data are collected using the S-line interrogator in a pre-defined interval and subsequently transferred to our FTP server for post-processing. Post-processing on the server side allows the data to be processed, evaluated and in general manipulate in any way still keeping the raw data on the side.

No significant strain (stress) changes are expected to occur on the structure even in use by the public transportation and only the natural behavior of the construction due to temperature changes and other minor changes is expected to be seen.

Figure 8 shows the strain behavior including the temperature changes during July-August 2017 gathered from segment D10. Measured values which can be seen on Figure 8 are representing total strain, mechanical and temperature strain to the structure, and therefore the temperature induced strain wasn’t excluded from the measurement in this particular case. It can be seen that the strain behavior on both sensors is following the temperature changes.

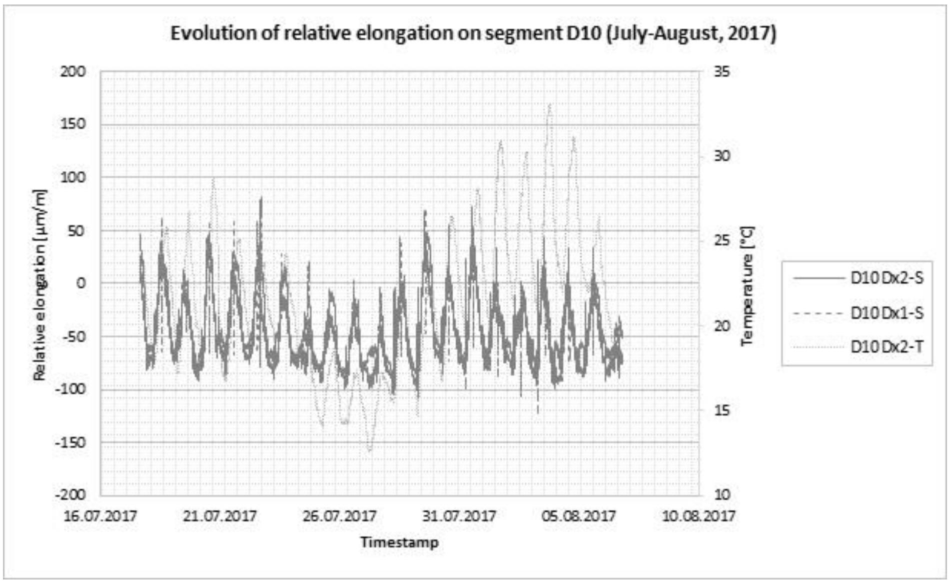

Figure 8: Long-term data gathered on segment D10 during July-August 2017.

5 CONCLUSION

Structural health monitoring is becoming an essential part in various industries implementing an early warning system and providing valuable data about the current state of engineering structures.

This paper is summarizing the challenge and difficulties while implementing an FBG based SHM into such complicated structure like a bridge under construction. The technique and technology used for creating the monitoring system shows high applicability, robustness, precise readings and easy to install solution with numerous advantages comparing to conventional electrical system. It has been confirmed that the fiber optic based system not only fulfilled the initial expectations but also can serve and provide valuable data during the whole life cycle of the system.

FBG sensors allow seamless integration into one system without the need of any additional technology. This advantage of the system allows a high modularity of the system even during the installation and highlights another advantage of the whole sensing network. It has been confirmed that the expected strain values during the subsequent launches of the bridge and as well during the static tests correlated with the measured values from the sensor arrays. The close correlation not only confirms the bridge model but also the reliability of the installed system and ensures that data acquired in the future will correlate with the state of the bridge.

Therefore, implementing a FBG based detection and assessment system for engineering structures referred as structural health monitoring (SHM) are supported and becoming state of the art not only in civil engineering but also in other sectors in order to provide valuable data about the integrity, safety of monitored structures and to ensure the ability to fulfill its intended function during the whole life cycle.