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Comprehensive permanent remote monitoring system of a multi-span highway bridge

COMPREHENSIVE PERMANENT REMOTE MONITORING SYSTEM OF A MULTI-SPAN HIGHWAY BRIDGE

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SUMMARY: As part of the reconstruction of a multi-span viaduct on a Slovenian highway, a permanent remote monitoring system with over 200 sensors was established. Several parameters are monitored on different parts of the viaduct by means of temperature sensors, accelerometers, strain gauges, long-gauge deformation and Fibre Bragg Grating (FBG) sensors. In this way strains, frequencies and temperatures on external prestressed beam cables, carbon fibre rebars used for the flexural strengthening of a deck overhang, pier caps and prestressed beams are measured and stored into the on-site central data acquisition system. This paper presents architecture of the permanent bridge monitoring system and preliminary results of the measurements.

KEY WORDS: permanent monitoring; structural health monitoring, bridge WIM; sensors; viaduct

1 INTRODUCTION

The statement that monitoring enhances our understanding of structures goes back to Leonardo da Vinci. In the 19th century the principles were established and the 20th century was devoted to developing basic methodologies. When computers, sensors and recorders became mature in the 1990s, the need for research and development was recognized by the European Comimsission and several projects related to monitoring were funded, e.g. the FP5 project IMAC [1], SAMCO Network [2], etc.

Conventional health monitoring systems have been developed to monitor bridge performance and, in some cases, the deterioration processes, with the aim to assess bridge safety. But these systems are only telling one half of the story, as they do enhance knowledge about bridge capacity but give no information about the causes of increased stresses [3]. In general, monitoring is focussed on applications in extraordinary cases and therefore does not reach daily practice. The value of monitoring must be better communicated with the bridge managers and owners, and must focus more on overall benefits of its implementation, with respect to extended lifetime of the bridges, improved mobility, environmental benefits etc. [4]. Therefore, as a part of comprehensive remediation measures undertaken on a multi-span highway bridge in Slovenia, the design and initial results of established monitoring process that measures both, response of the viaduct and the traffic loading, are presented in this paper.

2 HISTORY OF RAVBARKOMANDA VIADUCT

The first highway in Slovenia, the A1 motorway, started with the construction works of the Vrhnika - Postojna section in May 1970 and was divided into three subsections. In 1972, a Ravbarkomanda viaduct was constructed, crossing the two-lane railway line, state and local road (Figure 1). The viaduct consists of two separate structures. The right viaduct VA0174-D (traffic direction to Unec) and left viaduct VA0175-L (traffic direction to Postojna) consist of 17 and 15 spans, with total lengths of 591.4 m and 552.8 m, respectively. Both superstructures have four breaking units with five expansion joints.

Each superstructure consists of four prefabricated 2.2 m heigh I-shaped pre-stressed beams at 3.15 axial distances (Figure 1). These are connected with each other by pre-stressed transverse beams. The bridge deck is supported by elastomeric bearings. The supporting structure consists of polygonal hollow-box bridge piers and pier caps. This allows sufficient width to support the entire bridge deck. The columns were constructed with a sliding formwork, where, for ease of implementation, the unusual placement of stirrups, on the inner side of the longitudinal bars, was used [5]. Due to such implementation, stirrups cannot fulfill two very important tasks, they do not ensure the confinement of the concrete core and do not prevent the buckling of the longitudinal reinforcement.

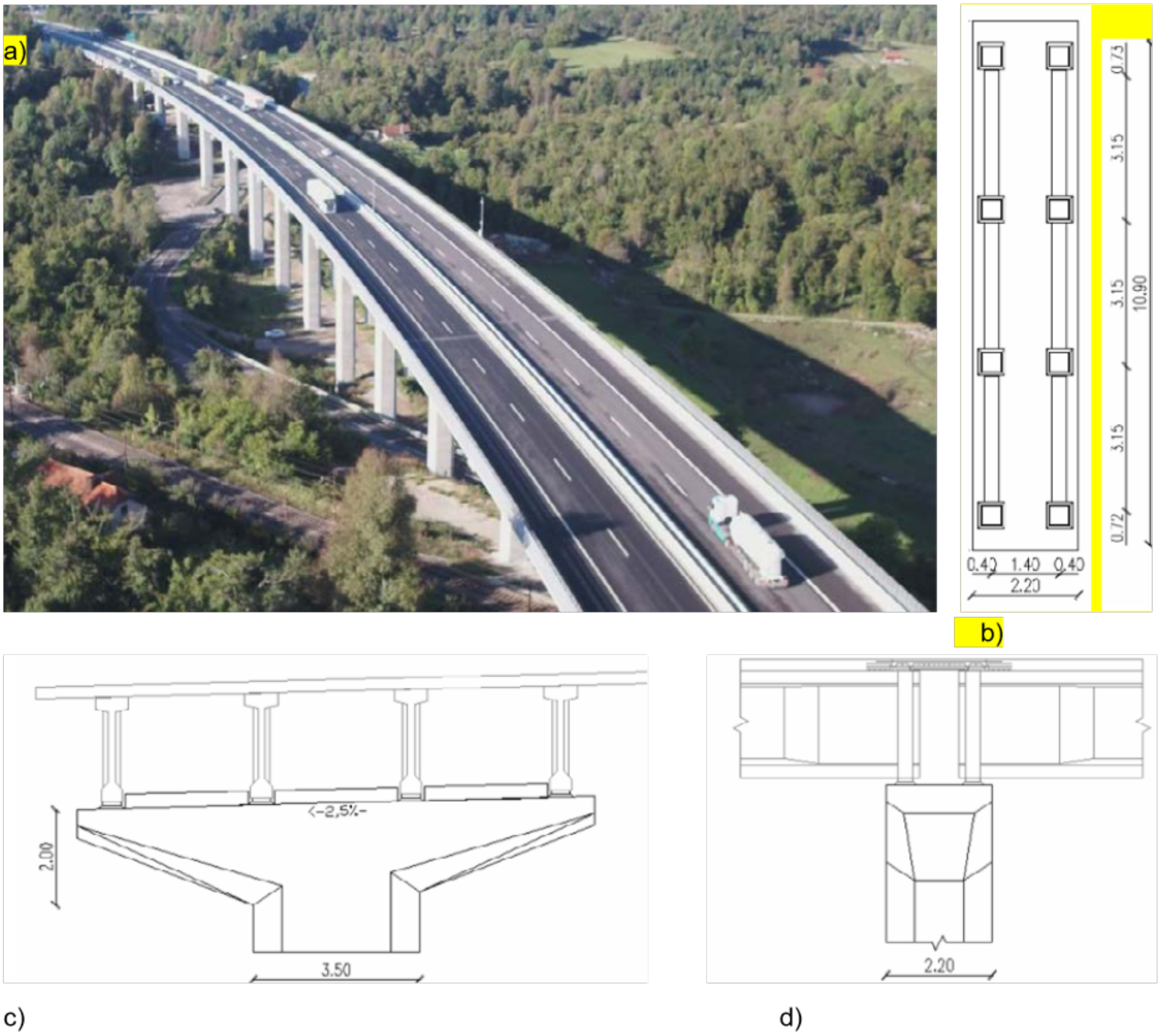

Figure 1: Ravbarkomanda viaduct: (a) aerial photo (Postojna direction), (b) plan view of pier cap, (c) pier cap and superstructure cross section, (d) side view of pier cap and superstructure

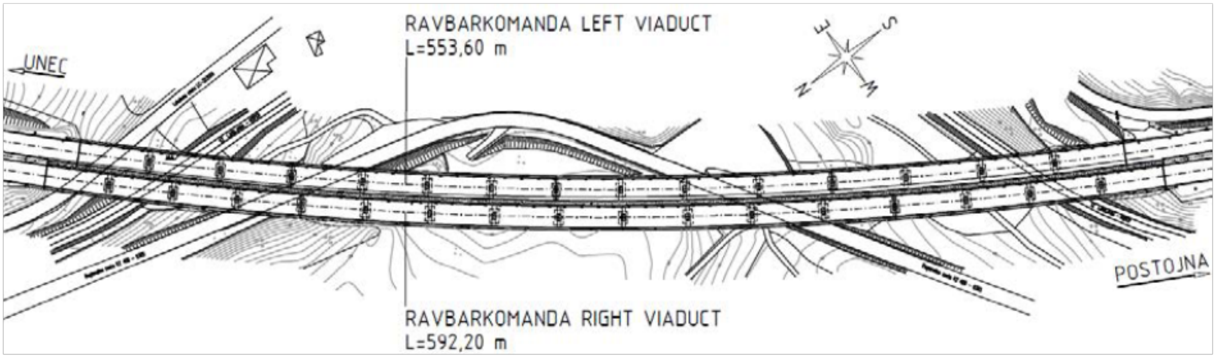

Figure 2: Plan view of Ravbarkomanda viaduct

The right viaduct is supported by sixteen 9 to 36 m high piers and the left viaduct by fourteen 14 to 36 m high piers. The polygonal cross-section of all piers is the same. The dimensions of the cross-section are 350/220 cm, with the corners cut at 60 cm with an angle of 45 °. The wall thickness is 30 cm.

During the nearly 50 years of viaducts history, several remediation works had been carried out. In 1988, the first rehabilitation works of the bridge piers were undertaken. In 1996, the major reconstruction of the superstructure was carried out, during which additional external cables were installed due to the corroded pre-stressed cables on the external I-shaped prefabricated beams (Figure 3, left).

Figure 3: Corrosion of prestressed I-shaped beam in 1996 (left) [6] and experimental studies of scaled bridge pier (right)

Analytical and experimental studies of the seismic response of the Ravbarkomanda viaduct and related box-shaped pillar structures have shown [7] that the combined bending-shear failure could occur in the case of shorter columns due to insufficient transverse reinforcement (Figure 3, right). On the basis of these studies, in 2008, the piers of the supporting structure were strengthened in order to increase the seismic capacity of the structure and to mitigate the damage in a case of severe seismic event. This was achieved by applying additional 10 cm thick concrete jacket around the bridge piers. The height of the concrete wrap corresponded to the design length the plastic hinge and the total height of the pier in the cases of higher and shorter piers, respectively, where the critical shear resistance of the columns was observed.

3 OVERVIEW ON MONITORING SYSTEM

Monitoring system, installed on the bridge, can be segmented in two groups. First part consists of the sensors, used for measuring the response of the structure (accelerometers, strain gauge sensors, long-gauge deformation sensors, FBG sensors). Second part is intended for measuring the loads, i.e. temperature sensors and strain sensors on the beams. The latter serve both for long-term monitoring of the bridge response and for measuring axle loads [8], which is important for advanced structural health monitoring system. In this way the impact of traffic can be deducted from the measured response of the bridge. Monitoring covers measurements on four key structural elements of the viaduct:

- strain and temperature measurements on the bottom side of the beams to monitor the performance of 50 years old prefabricated concrete beams,
- acceleration and temperature measurements on the external prestressed cables to monitor long-time losses or increases of pre-stressed forces,
- strain and temperature measurements on the carbon fibre rebars which are placed in the bridge slab, perpendicular to traffic direction, in order to strengthen the deck overhang in the high tensile stress regions, to monitor the effectivenss of strengthening and long time behaviour after being exposed to high temperature load during the pavement construction
- strain measurements in the high tensile stress regions of the pier caps to monitor flexural behaviour of neary 50 years old pier caps in case of increasing traffic loading.

There are two central data units located on the bridge for this monitoring project. Data from all sensors is stored at the on-site data acquisition system. The post-processing and evaluation of the measurements is performed on the off-site server, which is connected to the system by an optical connection.

The traffic loads are measured with a bridge weigh-in-motion (B-WIM) system. It applies outputs of the strain sensors, which are mounted on the lower side of the girders, temperature sensors and axle detection sensors. Detailed description of B-WIM system installation, calibration and data acquistion can be found for example in [9]. The weighing results are out of scope of this paper. Only the measurements with strain-gauges will be presented in this paper.

The scheme of the entire monitoring is shown in Figure 4. Blue colour indicates spans, where beam strains are measured, green lines indicates locations of the external prestressed cables where accelerations are measured, hatch indicates spans, where carbon fibre rebars strain measurements are performed and purple lines indicate location of pier cap's measurements.

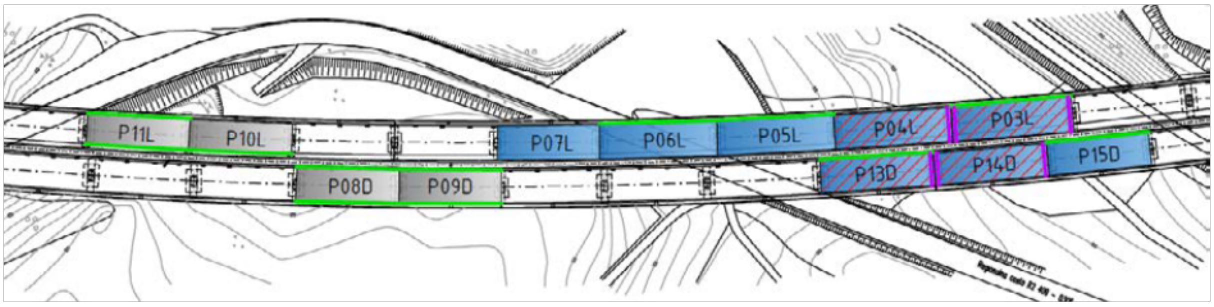

Figure 4: Scheme of monitoring

3.1 Strain measurements on beams

Flexural strains at the midspan of the beams are measured with 20 electrical resistance strain gauges in 3 spans on the right viaduct and with overall 26 electrical resistance strain gauges in 5 spans on the left viaduct. Figure 5 (left) shows strain gauge location at the midspan of the span number 15 on the right viaduct. On the Figure 5 (right), a closer look at the strain sensors is shown. Four strain sensors with a half Wheatston bridge were used at this location. Tempature near beam strain measurements location is captured by two temperature sensors in the span 14 of the right viaduct and by two temperature sensors in the span 4 of the left viaduct.

Figure 5: Two strain gauge locations on external and internal beams of the right viaduct – marked with red line (left) and 4 strain gauge sensors, all mounted at the same location on external beam of the left viaduct (right)

Data storage from all sensors to the on-site central data acquisition system runs continuously, while data post-processing is performed automatically every hour off-site on the central server, where hourly minimums, maximums and averages are calculated and compared with critical values. Figure 6 shows values of strains, induced by traffic in the period between January 2018 and June 2019. Traffic induced strains are calculated as the difference between maximum and minimum value within the measured event, wherby event is presence of one or more heavy vehicles on the bridge. Every point on the graph represents strains induced by one event.

3.2 Measurements of accelerations on external prestressed cables

One of the main reasons for rehabilitation of the Ravbarkomanda viaduct in 1996 was the severe corrosion, found on internal prestressed cables in the external prefabricated concrete beams. Load-bearing capacity of the superstructure was endangered and therefore the missing load-bearing capacity was ensured with additional external post-tensioned cables on the beams, which are located on the edges of superstructrure.

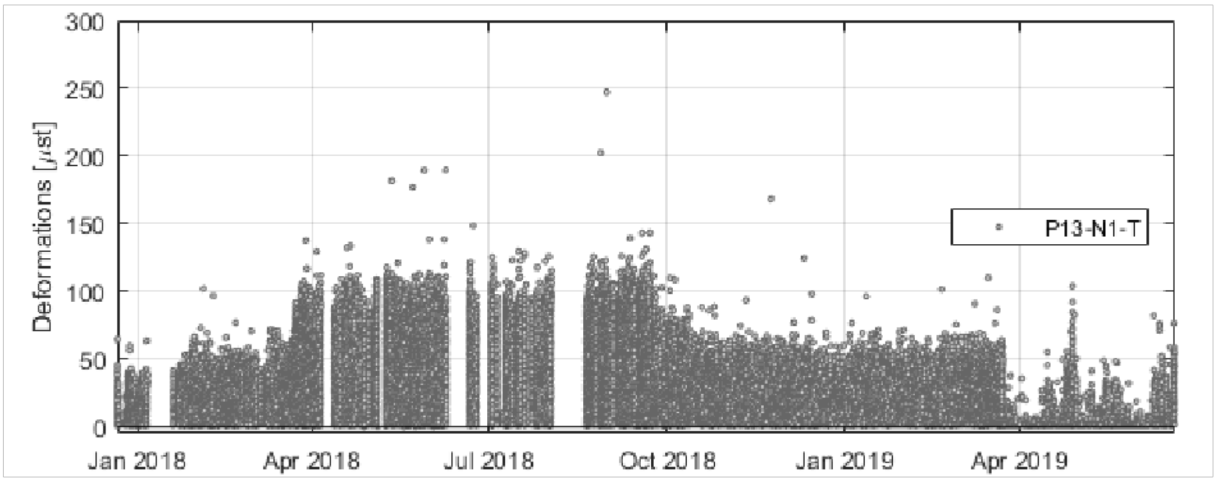

Figure 6: Traffic induced strains for beam in field number 13 of the right viaduct

External prestressing cables consist of High Density Polyethylene (HDPE) tubes in which prestressing steel strands, composed of 7 wires and the protective grout. Different configurations of prestressing cables, with different number of HDPE tubes or different number of strands are mounted on different beams. The 7-wire strand is shown in Figure 7 (left) and a prestressing cable consisting of 3 HDPE tubes with overall 6 strands is shown in Figure 7 (right).

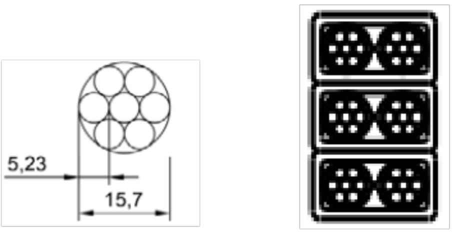

Figure 7: 7-wire prestressing steel strand (left) and prestressing cable with 3 HDPE tubes and overall 6 strands

Acceleration measurements of overall 12 cables on the right and 12 on the left viaduct are continuously undertaken. Additionally, the temperature measurements near accelerometers are performed using 4 sensors on each of the two viaducts. Accelerations of cables are measured with IEPE accelerometers mounted on the selected prestressing cables, as shown in Figure 8.

Figure 8: Prestressing cable consisting of 3 HDPE tubes and overall 6 strands with accelerometer (left) and accelerometer (right) on the left viaduct

Similarly as in the case of strains, data storage from sensors to the on-site central data acquisition system runs continuously, while data post-processing is performed automatically at 1-hour intervals. The aim of acceleration measurements is to monitor the fundamental frequency of the cable, which is related to the level of axial tension force in the prestressed cable. In this way the continuity of pre-stressing force is monitored indirectly. Every hour, the fundamental frequency is calculated within the 1-hour window, using the fast Fourier transform (FFT) [10] and is compared with the treshold values. As an example, Figure 9 shows the variation of fundamental frequencies in the field number 15 of the right viaduct in the period between April 2018 and June 2019.

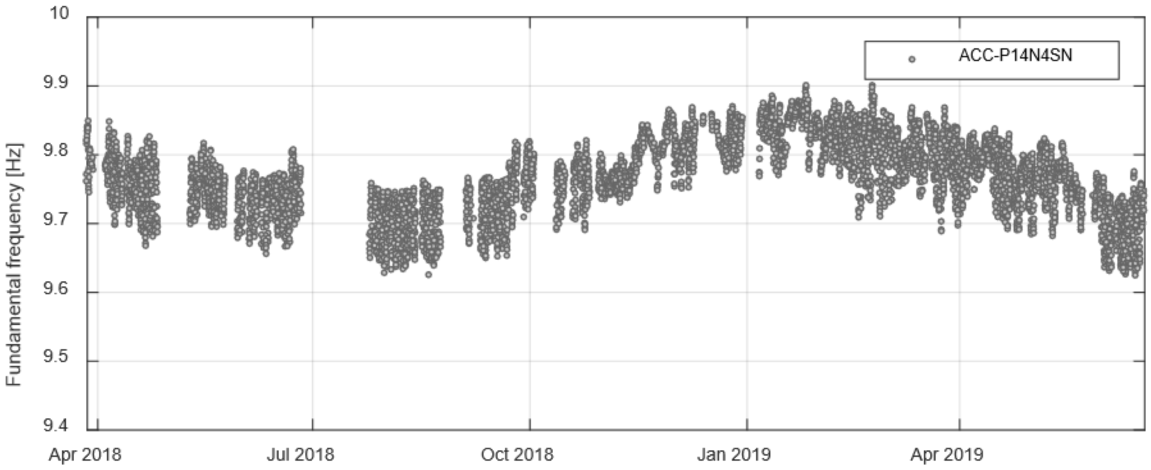

Figure 9: Hourly variation of fundamental frequencies of prestressing cable in field number 15 of the right viaduct

3.3 Carbon fibre rebar strain measurements

Deck overhangs were strengthened with near surface mounted carbon fibre rebars due the widening and installation of the concrete safety barriers. Overall, 40 FBG sensors were installed on the right and left viaduct, respectively, 20 pieces for each span (Figure 10).

Figure 10: FBG sensor glued on carbon rod (left) and installed carbon fibre rebars on the right viaduct (right)

Sensors were mounted on the carbon fibre rebars, as shown in Figure 10 (left). Rebars were afterwards installed in the precast grooves of the deck overhangs, glued with epoxy resin and covered with waterproofing and asphalt layer. Figure 10 (right) shows installed strain sensors in the span number 13 of the right viaduct. In addition, 16 temperature FBG sensors were installed in both viaducts, 4 sensors per each instrumented span. Time variation of the measured strains in carbon fibre rebars in the period between March 2018 and June 2019, induced by all loads except traffic, is shown in Figure 11. Each point on the graph represent hourly average of the minimum values measured within one minute block.

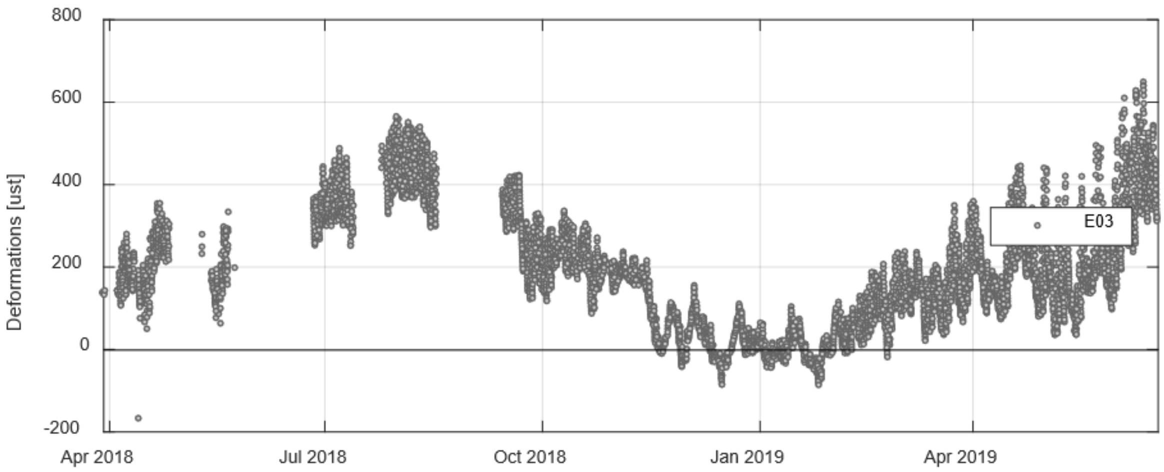

Figure 11: Hourly average strains in carbon fibre rebars, induced by all loads except traffic in the field number 13 of the right viaduct

3.4 Pier caps strain measurements

Overall 12 Smartec SOFO sensors were installed on a pier caps. Strain measurements are calcualted using the relative measured displacements divided by the sensor length, which is one or two meters. An installed sensor at the side of the pier cap in shown in Figure 12. In the Figure 13, hourly values of strains, induced by all loads (traffic, temperature, etc.) in the period between December 2018 and August 2019 are shown. Each point in the strain diagram represents hourly average of the measured strains.

Figure 12: Smartec SOFO sensor, installed at the side of the pier cap on the left viaduct: covered (a) and uncovered (b)

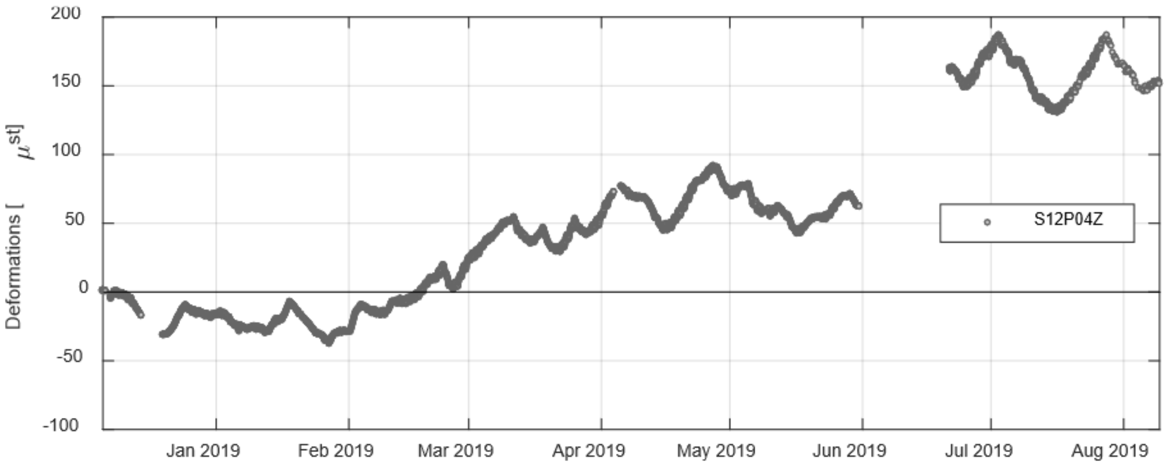

Figure 13: Hourly values of strains for sensor on the pier 12 of the left viaduct

4 CONSLUSIONS

The design and construction of the permanent monitoring systems on a multi-span highway bridge is presented in this paper. The bridge performance is monitored using over 200 sensors which are installed in order to measure the response of the bridge under traffic and ambiental loads. The system covers measurements on four key structural elements of the structure, i.e. pre-stressed cabels, carbon fibre rebars, pier caps and prefabricated beams. Acceleration and temperature measurements on the external pre-stressed cables are perfomed to monitor long-time losses or increases of pre-stressed forces. This is obtained by estimating the hourly variation of the fundamental frequency by analysing the spectral reposne of the cables. Strain and temperature measurements on the carbon fibre rebars which are placed in the bridge slab, perpendicular to traffic direction, are monitored to investigate the effectivenss of strengthening and long time behaviour ofcarbon rebars, after being exposed to high temperature load during the pavement construction. Strain measurements in the high tensile stress regions of the pier caps are performed to monitor flexural behaviour of neary 50 years old pier caps in case of increasing traffic loading. Finally, strain and temperature measurements are performed on the bottom side of the beams to monitor the long time behaviour of 50 years old prefabricated concrete beams.

The results confirm that the established monitoring system has effecitively detected the bridge response due to the environmental and traffic loads and has at the same time detected some significant events during the recondstruction of the structure, such as asphalt removal and change of traffic regime. In addition, invaluable data, in the cases of exceptional transport, was obtained, which can be used to verify performance of the viaduct in such extreme load cases. The results also imply that a less conservative and more optimal approach could be used in the assessments of realistic structural safety of bridges and, consequently, in the design of the necessary rehabilitation measures.

ACKNOWLEDGMENTS

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