Continuous monitoring of Chillon viaduct under environmental and operational variability conditions

Henar Martín-Sanz[1], Konstantinos Tatsis[1], Vasilis Dertimanis[1], Luis David Avendaño-Valencia[2], Eugen Bruhwiler[3] and Eleni Chatzi[1]

[1] Department of Civil, Environmental and Geomatic Engineering (IBK), ETH Zürich, Switzerland, chatzi@ibk.baug.ethz.ch
[2] SDU Embodied Systems for Robotics and Learning, The Maersk Mc-Kinney Institute, Syddansk Universitet , Odense, Denmark; avendano@ibk.baug.ethz.ch
[3]Structural Maintenance and Safety Laboratory (MCS), EPFL, Lausanne, Switzerland, eugen.bruehwiler@epfl.ch

ABSTRACT: Constructed in 1969, the Chillon viaducts were strengthened in 2015 with a layer of Ultra High Performance Fiber Reinforced Cement-based Composite (UHPFRC) cast atop their decks. In order to assess the efficacy of this rehabilitation solution, and further evaluate its long-term performance, a Structural Health Monitoring (SHM) campaign was implemented. Three months of monitoring data are shared with the community, with more to follow. The purpose of this preliminary analysis is to study the influence of Operational and Environmental Conditions (EOC) on the modal parameters and to further infer Performance Indicators (PIs) for assessing structural behavior [1].

Test Structure and Measured Data

The Chillon viaducts comprise two independent structures running in parallel, covering a total length of 2100 m. Each span is circa 100 m and its cross section presents a typical precast prestressed box girder section, featuring a depth varying from 5.0 m, at the supports, to 2.2 m at mid-span. In 2015, signs of Alkali-Silica Reaction (ASR) were discovered and the decks were strengthened with a layer of UHPFRC, and in 2017 a monitoring system was deployed on the bridge. In order to maximize the value of information, it was decided to instrument a representative span of 98 m, in the central portion of the viaduct. The described campaign includes 11 accelerometers distributed along the deck of the bridge, and four strain gauges and environmental sensors (measuring temperature and humidity) installed at mid-span. The accelerometers were placed in the center and at the edges of the bridge to capture torsional effects. The strain gauges were located directly on the rebar, aiming to capture fatigue effects in both longitudinal and transverse directions, as illustrated in Figure 2. The data is made available freely via Zenodo: https://zenodo.org/record/3234805#.XooIVogzZaR

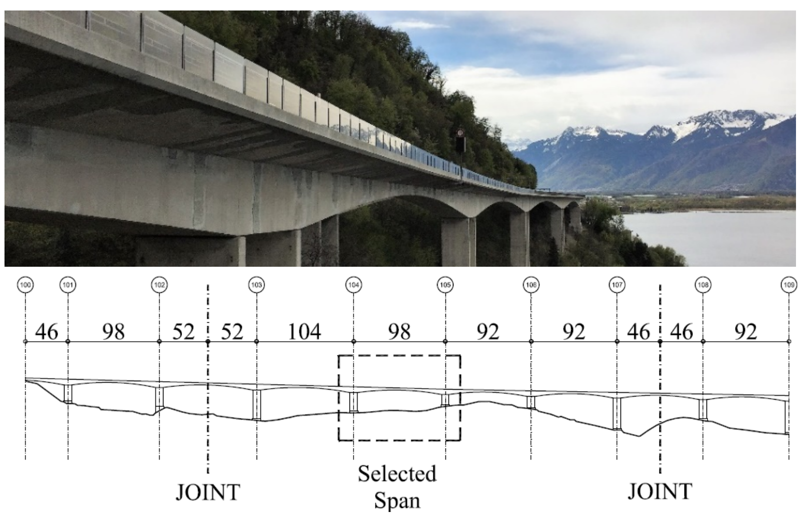

Figure 1 Elevation view of the Chillon viaducts and selected monitored span.

SHM Methodology and Results

The data was analyzed via adoption of the ERA-NeXT scheme for operational modal analysis. Frequency splitting and vanishing modes were observed the area below 10 Hz.

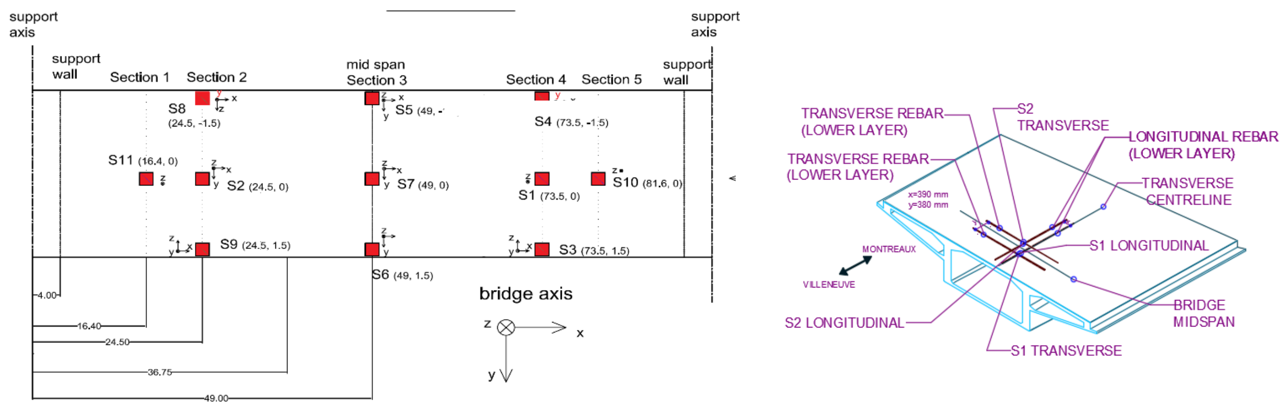

Figure 2. Position of accelerometers and strain gauges in the selected span of Chillon viaduct.

These effects were attributed to operational influences, an effect which was further investigated by means of a non-stationary analysis conducted via application of an SP-TAR model (Figure 3). Furthermore, the environmental influences were studied, and later modeled, for a better understanding of the stress levels experienced and therefore the eventually aggregated fatigue. After a clustering process, nine modes were identified whose evolution with temperature is depicted in Figure 4. As expected, a decreasing trend of the frequency is observed at increasing temperatures, particularly for the bending modes. This behavior was simulated via an updated shell-based Finite Element (FE) model, set up in SAP2000. To this end, the properties of certain parameters affected by temperature, such as elastic modulus of concrete, asphalt and bearing stiffness, were modeled as a function of temperature in the operational range of 5 to 30 ºC. The FE model proves successful in tracking the trends observed within the measurements.

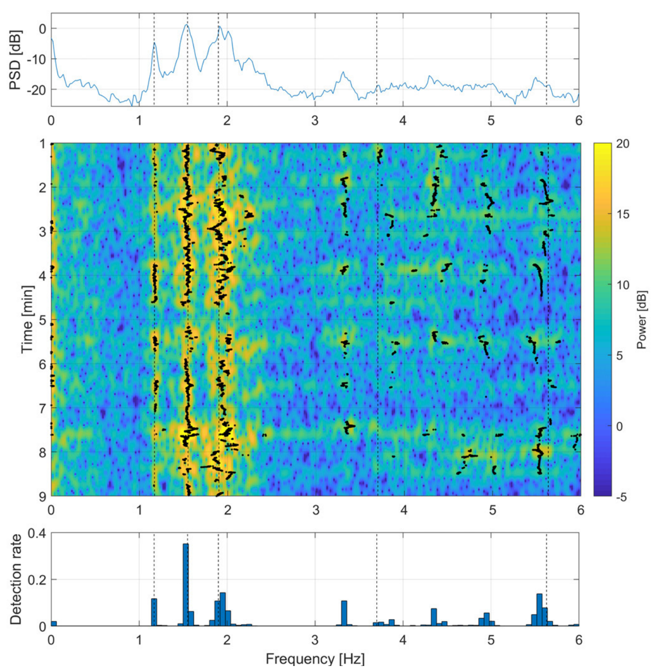

Figure 3. At the top, Welch periodogram. At the center, spectrogram of the signal with the instantaneous from the SP-TAR model overlaid. At the bottom, a histogram of the SP-TAR model-based instantaneous frequencies.

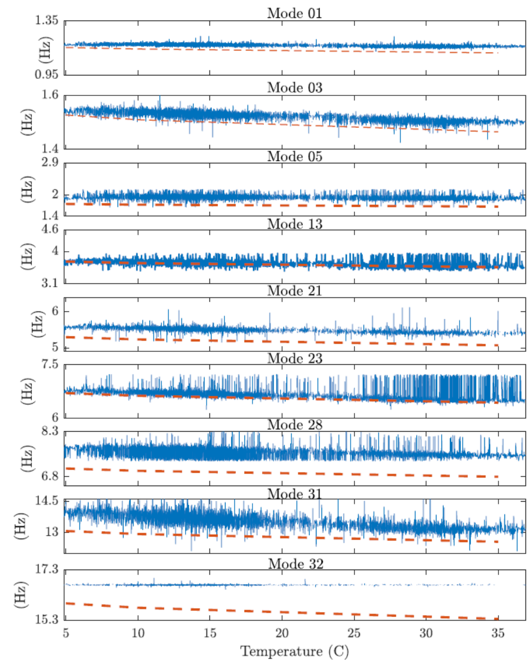

Figure 4. Frequency evolution for the measured (blue) and updated FE model modes (dotted orange) versus temperature. A decreasing tendency is observed with increasing temperatures.

As a next step, three different Performance Indicators (PIs) were obtained, in order to quantify the effects of the UHPFRC strengthening applied to the viaduct. We distinguish the function of these PIs into a) purely data-driven, i.e., fatigue obtained directly from the installed strain gauges (attached to reinforcement bars) and the long-term damage detection by monitoring frequency evolution, and b) hybrid PIs where a FE model is coupled to the data for the purpose of more intricate investigations, such as reliability analysis.

The first data-driven PI, namely fatigue accumulation, was evaluated by means of the Palmgren-Miner rule revealing that the accumulated damage lies in very low levels with structural safety ensured.

The next PI intends to quantify the bridge behavior in the long term. A global damage indicator was established, relying on tracking of the identified frequencies, but ensuring a regularization against influences induced from the variation of environmental and operational conditions (EOCs). In this work, we use Polynomial Chaos Expansion (PCE) and Independent Component Analysis (ICA), based on former work of the authoring team [2] in order to account for EOC variability and to eventually deliver a robust performance indicator (PI). Figure 5 illustrates the results for the first four modes for the three months of recorded data. PCE succeeds in capturing the regular EOC fluctuations, even for modes of higher dispersion, such as the 5th and 13th mode.

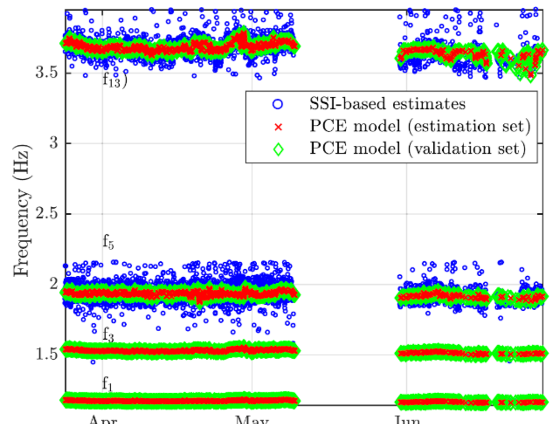

Figure 5. PCE results employing temperature and humidity as inputs, frequencies as output.

A final – hybrid – PI targets an estimation in terms of reliability. This is achieved via a hybrid calculation necessitating use of a FE model (in this case formulated in ABAQUS), which is configured on the basis of the available data. For calculating the performance of the original system, the UHPFRC layer is removed in the simulation model and the reliability calculation for critical quantities is performed anew. The results indicate that in terms of shear capacity, a reliability index $\beta = 3.1$ is obtained for the UHPFRC strengthened viaduct, versus a value of 1.85 for the original system, proving the effectiveness of the rehabilitation solution.

Lessons Learned

This work illustrates the effects of EOC influence on monitoring data, and describes a methodology to take this influence into account, as well as an approach for tackling the non-stationary effects that may be present in short-term monitoring windows. As a second focus, this case study is used for demonstrating the transformation of raw data into engineering PIs, aiming to provide a quantitative assessment of structural performance. Such a link is necessary for demonstrating the effectiveness of rehabilitation solutions and for attesting the Value of Information that stems from SHM.

Acknowledgements

The authors would like to acknowledge the following entities and people: the Swiss National Science Foundation (SNSF), which has supported this research within the context of project # 154060, the Swiss Seismological Service institution (SED), Mr. Dominik Werne and the IBK-Lab staff from ETH Zürich, the members of the MCS group in EPFL - who provided the strain data and assisted with the monitoring deployment, as well as the colleagues from the Chair of Structural Mechanics and Monitoring at ETH Zürich, who assisted in the experimental phase of this work.

References

[1] Martín-Sanz, H., Tatsis, K., Dertimanis, V. K., Avendaño-Valencia, L. D., Brühwiler, E., & Chatzi, E. (2020). Monitoring of the UHPFRC strengthened Chillon viaduct under environmental and operational variability. Structure and Infrastructure Engineering, 16(1), 138-168.

[2] Spiridonakos, M. D., Chatzi, E. N., & Sudret, B. (2016). Polynomial Chaos Expansion models for the monitoring of structures under operational variability. ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering, 2(3), B4016003. doi:10.1061/AJRUA6.0000872