Structural Health Monitoring of a Damaged Operating Bridge: a Supervised Learning Case Study

A. Cigada[1], F. Lucà[1], M. Malavisi[2], G. Mancini[2]

[1] Department of Mechanical Engineering,
Politecnico di Milano, 20158 Milano, Italy

[2] Department of Structural, Geotechnical and Building Engineering,
Politecnico di Torino, 10121 Torino, Italy

[3] SafeCertifiedStructure Ingegneria s.r.l, 10126 Torino, Italy

ABSTRACT

The aging of materials, combined with the persistence and alteration of both operational loads and atmospheric conditions, cause a decrease of the structural properties of civil structures. This raises questions of considerable importance when it comes into play the safety of infrastructure users, mainly related to bridges and roads. Therefore, monitoring and evaluating the health of such structures becomes of central importance, allowing a more efficient maintenance, aimed at preserving or recovering the required structural properties.

This article describes a case study where a structural health monitoring system has been installed on a damaged operating bridge, where the signs of heavy wear were first detected through visual inspections. Therefore, a network of accelerometers has been designed and installed to the purpose of monitoring the evolution of deterioration phenomena and testing some new approaches related to the use of MEMS sensors. In particular, sensors readings were collected in real-time in order to gain useful information about the dynamic behavior of the structure under ambient and traffic loads.

Data obtained from the monitoring system were used to support the decision of carrying out maintenance operations aiming at reinforcing the bridge, increasing its structural stiffness.

This result was achieved through the post tensioned reinforcement of the bridge, by means of external tendons. The vibration data were collected at different points along the bridge, before and after the maintenance operations, so that both the damaged and undamaged information are now known, suggesting a supervised learning approach for future monitoring of the structure. The modal parameters of the bridge, extracted from the data, have been used to verify the change in structural stiffness, confirming the effectiveness of the adopted intervention in improving the structural property.

Keywords*:* SHM, Bridge, MEMS sensors, structural dynamics, supervised learning

INTRODUCTION

The research field named Structural Health Monitoring (SHM) deals with the development of strategies for the automatic identification of damage in mechanical, civil and aerospace systems [1]. The main goal of a SHM strategy is to synthesize the information coming from different type of sensors installed on the monitored structure to obtain a constant knowledge of its structural performances. In this way it is possible to move from a "time-based" to a "condition based" maintenance; this mainly results in a more punctual and effective actions, with consequent economic advantage.

By framing the problem in the field of large-scale civil structures, the natural aging of materials and the effect of operational and environmental loads cause a health deterioration of infrastructures such as highway bridges and viaducts [2]; this reflects in serious issues for user security. Considering that most of these structures are near, or in some cases beyond, the life for which they were designed, the risk is that they no longer meet the standards requirements. Therefore, maintenance strategies assume a central importance and they can only be effective if the health status of the structures is constantly assessed.

This article describes an interesting case study of a damaged operating bridge located in Italy. Following visual inspections, the structure was found to be in a state of advanced deterioration and strengthening works were required, through the adoption of external pre-stressing tendons. In particular, this type of intervention improves the ultimate bearing capacity and thus the performances of the bridge, increasing the lifespan and durability of the structure.

In addition, the owner of the structure decided to install a SHM system for the future assessment of the structure. Despite the short time available between the decision to carry out the strengthening works and the start of operations, a series of sensors were installed on the deteriorated structure to track its behavior during the maintenance procedure. Therefore, different accelerometers and inclinometers have been used to verify the effectiveness of the intervention from a dynamic and static point of view. These have not been installed according to a modal analysis design; the very short time needed for the restoration works only allowed to set up a line of sensors, for a check on natural frequencies and modal damping, and only roughly accounting for the mode shapes; all the same, this has been considered a very important occasion to compare a damaged and undamaged bridge behavior in short times.

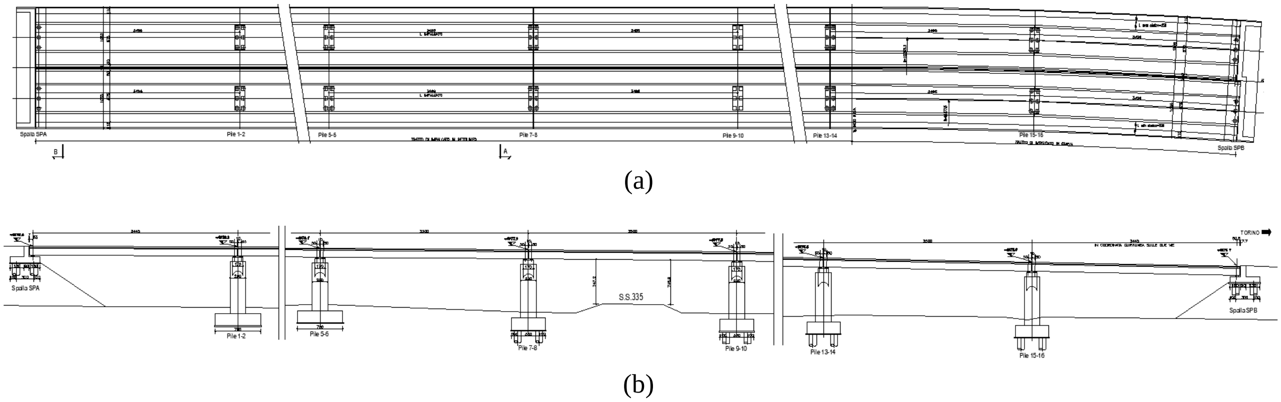
The measurements started before the strengthening works so that a dataset representative of a damaged state is now available; this is of considerable importance in a supervised learning perspective. Indeed, once a damage feature is chosen to represent the state of the structure, this family of approaches searches for damage through the correspondence between data coming from the monitored structure and data related to the damaged structure [3]. In case of civil structures, data referred to the damaged state are usually not available, apart from some case studies [4], limiting the applicability of supervised strategies.

This paper describes the application of some simple data analysis techniques applied to the data recorded before and after the strengthening works. In particular, the structure asset is derived from the clinometer data while the dynamic characteristics are obtained from the acceleration ones. Both methodologies provided very clear representations of the state of the structure before and after the maintenance works, so that it is possible to hypothesize a future development of a supervised learning SHM strategy.

THE MONITORED STRUCTURE: A PRE-STRESSED CONCRETE BRIDGE

The monitored structure is a pre-stressed concrete bridge from the early 1965s, located in northern Italy. This bridge, due to its geometric and design features, can be considered as representative of many highway infrastructures in Italy. In fact, pre-stressed concrete was a very common way of designing bridges at that time.

The structure is composed by two independent roadways, each characterized by three simply supported pre-stressed concrete spans. The span is 35.0 m long and the cross-section is a pre-stressed reinforced concrete slab with a constant height in the longitudinal direction of about 1.5 m, as shown in the plan view, elevation and cross-section of Figure 1 and Figure 2.



(a)

(b)

Figure 1. (a) Plan view and (b) elevation of the monitored bridge

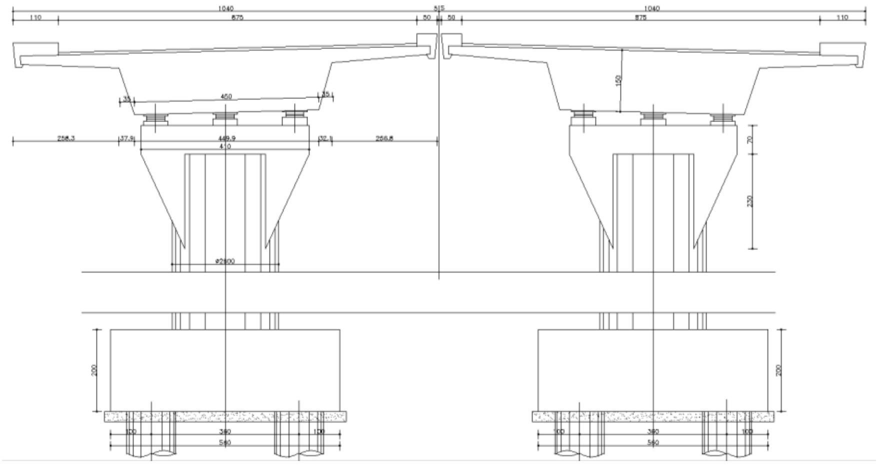


Figure 2. Cross-section of the monitored bridge

THE MONITORING SYSTEM

A structural health monitoring system composed of 90 biaxial inclinometers and 90 triaxial accelerometers has been installed on both carriageways of the viaduct. In particular, 45 inclinometers and 45 accelerometers were installed on the longitudinal beams, as reported in Figure 3. The gateways, one for each carriageway, are located between spans 5 and 6. Each of the 9 spans is therefore equipped with a chain made up of 5 sensors. A power line communication has been adopted to connect all the different devices of the network.

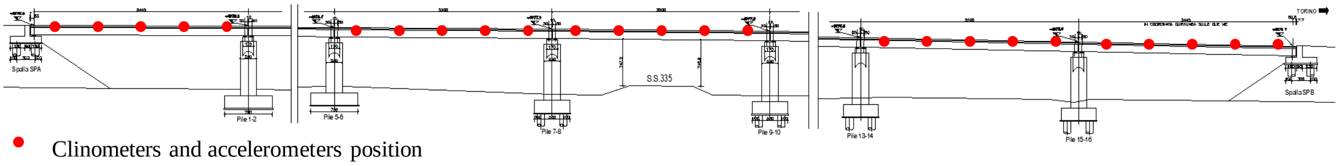
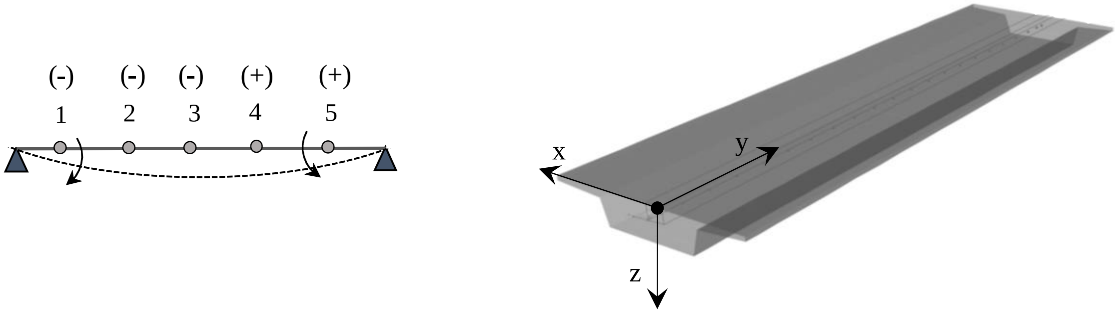


Figure 3. Instrumented cross-sections

The biaxial MEMS clinometers installed on the viaduct have two measuring axes x and y, corresponding respectively to the transversal and longitudinal direction of the bridge, meaning that the axis are respectively perpendicular and parallel to the longitudinal extension of the deck in the horizontal plane; the sign conventions adopted for the rotations are shown in Figure 4 (a). The triaxial MEMS accelerometers installed on the viaduct have the three measuring axes x, y and z oriented as shown in Figure 4 (b). The x axis is the transversal direction of the deck, y axis is parallel to the longitudinal extension of the spans and z axis corresponds to the vertical direction. Both clinometers and accelerometers are equipped with a 32-bit microcontroller for data processing at sensor level.



(a) (b)

Figure 4. (a) Signs convention for clinometers; (b) Measurement axes (x, y, z) orientation

This choice of sensors layout deserves some deepening, as the use of MEMS allows to adopt a wider number of measurement points in a trade-off against their expected performances. Preliminary laboratory testing has allowed to fix the MEMS sensors features, not so far from those of more expensive instrumentation, anyway suitable for giving the needed information. Conversely their low cost has allowed to have a very dense bridge sensing, which was considered of fundamental importance for the planned operation. Consequently, dealing with the huge data streaming represents the real challenge that forced a new data evaluation strategy.

A data processing protocol was developed to transform the readings coming from the sensors into "consistent" data, meaning significant data for the subsequent numerical modelling phases. The data acquisition from each clinometer takes place sequentially starting from the gateway at a predetermined time interval, which can be modified by a remote operator. The data acquisition of the entire sensor network is executed at regular time intervals of different length, depending on the elapsed time before all the sensors are interrogated (polling cycle). Each "read" instance includes the acquisition of the signals sent by a single sensor; only at the end of this instance, the next sensor is interrogated by the gateway.

Each inclinometer acquires a record of 1 second with a sampling frequency of 208 Hz (the sampling frequency can be updated remotely); some statistical quantities such as the mean value, the standard deviation, the maximum and minimum are then evaluated for the rotation; also the temperature and the relative humidity are recorded. If an error occurs in the interrogation of a sensor, the procedure is repeated before switching to the next sensor. Therefore, the time needed in order to complete the interrogation of all sensors is variable, depending on the occurrence of communication errors in the entire sequence of readings. The gateways store the data received locally in a buffer memory and forward it via a 3G mobile network to the Cloud database.

As for the accelerometers, the acquisition is continuous, with a sampling frequency of 100 Hz on the 3 measurement axes. Only data collected in pre-defined intervals during the day are sent to the cloud, for a better energy resources exploitation, as data transfer for storage in the cloud environment waste most of the energy in the overall balance. Fifteen minutes of continuous acquisition every 4 hours are recorded and sent to the cloud (also the frequency of this process can be modified remotely). In addition, some threshold levels have been set in order to identify anomalous scenarios; in the event that these thresholds are exceeded at any time of the day, the data around the anomalous event are stored in a local cache memory, a Solid State Disk located on the gateway and subsequently transferred to the cloud, in addition to the data sent with the explained procedure.

To finish with, at the cloud level, data coming from different sensors are stored in a dedicated database; data are then progressively extracted from the database, normalized with respect to the temperature and stored back for subsequent uses. In this phase, corrupted data are discarded. In the end the algorithms developed for data analysis are used to have a picture of the health of the structure, from a static and dynamic point of view.

STRENGTHENING WORKS OF THE PRE-STRESSED CONCRETE BRIDGE

The deterioration and the consequent performance reduction of the existing bridges, due mainly to both the structural aging and the increase in the weight and volume of traffic loads, results in localized or global damages in most of the bridge structures.

For the case study analyzed in this paper, serious structural deficiencies were identified in a particular span of the bridge following a visual inspection campaign, in which some longitudinal cracks were observed under the concrete slab. More in-depth investigations have therefore been carried out and a significant loss of pre-stressing in the investigated span of the bridge was detected due to the breakage of a significant number of pre-stressing tendons in the concrete slab.

The failure of pre-stressing tendons was probably caused by a widespread corrosive phenomenon, as shown in Figure 5.

Therefore, a network of sensors was designed and installed to the purpose of monitoring the evolution of deterioration phenomena and, at the same time, checking the effectiveness of a reinforcement intervention. In fact, following the identification of the damage, the infrastructure operator decided to carry out a reinforcement intervention on the structure. In particular, the introduction of additional external pre-stressing tendons has been chosen as a method to strengthen the structure.

Figure 5. Visual inspection campaign carried out on the bridge.

This method has proved to be very useful in increasing the capacity of concrete span bridges. External pre-stressing tendons were thus placed outside the concrete section in May 2019 and the pre-stressing force was transferred to the concrete by means of end anchorages. The application of external pre-stressing in strengthening should lead to a structural system in which the stiffness is increased. In fact, the application of an axial load combined with a hogging bending moment should reduce in-service deflections, consequence of an increased stiffness.

However, the effectiveness and the corresponding effect given by the introduction of external pre-stressing tendons as bridge reinforcement method is not so easily assessable after tendons installation.

In the following paragraph, the main results deriving from the monitoring of the described bridge, before and after the intervention, will be presented in order to verify the change in structural stiffness, confirming the effectiveness of the adopted intervention in improving the structural properties.

STATIC AND DYNAMIC MONITORING DURING THE STRENGTHENING WORKS

This paragraph summarizes the main results deriving from both clinometers and accelerometers after the reinforcement installation. Into details, a comparison between the bridge behavior before and after the reinforcement has been performed.

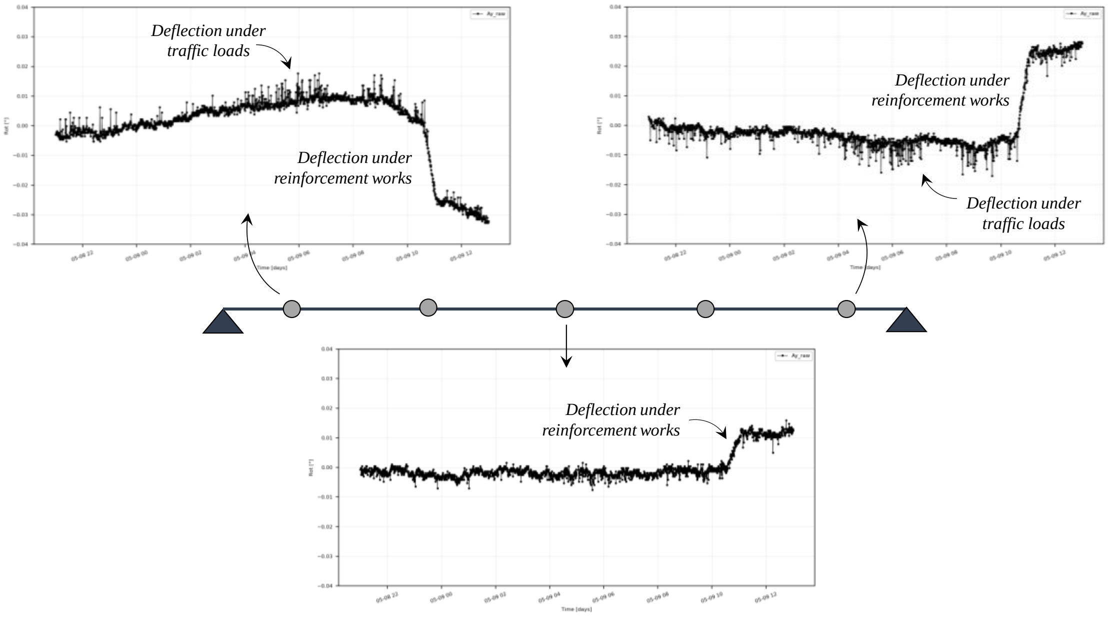


Figure 6. Tilt measurements straddling the strengthening works

The strengthening works took place on May 9th, 2019. During the restoration works the highway was open in both directions. The event was entirely recorded by both clinometers and accelerometers.

Regarding the clinometer readings, data were recorded continuously, collecting a measurement every 30 seconds. During the works, there were no relevant temperature changes, so environmental variations can be neglected in their effect on measurements.

A first analysis of the clinometer raw data highlighted an instantaneous shift in the average of tilt readings when the external force was transferred to the bridge members (May 9th, 2019, morning). Figure 6 shows tilts data recorded on the reinforced span by the two sensors located near the span ends and by the sensor positioned at mid span, in a time interval straddling the reinforcement intervention, namely from 01 to 05 May 2019.

As clearly shown in Figure 6, a significant shift in tilt values has been recorded by all the sensors. In particular, it is possible to observe that the tilt variation due to the strengthening works occurred in the opposite direction with respect to the bridge deformation under traffic loads, indicating that the external pre-stressing has caused a counter-balance in the bridge. It is also evident that the sensor located at the center of the span, from which a zero rotation value is expected under load, showed a considerable shift in the tilt average value, indicating the presence of a damaged area in the middle of the span (the presence of a plastic hinge has been hypothesized).

Starting from tilt data recorded before and after the reinforcement intervention, it was possible to calculate the deformation experienced by the bridge under the pre-stressing intervention. Figure 7 shows the bridge deformation, in terms of vertical displacements, experienced by the structure following the strengthening works. The red curve was obtained by linear interpolation of the tilt values recorded in the y direction by the sensors, after removing the average value measured before the intervention.

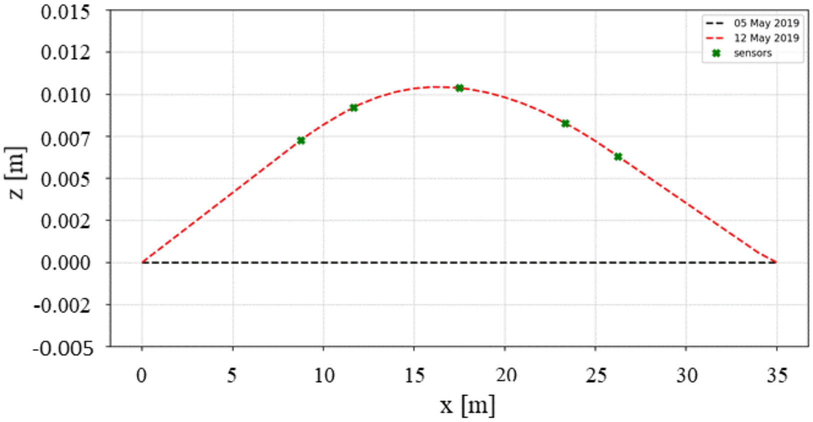


Figure 7. Deformation experienced by the bridge during the strengthening works

As can be seen from the graph, following the reinforcement intervention, the structure experienced a camber of about 1 cm at the centreline of the span.

As for dynamic readings, the use of accelerometers allowed for the evaluation of the structural behaviour under the reinforcement works by observing the dynamic response of the deck.

The fundamental assumption of vibration-based damage detection is that the damage will alter structures properties such as the stiffness, mass or energy dissipation which, in turn, will reflect in a change in the measured dynamic response of the system [5]. The most common features that can be identified from the measured response time records are the common modal properties of resonant frequencies and mode-shape vectors.

The MEMS accelerometers installed on the bridge acquired data at a sampling frequency of 100 Hz, 15 minutes every 4 hours due to streaming limitations of the entire system, resulting in a difficult application of accurate Operational Modal Analysis

(OMA) techniques to identify mode-shape vectors. For that reason, although being conscious about the limits of this approach [5]–[7], resonant frequency shifts have been used as data feature for damage detection at this preliminary stage (this can be checked on all sensors).

Since the signals are of random nature, the power spectral density (PSD) was used to evaluate the system natural frequencies. The averaging process has been carried out with a sub-records length of 200 s, overlap of 66% (Hanning window). The peaks of the PSD correspond to the natural frequencies of the structure under examination.

Figure 8 shows the PSDs calculated for the sensor located at mid span in the three directions x, y, z for two days, before and after the strengthening works (May 5th, 2019 and May 12th, 2019). It can be observed that the stringing caused a stiffening of the system; this is proved by a shift to the right of the natural frequencies of the span. This translation is more evident in the y and z directions, while in the x direction, transversal to the longitudinal extension of the viaduct, this variation is hardly recognized. This is consistent with the observation that external pre-stressing causes a flexural stiffening of the structure mainly in the y-z plane, with minor effect in the x-y plane.

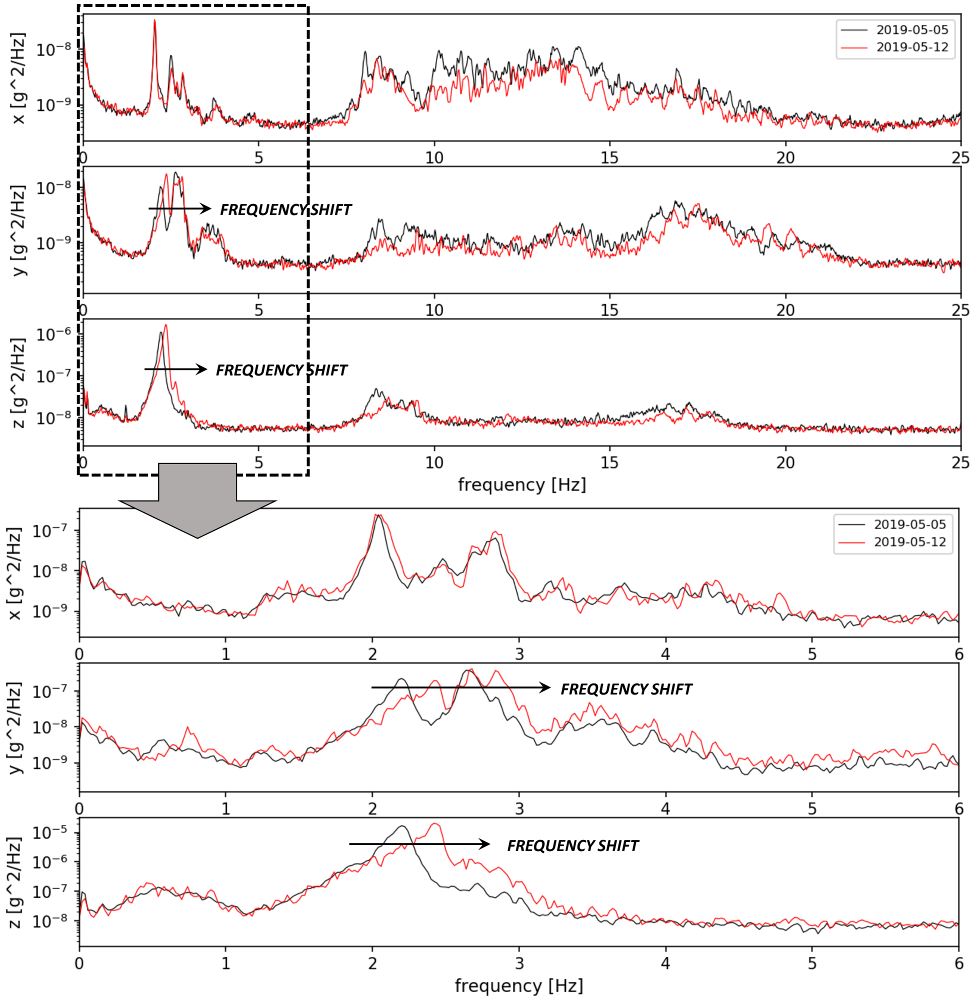


Figure 8. PSD of the sensor located in the center of the span before (black) and after (red) the strengthening works

Although the PSD curve has been used to observe the overall effect of the strengthening works, the Frequency Domain Decomposition (FDD) has been used as OMA methodology to get a more accurate identification of the natural frequencies. The theory of this well-known technique [8] is based on the assertion that any change in the state of the structure can be seen as a linear combination of the eigenvectors, which represent the modes of the structure. It is therefore possible to decouple the components of the various modes through a singular value decomposition (SVD) of the PSD matrix. The advantage of this method lies in the fact that it is possible to accurately distinguish modes that are close in frequencies.

As shown in Figure 9, the presence of coupled modes is pointed out by the co-existence of different curves, related to different singular values, in the same frequency range.

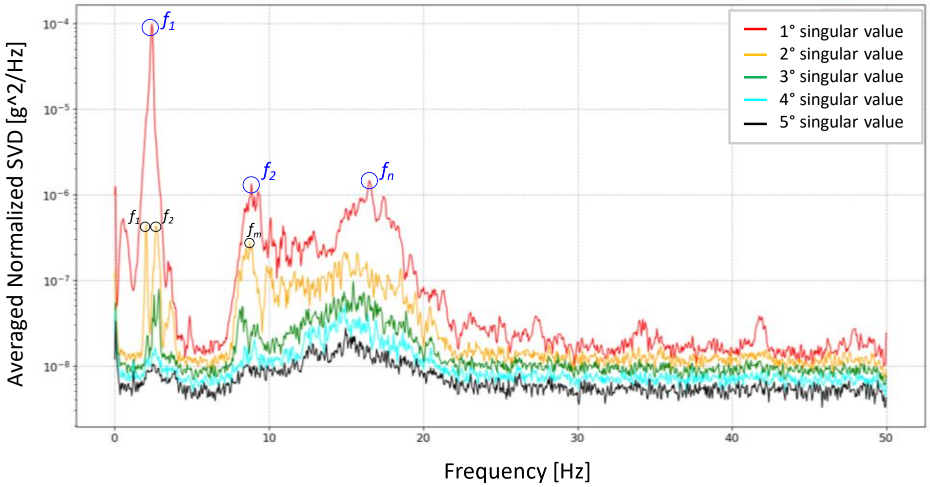


Figure 9. Singular values diagram for the monitored bridge

A stable peak-picking analysis has been performed in order to track the evolution of the natural frequencies over time. The peak-picking method assumes that each significant peak in the frequency-response function corresponds to exactly one natural mode. Close to a peak, the system is assumed to behave like a one-degree-of-freedom damped harmonic oscillator.

In Figure 10, the trend of the first resonance frequency, corresponding to the mode at 2.2 Hz, is reported over time.

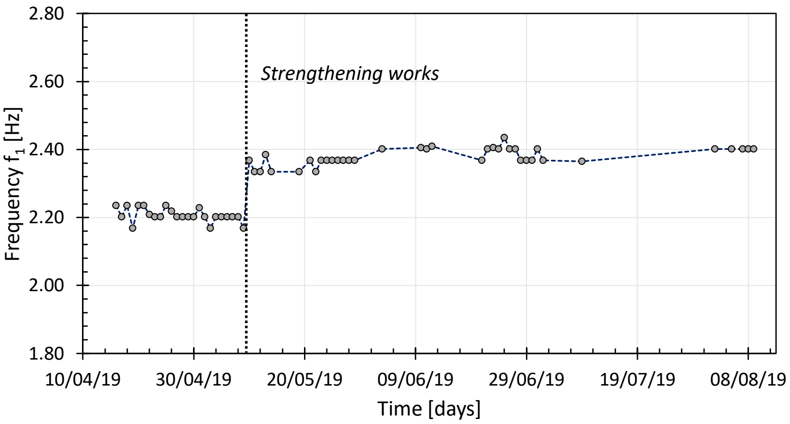


Figure 10. Frequency evolution over time (before and after the reinforcement)

It can be clearly seen that a sharp jump in frequency is detected in correspondence of the strengthening works (May 9th, 2019), indicating a stiffening of the structure.

However, the possibility of observing such a frequency shift is strongly influenced by the frequency resolution. The uncertainty related to the identification of natural frequency values, and consequently related to the extent of the recognizable frequency variations, could be reduced by using longer windows for the estimation of the averaged PSD. Nevertheless, in this specific case study, a compromise was found between the need to have a large number of sensors to be installed on the structure in a short time and data accuracy in identifying changes in the modal characteristics of the structure before and after the reinforcement.

CONCLUSIONS

This paper discusses the case study of a Structural Health Monitoring system installed on a bridge in an advanced state of deterioration, where a widespread corrosive phenomenon caused the failure of a significant number of pre-stressing tendons, mainly on a specific span. Just before the beginning of the strengthening works, a series of MEMS sensors, both clinometers and accelerometers, were installed on the structure allowing to gather very significant data, mainly for two purposes.

First of all, which is the part that is mainly discussed in this paper, the sensors allowed to monitor the evolution of the structure following the maintenance works, thanks to a new architecture, privileging some items at the expenses of others. Both the evaluation of the new asset of the monitored span, obtained by the rotations acquired by the clinometers, and the changing of the dynamic properties in terms of stiffness, obtained from the acceleration data, confirmed the effectiveness of the intervention with external pre-stressing tendons.

The second very important aspect is that the data coming from the structure in damaged conditions have been observed and this represents a very rare case in the field of SHM of real operating civil structures. Therefore, knowing the outputs of the analyzes obtained when the structure was in a state of advanced and widespread deterioration, the use of supervised learning techniques can be adopted allowing to have indications on the progress of pre-stressing loss for future SHM purposes

REFERENCES

[1] C. R. Farrar and K. Worden, “An introduction to structural health monitoring,” *CISM Int. Cent. Mech. Sci. Courses Lect.*, vol. 520, pp. 1–17, 2010.

[2] K. Wardhana and F. C. Hadipriono, “Analysis of recent bridge failures in the United States,” *J. Perform. Constr. Facil.*, vol. 17, no. 3, pp. 144–150, 2003.

[3] C. R. Farrar and K. Worden, “Structural health monitoring: a machine learning perspective,” 2013.

[4] G. Bertagnoli, F. Lucà, M. Malavisi, D. Melpignano, and A. Cigada, “A large scale SHM system: A case study on pre-stressed bridge and cloud architecture,” *Conf. Proc. Soc. Exp. Mech. Ser.*, pp. 75–83, 2020.

[5] C. R. Farrar, S. W. Doebling, and D. A. Nix, “Vibration-based structural damage identification,” *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.*, vol. 359, no. 1778, pp. 131–149, 2001.

[6] S. W. Doebling, C. R. Farrar, and M. B. Prime, “A summary review of vibration-based damage identification methods,” *Shock Vib. Dig.*, vol. 30, no. 2, pp. 91–105, 1998.

[7] W. Fan and P. Qiao, “Vibration-based damage identification methods: A review and comparative study,” *Struct. Heal. Monit.*, vol. 10, no. 1, pp. 83–111, 2011.

[8] R. Brincker, L. Zhang, and P. Andersen, “Modal identification of output-only systems using frequency domain decomposition,” *Smart Mater. Struct.*, vol. 10, no. 3, pp. 441–445, 2001.