Bridges continuous dense monitoring network: a framework to support the infrastructures assessment and management process

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ABSTRACT: Bridge infrastructures in Europe are facing growing risks induced by the combination of natural and man-induced hazards, ageing, progressive damaging processes as well as the evolution of the type and composition of the traffic loads. In this context, the structural assessment of the existing structures, with special attention to those closer to the end of the design life, the prioritization of the structural interventions and the optimization of the maintenance schedules become a key issue of the asset management plan. As such, timely and accurate information from monitoring of structures, integrated with inspection and testing, is crucial to enable appropriate diagnostics to guide cost-effective safety assessments and decisions on repairs, strengthening and renovations. This paper describes the process of collecting information and assessing structural performance through the data analysis to actively support the maintenance, repair and strengthening activities. A selection of Sacertis case studies on the use of dense sensing on an Italian bridges network of over 50 bridges is hereby presented. Four case studies are detailed where MEMS sensors have been installed based on the specific structural need, with different complexity, with the purpose of monitoring the evolution of deterioration process, supporting a data-informed design of the strengthening intervention as well as providing evidence of the effectiveness of interventions. Both static and dynamic behaviours are analysed as indicators of the structural performance.

Keywords: SHM, maintenance, dense sensing, structural performance, MEMS sensors

1 INTRODUCTION

The relevance of the close relationship between performance safety assessment, monitoring and maintenance strategies in the field of existing infrastructures is progressively increasing. The operational and structural interventions significantly influence the service life of an infrastructure, for which it was previously designed. As the good quality of construction materials takes a fundamental part to reach the target durability required for a structure, correspondently the maintenance strategy may play a lead role to retain the structural performance during its service life. During the first design phase, a conservative analysis approach allows to guarantee greater safety margins for the structure, without entailing significant cost increases; on the other side, a safety assessment of existing structure adopting conservative assumptions may involve repairs or replacements that are sometimes unnecessary and costly.

Serviceability limit states correspond to the states beyond which specified demands for a structure, or a structural component related to its normal use or function are no longer met (Fib MC2010, 2013). The serviceability of a structure is the purpose of a maintenance strategy to guarantee the required functionality to the users and this can be obtained by relating it with the current condition of the existing structure.

Starting from a single structural component of an infrastructure, scaling up to the entire structural system and even to an infrastructures network, it is necessary for Road Operators to follow a standardized process to reach the purpose of controlling its operational performance in a reasonable way in terms of cost-effectiveness and feasibility (H2020 IM-SAFE).

This paper describes the process of collecting information and assessing structural performance through the data analysis to actively support the maintenance, repair and strengthening activities. A selection of Sacertis case studies on the use of dense sensing on an Italian bridges network of over 50 bridges is hereby presented; the aim is to demonstrate the current need of asset management to shift towards a proactive maintenance approach, regarding not just a single structure but considering each structural system as part of a wider infrastructures network. This can be analysed as a population of similar structures, with the aim to compare structural behaviours, identify commonalities as well as differences in the condition rating, to prioritize further investigations and/or structural interventions. Dense monitoring, integrated with surveys, inspections and specific testing, whenever required, is one of the key tools available nowadays to track structural parameters on a quasi-continuous basis: significant changes in the data relating to the condition of the structure may be a clue about the development or evolution of damage process and may activate timely interventions.

2 BRIDGE CONTINUOUS MONITORING

2.1 *Data-informed safety assessment*

Data-informed safety assessment is the most effective approach to lead, in the appropriate manner, the through-life management of the infrastructure. The aim of a decision maker is to handle a few key indicators to represent in an exhaustive way the performance of the asset, leading the infrastructure management towards the direction of maximum benefit with minimum loss. Transposed on the infrastructures field, with hundreds of assets to manage, the aim of a smart SHM (Structural Health Monitoring), intended as a decision tool to integrate and sometimes to trigger safety assessment, is to have distributed sensors, an efficient data-collection network and an improved data management capability, to provide fast and reliable evaluations on the performance of the monitored structures (Farrar C.R. et al.,2010, Farrar C.R. et al.2006). Its application to civil infrastructures is often challenged by the lack of scalability of sensing solutions, due to the large geometries under monitoring and cost implications. To address this challenge, a solution is to create relatively low-cost and dense sensor networks. The chance to apply a dense sensing monitoring is ensured by the low pricing of each sensor unit, that on one side means reduced performance if compared to devices used for laboratory tests, on the other side the higher number of sensors and the availability of some redundancy permit to retrieve structural information content representative of the global behaviour of the structure (Alovisi I. et al.,2022).

Pros of having many devices measuring almost continuously are also represented by the capability of performing simplified data analysis at the sensor level, distributing the system cleverness on edge. Providing a dense sensing in both time and space means managing impressive data flows, that can be handled thanks to an IoT cloud platform able to store and process a high quantity of information, in almost real time, with the effort to make them consistent by cleansing data from environmental influences. The handling of such dataset would be complicated without mathematical approaches of data mining, clustering or artificial intelligence techniques (Farrar, C. R., 2013), as the interpretation of the structural content would be incomplete if not supported by a detailed and customized structural analysis to feed and be compared to data coming from the monitoring system. The chance to simulate the real structural response with a Finite Element Model and to update it, based on measurements registered on site, permits to adjust the model mechanical parameters to represent the actual structural behaviour of existing structures, and to define threshold levels that allows to intervene when conditions diverge from standard trends. In this direction, the gathered data should feed appropriate key-performance indicators and should serve as input for structural diagnostic procedures. The anomaly detection represents a decision-making trigger regarding the status of the operational life of the structure. Alerts are generated by means of a continuous comparison of the measured signals, analysed and aggregated to represent structural information, with pre-identified alarm levels. If properly integrated in a smart IoT Cloud infrastructure, with the capability of sending communications to stakeholders when an extreme event occurs, the continuous monitoring system may help identify when the end of the structure service life has been reached (Sousa H. et al., 2019, Diamantidis D. et al., 2019, Thöns S.,2019). Normally, when not such severe conditions are met, the monitoring system allows to follow the evolution of the structural behaviour, triggering on time further investigation or eventually more detailed assessment to evaluate if a structural intervention upgrade is needed.

2.2 *Monitoring approaches depending on structural conditions*

Depending on both the structural scheme of the structure and the anomalous mechanism to investigate, the monitoring system has to fit different needs and the approach of the engineering analysis follows the complexity of the structural problem. Often, a local mechanism can affect the global behaviour and in that case the performance monitoring necessarily implies numerical modelling and deeper analyses to localize potential damage. The relationship between the available data, the need of assessment over time and the maintenance strategies optimization has led to the development of different steps of the assessment of new and existing structures, focusing on various levels (network, system and component); the structural monitoring activities feed the data-informed safety approaches at each step. In this paper four examples of sensors systems are described, starting from a local monitoring of critical zones of a single structure, continuing with the global monitoring of a prestressed concrete bridge subject to strengthening, ending with a network monitoring project that is currently ongoing along on an Italian highway. Common to all these case studies regarding existing bridges, in which their own actual status is often influenced by the ageing degradation of material, construction errors, lack of maintenance or a variation in their structural capacity, is the need to handle the safety assessment supported by both a good knowledge of the structure and a reliable data acquisition process. In many cases monitoring a single key component would not be enough to fully represent the structural behaviour and damage process evolution and, as such, a dense sensing monitoring is preferred. In the network case study, a high level of approximation analyses of the bridges composing the network has been required to support the monitoring and diagnostics, as the monitored structures have been accurately selected and classified as 'high priority' after a thorough risk analysis and prioritization of the interventions over the network.

3 FIELD CASE STUDIES

3.1 *Single component monitoring*

In certain scenarios, based on the phenomenon to monitor and the characteristics of the structure, it may be convenient and more effective to limit the analysis and investigations on individual components behaviour instead of applying diffuse monitoring. Two examples are presented below, for which it has been possible to apply this monitoring solution.

3.1.1 *Gerber half-joints monitoring*

The first application is about an Italian highway viaduct built by alternating a system of continuous bearing spans with simply supported spans. The connection between the spans is made by Gerber half-joints which, as known, constitute critical elements for the structure. Figure 1 shows the planimetric layout of the deck and a zoom relating to the single monitored portion.

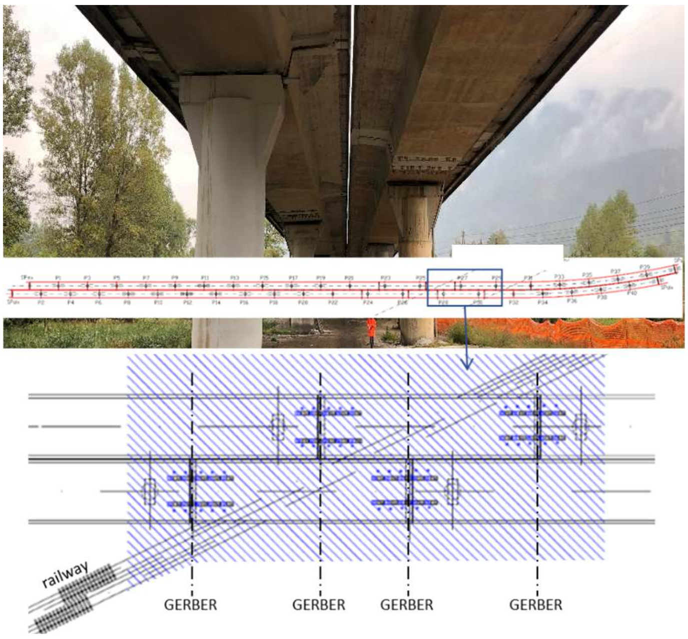

Figure 1: a) Deck of the viaduct; b) Plan view with zoom on monitored portion.

The monitoring system has been required for four Gerber half-joints located on the spans overpassing the railway line, considered a highly sensitive structural spot. The need to instrument these structural elements arose from the site survey when diagonal cracks were found on the structure in correspondence of half- joints. Initially, to control the phenomenon, a strengthening intervention was carried out using vertical post-tensioned bars; at a later stage, to monitor any potential evolution of the crack pattern, the Road Operator decided to intervene installing a sensing system made of clinometers, located near the joints, and crackmeters to continuously monitor the opening of the cracks already existing.

For each joint the monitoring system is composed as follows:

- 10 clinometers (6 on the bearing span, 4 on the supported one)
- 8 crackmeters (4 on the bearing span + 4 on the supported one)
- A power line communication to connect all the sensors with the gateway;
- 1 gateways, which collects and pre-processes the data before sending them to the cloud database via a 4G mobile network;
- A cloud server for data storage and computational ability to run more complex analyses.

In total there are 40 clinometers and 32 crackmeters on the structure.

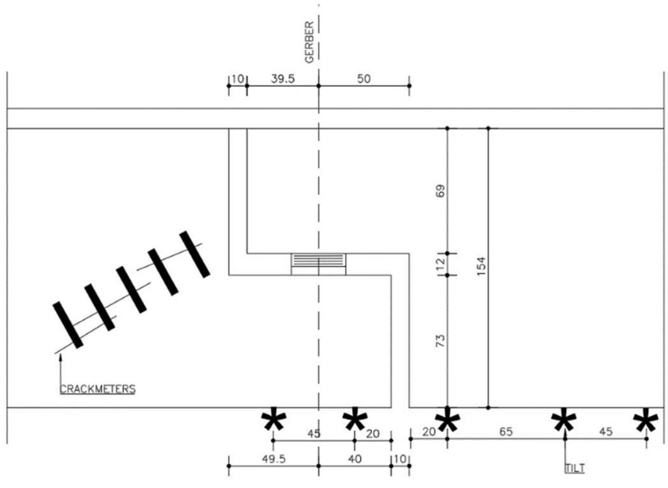

Figure 2: Front view of Gerber half-joint monitoring scheme with tilts on the bottom of the beam and crackmeters on the cracks

This system allows to monitor in real time the deformative behaviour of the structure, detecting a possible loss of stiffness of the deck due to the formation of new cracks (well detected by clinometers) or due to the progressive opening of existing cracks already monitored (well identified by both the crackmeters and clinometers). Thanks to this localised monitoring, it is possible to ensure safety for users of both the highway and the railway systems, by limiting or promptly interrupting the traffic by means of dedicated protocols that are activated when certain warning/alarm thresholds are exceeded.

Figure 3: View of the bottom of the beam with gerber half-joint monitoring system

Because of the strategic position of the viaduct, after the gained experience on this real time local monitoring, and due to its static scheme, the extension of the structural monitoring system to cover five spans (for each direction of traffic) has been designed recently, integrating tilting and acceleration over three axes to instrument longitudinal beams and piers. The aim of this newly required monitoring is to increase the knowledge of the behaviour of five sub-systems (piers, bearing and supported beams) whose structural response is strictly and directly correlated with a potential failure of the Gerber half-joints, already under monitoring. The system is now under production, and it will be ready for the installation in the early 2022. After the installation, a Finite Element Model will be used to simulate the expected behaviour, based on the available information about structural characteristics, integrated with survey and material testing to support the theoretical assumptions. The Finite Element Model will be calibrated following an updating process that aims to minimize the difference between the expected response and measured one, in correspondence of the sensing points, under known load conditions. After the described procedure to characterise the numerical model, the knowledge of the monitored sub-systems will be accurate enough to analyse potential failure scenarios and to set appropriate thresholds levels, to feed the Sacertis monitoring system and to permit the activation of communication protocols in case of their exceedance.

3.1.2 *Differential settlements monitoring*

The second application is about the monitoring of the relative displacement between the piers belonging to the two separate ways of a highway viaduct. The original structure was composed of a single deck with a single way of transit. The need of enlargement and the subsequent construction of the second carriageway has required building an adjacent alignment of piers, linked to the pre-existing ones to support the new deck, as shown in Figure 4.

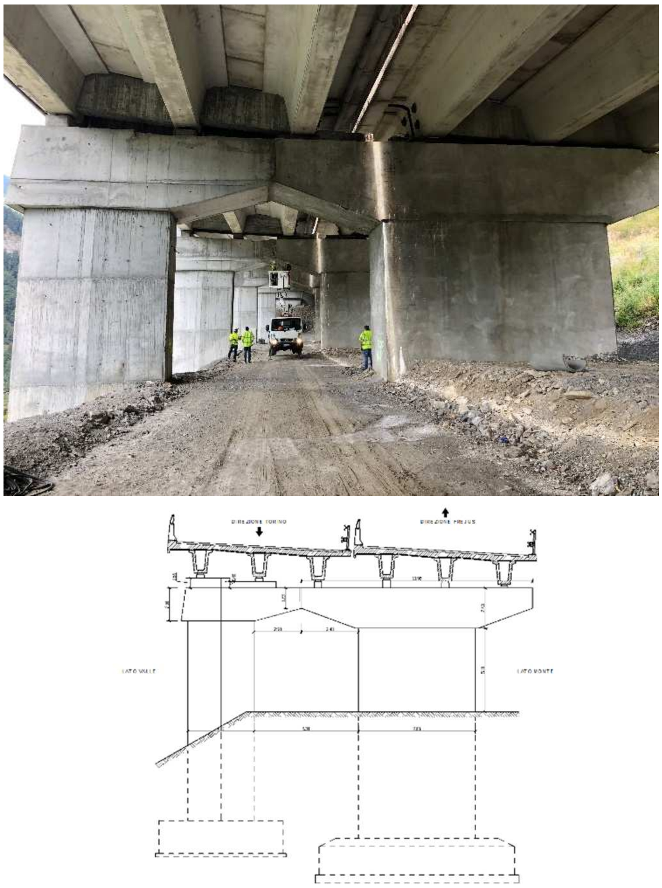

Figure 4: a) Picture of the inner deck of the viaducts; b) Cross-section of the monitored bridge

According to the design calculation, the piers should be connected at the level of the pier-caps but, because of an occurred construction error, the needed reinforcements to connect the pier-caps were not installed. In the following years, due to the relative movement between piers, caused by differential ground displacements, a crack of about 2-3 centimetres arose as shown in Figure 5.

Figure 5: Above cracks view

The Road Operator appointed Sacertis to provide a local monitoring system on a portion of the viaduct, consisting of 1 span and 4 piers, to detect the evolution of the displacement between the two structural elements.

The installed system consists of:

- 4 biaxial inclinometers + 4 triaxial accelerometers, placed at the ends of specific beams of the monitored span;
- 6 biaxial inclinometers + 4 triaxial accelerometers, placed on top of the monitored piers;
- 4 biaxial inclinometers, placed at the base of the monitored piers;
- 4 straight position transducers (crackmeters);
- A power line communication to connect all the sensors with the gateway;
- 1 gateway, which collects and pre-process the data before to send them to the cloud database via a 4G mobile network;
- A cloud server for data storage and computational ability to run more complex analyses.

Figure 6: Sensors applied in the middle of the crack

The installed sensing system allows Sacertis to evaluate any further relative movements that may cause stability problems to the structure. The system monitors in real time both the relative translations and the rotations of the structural elements, as well as vibrational anomalies (Farrar C.R. et al., 2001, Doebling S. W. et al.,1998), allowing to take prompt operational actions (reduction of traffic) in case of exceedance of pre-defined alarm thresholds. As for the previous application case, the flexibility of the system enables potential integration of further instrumentation to switch from the monitoring of individual components to a diffuse one.

3.2 *Dense sensing on a single bridge*

This section describes an example of reactive maintenance (intervention after poor performance or breakdown is observed) with the application of a system made of triaxial accelerometers and biaxial clinometers, based on MEMS technology, for the real-time SHM on a 35-years old highway prestressed concrete bridge (Bertagnoli G. et al.2020, Cigada A. et al. 2021).

Built in Northern Italy in the first half of 1980s, the bridge has two independent roadways, each composed of nine simply supported 35m spans, for a total length of 315m. The cross section is characterized by a trapezoidal prestressed concrete slab with a constant depth of 1.5m and two transversal cantilevers. Figure 7 shows respectively the plan view and the elevation of the bridge and the cross section.

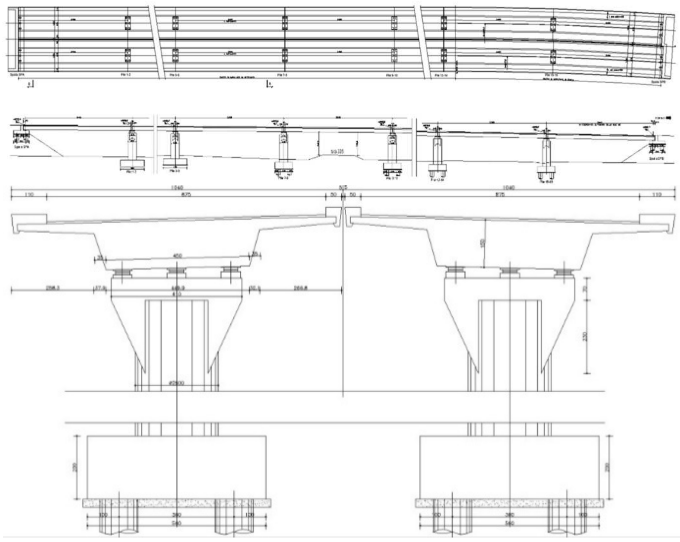

Figure 7: a) Plan view and elevation of the bridge; b) Cross-section of the monitored bridge

The urgency to monitor the structure was due to the detection, during a visual inspection, of a diffuse crack pattern in the midspan region of a simply supported deck. Concrete cracking was related to the failure of some tendons because of the structural aging, the increase in the weight and volume of traffic loads and the corrosive action of de-iceing salts. The structure was classified as ‘high priority’ (structural conditions with high potential danger for users) within its network; the status of advanced deterioration made it necessary to strengthen the deck by means of an external prestressing system improving the bearing capacity and increasing both the durability and the safety level, as well as installing a monitoring system to control the evolution of the damage scenario.

Figure 8: View from the bottom of the deck

The versatility of the SHM system made it suitable for a twofold purpose: in the short-term, it was used to avoid the traffic stop, while waiting for the reinforcement and to measure the structural effects related to restoration; conversely on the long-term instead, it was used to monitor the structural response evolution, allowing for a more efficient “condition-based” maintenance rather than a traditional "time-based" one.

The monitoring system is composed as follows:

- 5 biaxial clinometers and 5 triaxial accelerometers per span (180 devices);
- A power line communication to connect all the sensors with the gateway;
- 2 gateways, one per roadway, which collect and pre-process the data before to send them to the cloud database;
- A cloud server for data storage and computational ability to run more complex analyses.

Installing the system before maintenance permitted to appreciate the evolution of the structural response during and after the strengthening works. Figure 9 shows the sudden shift in the rotation sensed by the tilt sensors due to the application of external prestressing. The intervention was performed without any traffic reduction on the viaduct; thus, the sensors also recorded the deformation effect under moving vehicles. It should be highlighted that the tilt variation is opposite in versus to the one produced by traffic loads, as prestressing causes a camber in the deck.

Another interesting effect that can be appreciated is the one registered by the sensor placed in midspan. While under standard condition, it experiences null rotation, in the present application it recorded a significant rotation shift due to the presence of a damage in the middle-span region.

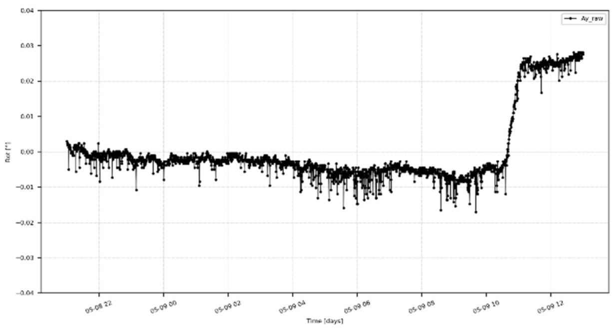

Figure 9: Tilt measurements along the span. (Cigada A. et al., 2021)

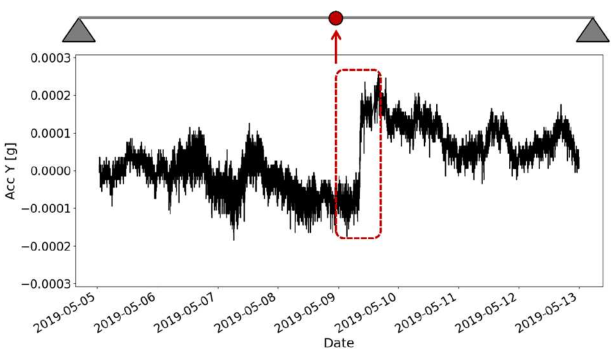

Figure 10: Tilt measurements in the middle-span. (Cigada A. et al.,2021)

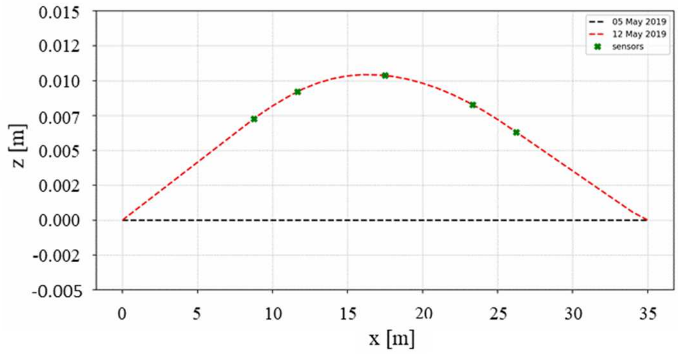

Figure 11: Deformation experienced during the strengthening works. (Cigada A. et al., 2021)

From the rotation measurements it was also possible to evaluate the residual displacement of the deck caused by prestressing.

shows the results, the red curve represents the vertical displacements of the slab at the end of the strengthening works.

As for the dynamic response (Brincker R.,2001), the accelerometer recordings were used to develop a Power Spectral Density (PSD) analysis to evaluate the natural frequencies of the deck before and after maintenance, the curves for X (transverse), Y(longitudinal) and Z(vertical) directions are shown in Figure 12. As expected, the main difference was appreciated in the Y and Z axes since prestressing has a stronger influence on Y-Z plane.

As result of the high sensitivity level of the monitoring system experienced during the strengthening works, the Road Operator has decided to extend the monitoring system to all spans of the viaduct, as a mean to prevent further similar structural damages.

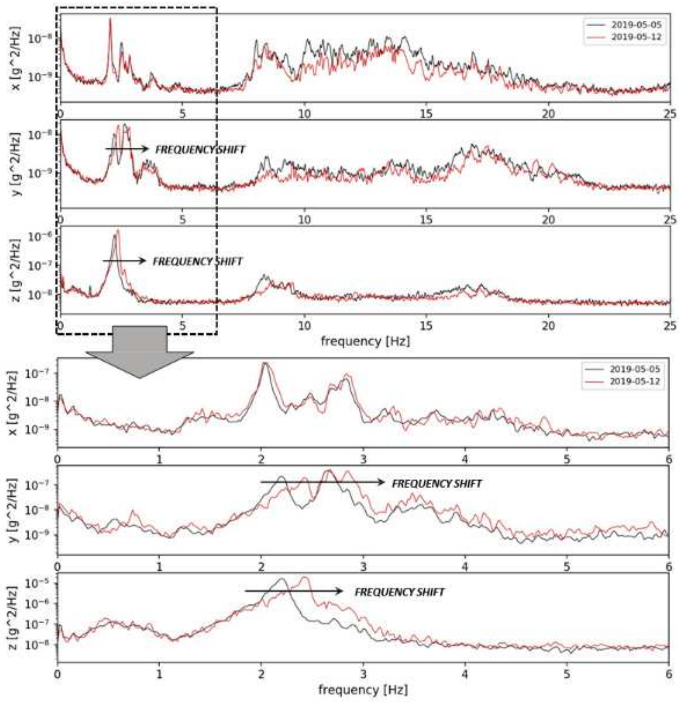

Figure 12: PSD of the midspan sensor before (black) and after (red) the strengthening works. (Cigada A. et al., 2021)

3.3 *Dense sensing on a roadway bridges network*

This section describes an example of dense sensing monitoring system, with devices distributed along roadway networks of bridges, underlining the safety assessment needs and the asset management process followed, derived from direct expertise. The assessment flow appears strongly aligned with the oncoming trends of the standardisation guidelines developed as part of the H2020 IM-SAFE European Project (H2020 IM-SAFE). The SHM system developed by Sacertis, including dense sensor nodes, cloud, data analytics and diagnostic techniques, is currently active on more than 50 bridges within the Italian road network.

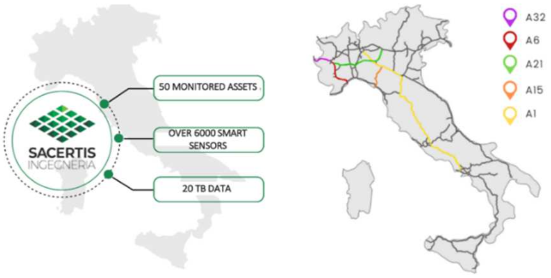

Figure 13: Monitored roadway bridges at 2021.

The general framework process, that has driven Road Operators to monitor several bridges on the same highway, is a decision procedure which allows to handle hundreds of structures, for which it aims to identify the most effective investigations and interventions required to satisfy the target reliability requirements and/or to reduce the uncertainties regarding their current condition and future performance.

The safety assessment at the network level is primarily aimed at focusing on management control and attention to those assets that could potentially be unsafe for users, and as such requiring deeper investigation or rapid intervention to mitigate harsh environmental conditions; throughout a prioritization of the maintenance interventions, depending on the structural conditions, the management is able to organise budget and efforts, following a hierarchical list of activities. This first simplified assessment is done by reviewing relevant technical documentation, integrated with condition surveys and structural investigations. By means of this first preliminary classification, structures in the worst conditions, with respect to the operational safety, are selected for urgent repair actions. When the priority list has been identified, those structures for whom the intervention is not immediate (structural strengthening deferred in time) are designated to be monitored to detect changes in structural behaviour that can occur if conditions worsen. The monitoring activities and outcomes, in the period preceding the intervention, are suitable for a dual purpose: in the short-term, the monitoring system is used to follow the structural response under operating traffic conditions, to avoid critical evolution of expected and/or unexpected structural mechanisms and to act in time, promoting operational interventions in case of need (as reduction of the traffic load); on the long run instead, it is used first to characterise the actual behaviour of both the local component and the global static scheme to validate theoretical assumptions adopted for the reinforcement design, whilst later, during the construction site transitory period, the dense monitoring allows to partialize the system, removing parts that directly interfere with on-site activities, and to control the structural response of the repaired structure. In a real case, it has been registered the effect on a structure, due to an excavation that was preparatory for the following reinforcement of pilar foundation. In this case, the behaviour of a structural frame (beam-pier) has been affected by a local settlement of about three centimetres, that has been well sensed by biaxial inclinometers placed on top of the interested pilar and on the end of the previous span; the measurements, once processed by dedicated algorithm, have shown residual and permanent rotations on the structural node to represent the occurred kinematics. As outcomes of this event more detailed investigations and tests before completing the construction activities have been activated. As trigger for further actions, dense monitoring may also underline the need of specific component detailed safety assessment; in these cases, the contribution of continuous data helps to lead analysis on structural problems, identified most of time thank to the comparison between the expected behaviour simulated with numerical models and real measurements. Even if an anomalous behaviour is not registered, monitoring data can provide useful information regarding the materials degradation processes, and thus guiding the engineer to update the theoretical modelling assumptions, to catch real conditions of the structure and to discriminate further dangerous evolution.

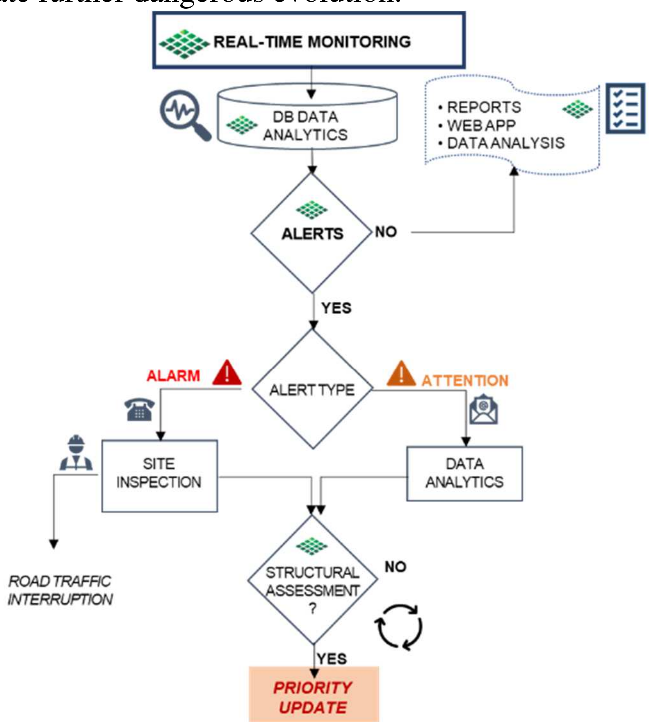

Figure 14: Flow of actions after monitoring alerts.

In Figure 14 it has been represented the flowchart currently used by Road Operators, after receiving the alert communication, sent by Sacertis Monitoring System.

Following this roadmap, when the monitoring System notifies a potential alarm scenario, with regards to the operational serviceability of the structure, the actions to be immediately activated concern both the site inspection to investigate visible effects of eventually occurred damage and deeper structural analysis driven by the registered signals to perform a data-informed safety assessment.

The monitoring system can catch the effect of potentially dangerous scenarios, but the technical interpretation of the effects can allow to identify multiple structural causes and the engineering judgment and diagnostic expertise have the complementary role in the monitoring assessment process.

4 CONCLUSIONS

This paper discusses the strategic role of Structural Health Monitoring system in supporting the management process to identify the most effective investigations and interventions required to satisfy the target reliability requirements and/or to reduce the uncertainties regarding current condition and future performance of infrastructures. Depending on both the structural scheme of the structure and the anomalous mechanism to investigate, the monitoring system has to fit to different needs and, consequently, the approach of the engineering analysis follows the complexity of the structural problem. Dense monitoring is preferred when global structural behavior is to be investigated; if from one side the cost-feasibility of a diffuse sensing system implies lower quality sensors, on the other side the redundancy of measurements points allows to identify phenomena affecting the global behavior of a structure. Continuous dense monitoring implies managing big quantities of data, in terms of streaming acquisition, storage, processing and analysis. The technology system (hardware, software, cloud) has to be as robust as versatile to perform over time in the right manner fitting, time by time, the always different structural framework to monitor. Data-informed assessment, at any requested level of detail, leads the shift of the management control from reactive approach to proactive maintenance. Four case studies are described to represent different needs arranged with monitoring systems calibrated on the structural effects to investigate: cracks on Gerber Joints, cracks on pier caps, crack pattern in the mid-span region of a simply supported deck, The fourth case study shows the monitoring network solution applied on Italian roadways, including field examples of detection.

The lesson learned to appreciate based on the real applications presented hereby, is the effective role that monitoring plays in the decision-making process, guiding Road Operators to data-supported operational actions.

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