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# Exploring the Multifaceted Aspects and Benefits of Structural Health Monitoring

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**Abstract.** The degradation and failures of structures present considerable threats to both the economy and society, underscoring the need to address safety risks and maintenance deficiencies. These issues, combined with the aging of structures and progressive deterioration, require improved structural safety assessment methods and strategies to ensure accurate evaluation of the remaining service life. Structural Health Monitoring (SHM) is crucial in addressing these challenges. These systems primarily ensure safety concerning Ultimate Limit States and protect lives. Additionally, they offer benefits such as supporting proactive maintenance, monitoring traffic load variations, understanding structural behaviour under different conditions, and evaluating the effectiveness of retrofitting interventions. In this paper three case studies, related to reinforced or prestressed concrete bridges monitored in continuous and in real time by Sacertis Ingegneria, showcase the effectiveness of SHM systems demonstrating how these systems can effectively identify behavioural variations due to different causes, supporting the maintenance and safety of aging infrastructures.

**Keywords:** Structural Health Monitoring, SHM, Proactive Maintenance, Structural Behaviour.

## 1 Introduction

The deterioration and malfunction of structures and infrastructures, pose significant risks to both the economy and society [1]. Recent years have witnessed a growing number of disasters highlighting the urgent need to address safety risks and maintenance deficiencies [2]. These issues, compounded by the ageing of structures and progressive deterioration processes, necessitate an improvement of structural safety assessment methods and strategies to ensure the remaining design service life of these structures is accurately evaluated.

A key strategy in addressing these challenges is the implementation of Structural Health Monitoring (SHM) systems [3]-[5].

The primary purpose of SHM systems is to ensure safety in relation to Ultimate Limit States and protect human lives. However, they also offer numerous additional benefits, including support for proactive maintenance, monitoring of traffic load variations, comprehensive understanding of structural behaviour under different operational conditions, evaluation of retrofitting interventions effectiveness, and more [6]-[11].

In this paper, three case studies under continuous monitoring by Sacertis, a leading Italian company in the field of structural health monitoring, are presented. These case studies demonstrate how a monitoring system can be effective in identifying behavioural variations due to distinct causes and specifically:

- The first case demonstrates how a SHM system can be used to apply a proactive maintenance-based approach on a structure. The system provides real-time data on structural health, allowing for early detection of minor issues that, if left unaddressed, could lead to significant damage. This enables maintenance teams to perform targeted interventions, addressing problems early and preventing them from developing into larger, more costly issues. Proactive maintenance not only enhances the safety and reliability of the structure but also optimizes maintenance resources and reduces overall lifecycle costs.

- The second case illustrates how a SHM system enables comprehensive characterization of a structure, capturing variations in behaviour due to seasonal temperature and environmental conditions changes. This global understanding of a structure performance is critical for accurate assessment and management. For instance, SHM data can reveal how a bridge performance changes with temperature fluctuations or how it responds to different environmental conditions over time. This detailed characterization helps engineers develop more precise maintenance and reinforcement strategies, tailored to the specific needs of the structure.
- The third case shows how a SHM system can play a crucial role in evaluating the effectiveness of reinforcement interventions. When a structure undergoes reinforcement, it is essential to assess whether the intervention has successfully restored or improved its structural integrity. SHM systems provide continuous data on the performance of the reinforced structure, allowing engineers to verify the effectiveness of the intervention and make any necessary adjustments. This approach ensures that maintenance efforts are both efficient and effective, ultimately enhancing the safety and longevity of the structure.

# 2 Monitoring for proactive maintenance

## 2.1 The case study

The case study is a highway reinforced concrete bridge built in the late 1960s, located in Northern Italy [12]. The viaduct has a total length of 105m and it is made of 6 span; the deck is a girder with five longitudinal beams and three transversal beams and it is 10.5m wide. The static scheme shows the presence of half joints creating an alternance of supporting and supported spans (span no. 3 and 5 supported spans). The first span is the only one simply supported between pier and abutment.

The primary beams have a total depth of 2.7 meters, while the reinforced concrete slab has a constant thickness of 0.20m. The geometry of the case study is shown in Figure 1.

A permanent monitoring system was installed on the bridge in 2019 to control its static and dynamic behaviour over time. The system consists of MEMS biaxial inclinometers and triaxial accelerometers, located on the edge beams. The sensors are wired and connected to a local gateway, which collects data before storing them in the cloud. The layout of the SHM system is shown in Figure 1: for each span and each edge beam, 5 inclinometers and 3 accelerometers are positioned at key points for a comprehensive diagnostic of the static and dynamic behaviour (near the supports, at the quarters, and in midspan). The accelerometers sample at 100Hz along three orthogonal axes: the Z-axis (vertical), the Y-axis (longitudinal in the plane of the deck), and the X-axis (transversal in the plane of the deck). Clinometers, on the other hand, acquire data when queried by the gateway according to a polling cycle and measure along the two axes lying in the horizontal plane (X-axis and Y-axis).

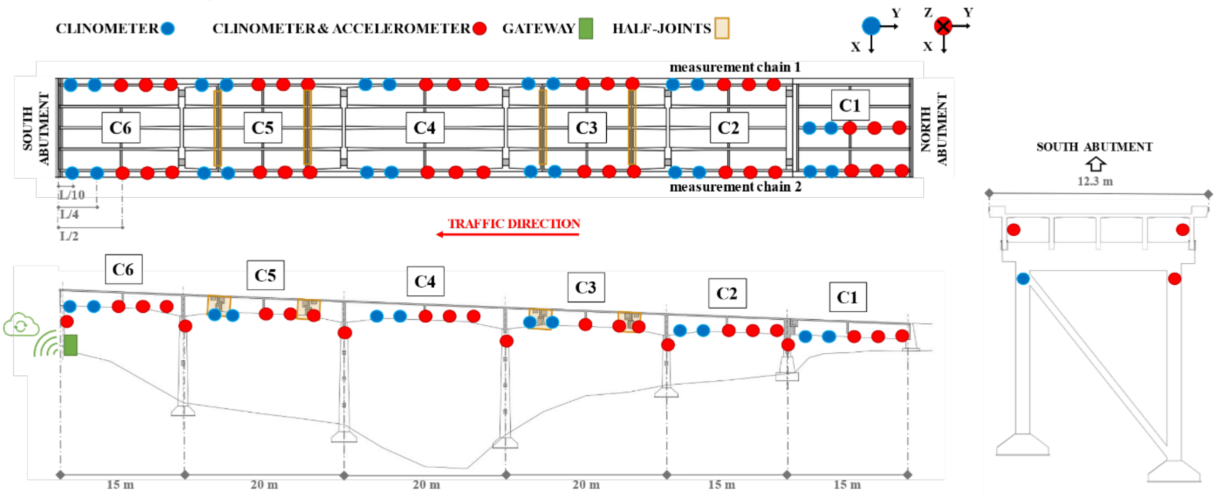

*Figure 1: Monitoring for proactive maintenance - Case study geometry and SHM system.*

## 2.2 Monitoring history

Bridge monitoring started in 2019 with a Model-Driven approach, following the timeline described in Figure 2. Initially, just after the installation of the monitoring system, static load tests were performed by loading each span of the bridge with two 40-ton trucks in different configurations (both symmetric and asymmetric). Data recorded by inclinometers during these tests, combined with modal information extracted from accelerometers under operational conditions, were used to update the numerical model of the structure. A digital twin of the bridge, representative of its real behaviour, was thus obtained. From this model, damage indicators (DIs) were selected to monitor any appearance of damage over time.

Some damage scenarios were hypothesized and simulated on the numerical model, obtaining the critical values for each of the selected DIs, which are monitored over time with automatic controls running both at the gateway (semi real-time controls) and cloud (medium-long period controls) levels. Alongside these DIs and their related Model-Driven thresholds, Data-Driven Indicators were also chosen and initialized with appropriate algorithms running at various frequencies automatically, responsible for detecting any change in the bridge behaviour (anomaly detection) compared to what was recorded during the initial training period. In this case, thresholds are computed using statistical or more advanced machine learning approaches.

*Figure 2: Case study 1 - Monitoring timeline.*

Among the Data-Driven Indicators, one was selected and monitored over time to recognize eventual impulsive and short-term anomalous vibrations related to high-energy events occurring in specific areas of the bridge (e.g., near the supports, on a specific beam, on abutments or piers, etc.). This indicator is calculated with an algorithm that processes data recorded by accelerometers and computes, in semi real-time, synthetic parameters to recognize short-term vibrational events with very high energy (e.g. standard deviation over 1 second of sampling). The robustness of the control is ensured by working on groups of sensors, preventing the notification of false positives due to anomalies in sensor signals. The algorithm was activated after defining the vibrational baseline behaviour of the structure over a consistent 3-month training period, computing thresholds with a data-driven approach, and proved effective in triggering maintenance interventions.

Indeed, in February 2021, about 3 months after the activation of the Anomaly Indicator, the SHM system notified the exceedance of the thresholds for a group of sensors located near the expansion joint between spans C1 and C2, indicating an anomalous increase in vibration levels in that area. The other Key Performance Indicators (both static and dynamic, Model and Data-Driven) did not show any alerts or anomalies.

The anomaly detection triggered a site inspection, which revealed several defects along the entire pavement and significant local damage to the expansion joint where the anomaly was identified. This confirmed that the acceleration impulses due to vehicular traffic were accurately correlated with poor road surface conditions and local damage. As a result, proactive maintenance interventions were initiated, and the structural joints were promptly replaced in April 2021.

However, the intervention was not fully effective. By June 2021, the viaduct still showed increased STD values, progressively spreading across the entire deck. The Sacertis SHM system alerted the road operator in near-real time about potential damage. It was confirmed that poor installation conditions of the joints, with bitumen flowing within the joints, were hindering proper structural thermal expansion. A second intervention was required in July 2021. After this intervention, structural vibrations returned to standard values.

The anomaly detection procedure uncovered vibrational anomalies and localized damages, ultimately verifying the effectiveness of maintenance interventions. These findings supported asset management in optimizing proactive maintenance strategies.

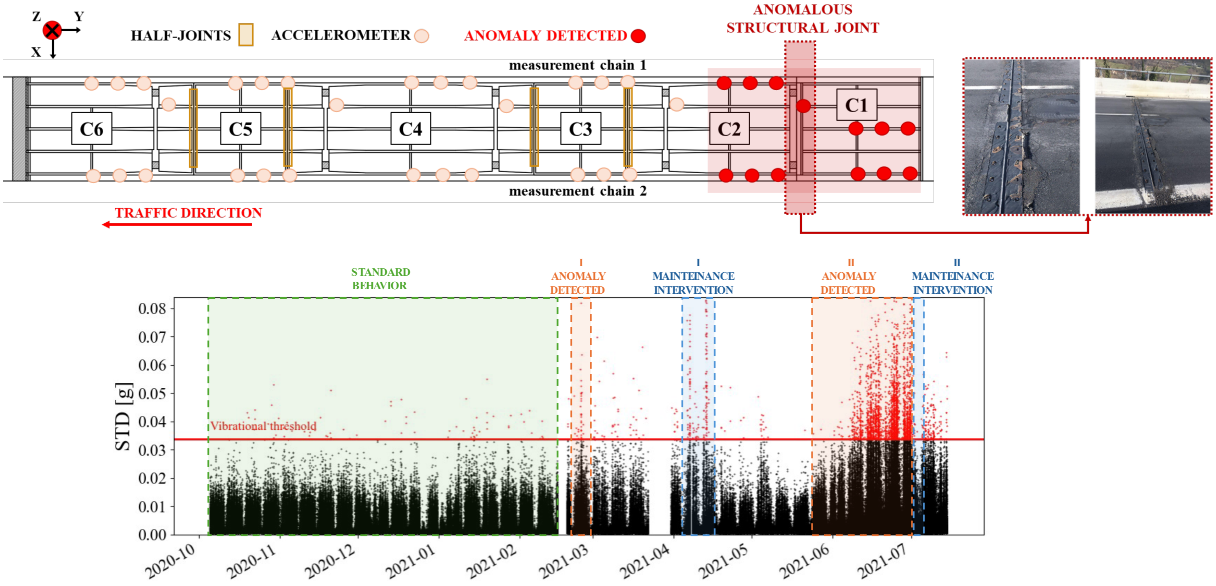

*Figure 3: Case study 1 – Vibration anomalies.*

# 3 Continuous monitoring for a comprehensive structure baseline characterization

## 3.1 The case study

The viaduct is a reinforced concrete structure built in the late 1950s and located in Northern Italy [13]. It spans approximately 118 meters in total length, segmented in three independent portions by two structural joints. The external sections measure respectively 18m (2 spans) and 8m (1 span), while the central one is 92m long and is composed by 5 continuous spans (longest span 32m). The deck girder is composed of 5 beams with variable height from 2.9m to 3.7m, and a slab with a thickness of 0.27m. The pier frames feature two H-shaped concrete cross sections, jointed by transverse beams, as depicted in Figure 4.

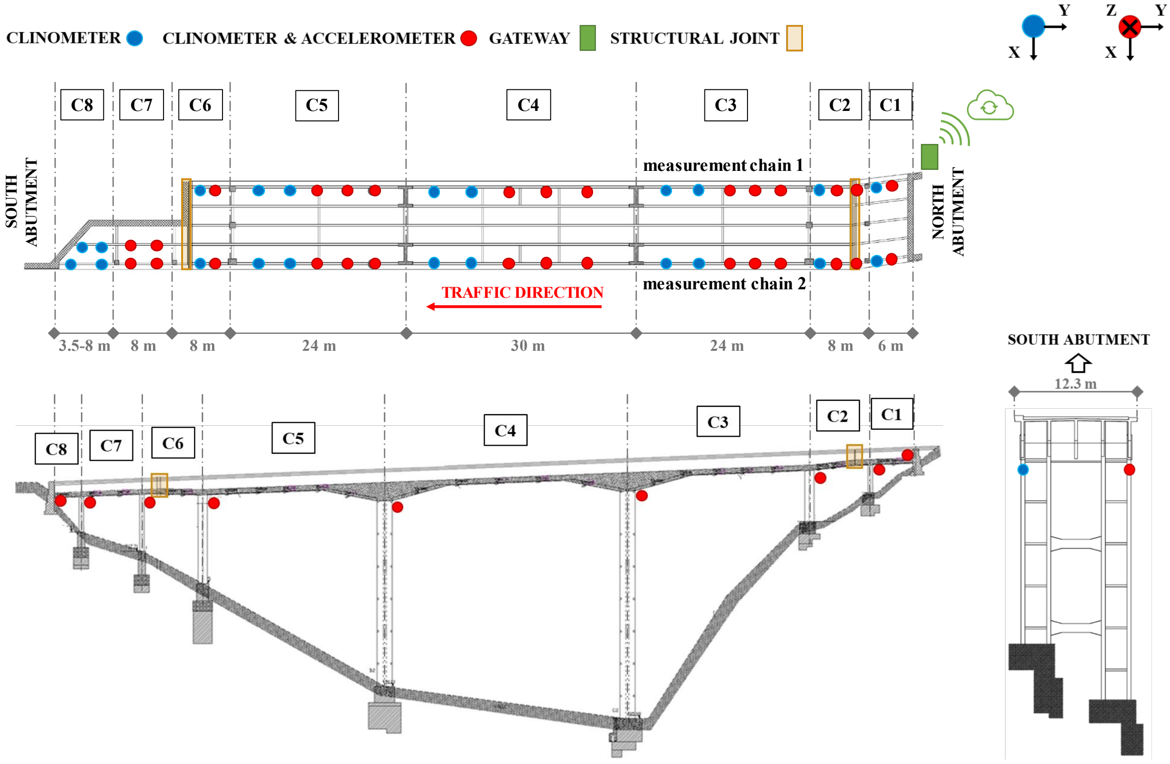

*Figure 4: Case study 2: Geometry and SHM system.*

The monitoring system is composed by a wired network of 67 biaxial MEMS clinometers and 38 triaxial MEMS accelerometers, installed on the edge beams in the key points for a comprehensive diagnostic of the static and dynamic behaviour as shown in Figure 4, except for spans C7 and C8 that, due to installation difficulties, have a dedicated sensors layout. Two networks managed by the same IoT gateway enable the collection of both slow-varying data and dynamic data: the former uses a power-line-based architecture, and the latter employs a CAN-BUS network. The data are pre-processed and filtered at the gateway level, with only significant information sent to the cloud for further analysis and long-term storage. The biaxial MEMS clinometers installed on the viaduct sample at 208Hz and measure along two orthogonal axes: Y-axis (longitudinal in the plane of the deck), X-axis (transversal in the plane of the deck). Accelerometers sample at 100Hz and measure along three orthogonal axes: Z-axis (vertical), Y-axis (longitudinal in the plane of the deck), X-axis (transversal in the plane of the deck). Anomaly conditions detected by different sensors, correlated in space and time, along with multi-parameter cross-checks, enhance the SHM system reliability by minimizing false alarms. When thresholds are exceeded, alerts are sent to the cloud with attached severity metadata for appropriate handling.

### 3.2 Monitoring history

In the case of this application as well, a Model-Driven approach was chosen as monitoring strategy. The system was installed in the summer of 2019, and after an initial characterization period, both Model- and Data-Driven algorithms for selected KPIs were activated. The monitoring of the structure dynamic behaviour was conducted in both the time and frequency domains, aiming to track vibrational levels (time-domain) and modal parameters (frequency-domain).

Thanks to these controls, this case study serves as an example of how a permanent monitoring system can be more effective and advantageous than a discrete one. Additionally, the importance of a Model-Driven approach for gaining complete knowledge of the bridge is demonstrated, highlighting the need for a structural interpretation by technical and specialized personnel to comprehensively diagnose any anomalies triggered by the system.

Before delving into why this case study exemplifies the benefits of continuous monitoring, it is necessary to provide a brief description of the monitoring history of the structure.

After three months from the installation of the system, the baseline of the structure was established. By focusing on accelerometers data, the main vibration modes of the structure were identified and characterized with the relative modal parameters. This dynamic information, along with data obtained from specific proof loading tests, was used to feed a genetic algorithm to update the numerical model, making it representative of the actual behaviour of the structure. The baseline was established in autumn (Table 1), and the natural frequencies were used as a reference for activating an automatic control to monitor any variations in their values (thresholds were set based on both damage simulations on the FEM model and Data-Driven approaches). The choice of a permanent monitoring system demonstrated its advantages by highlighting the presence of different dynamic configurations of the bridge that change based on external thermal conditions. Continuous monitoring of frequency values over time revealed a modification in the modes of vibration during the winter season, when a longitudinal mode appeared, as shown in the PSD of Figure 5, along with slight modifications to other minor modes of vibration. This new dynamic configuration persisted only for a few months: once the winter season ended and temperatures began to rise, a return to the baseline configuration was observed in the spring season.

With the arrival of summer, the structure experienced a new thermal condition, resulting in a new and previously unobserved dynamic behaviour. In this season, the lateral mode showed a considerable increase in frequency value and a change in the modal shape, as highlighted in Figure 5.

*Table 1: Case study 2 - Frequency values in different seasonal conditions.*

| MODE OF VIBRATION | SPRING/AUTUMN FREQUENCY [Hz] | SUMMER FREQUENCY [Hz] | WINTER FREQUENCY [Hz] |
|---|---|---|---|
| Lateral | 1.83 | 2.80 | 1.80 |
| Longitudinal | - | - | 3 |
| Flexural | 4.40 | 4.77 | 4.60 |
| Flexural | 8.60 | 9.40 | 8.45 |

With the help of the FEM model, the observed variations in the modes were correctly interpreted, identifying the structural reasons for these changes. Numerical simulations demonstrated that the bridge undergoes different static schemes based on external thermal conditions and the varying states of the expansion joints, which were modelled with non-linear links. By adjusting the stiffness of these links for all translational degrees of freedom (in both the horizontal and vertical planes) according to the state of the joints (closure/opening) over a year, the three different configurations were reproduced. For example, in summer, the longitudinal expansion of the deck likely causes the joints to close, leading to a global stiffening of the structure. This effect would be even more pronounced if debris were present inside the joints.

In conclusion, this case study proved how continuous monitoring, combined with a Model-Driven approach, can effectively and accurately characterize the structure. If discrete dynamic tests were performed instead, there could be a misunderstanding, mistaking changes in dynamic parameters due to temperature for modifications induced by damage.

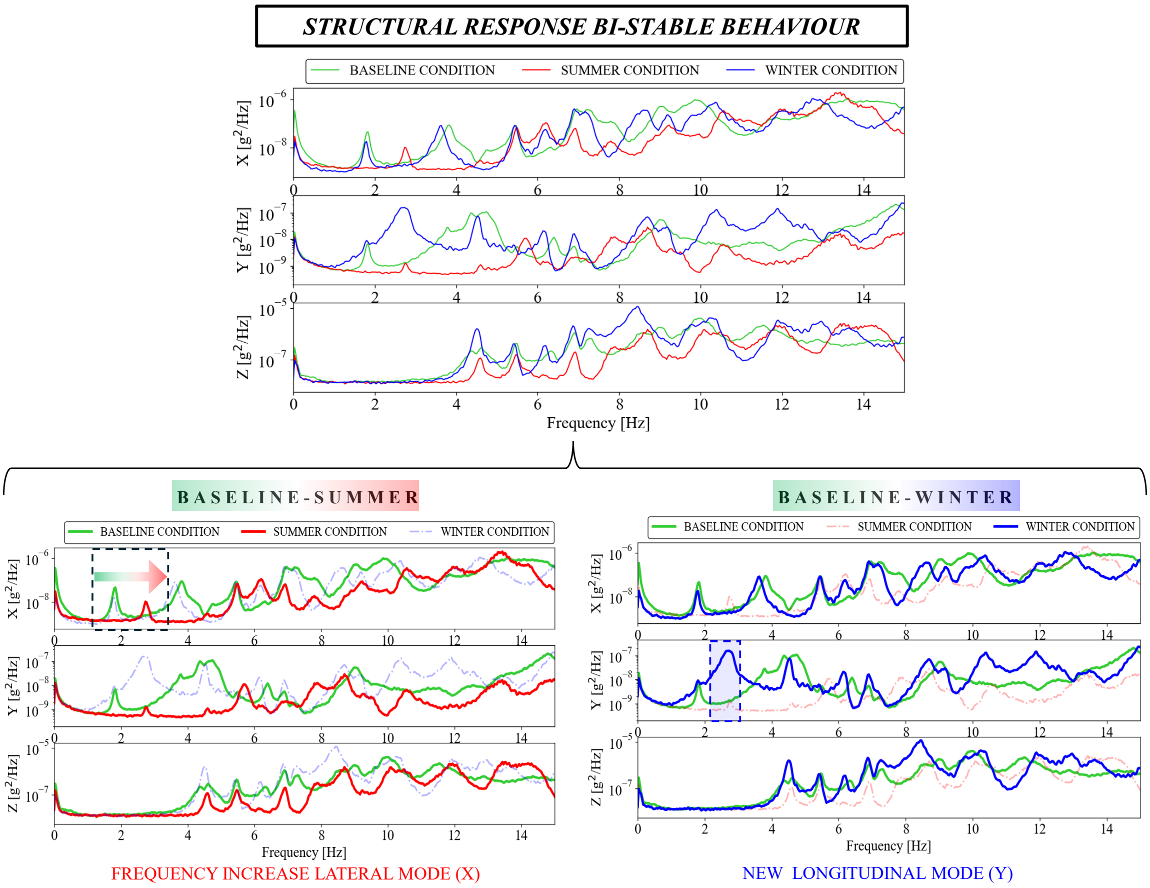

*Figure 5: Case study 2 - Seasonal dynamic configurations.*

## 4 Monitoring for assessing the efficacy of retrofitting intervention

### 4.1 The case study

The structure is a highway prestressed concrete bridge located in Northern Italy and constructed in the early 1980s [14]. The bridge consists of two independent decks, one per carriageway, each featuring nine simply supported 35m spans, for a total length of 315m. The cross section of the deck is a prestressed concrete slab with a constant depth of 1.5m and two transversal cantilevers. Figure 6 shows a view of the bridge.

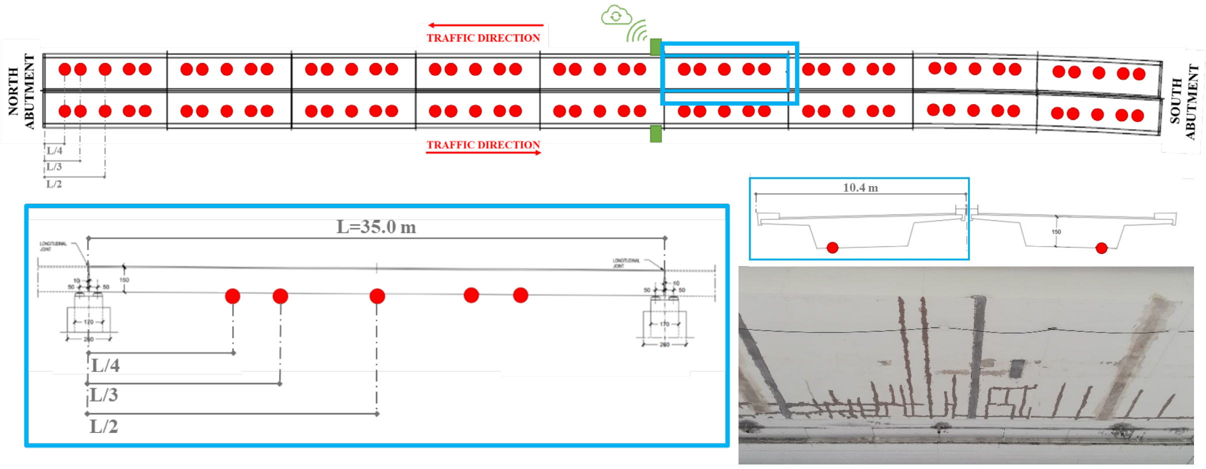

*Figure 6: Case study 3 – Geometry, SHM system and view of the cracking pattern after the inspection.*

The SHM system was installed to monitor the evolution of the structural behaviour tracking an eventual damage progression because, during a periodic inspection, it was found a widespread crack pattern in the midspan region of a span. The concrete cracking was attributed to tendon failure due to structural aging, the corrosive effects of de-icing salts and the increased weight and volume of traffic loads.

To restore bearing capacity and safety levels, it was designed a deck strengthening intervention using an external prestressing system placed on the bottom surface of the slab.

The SHM system enabled to monitor the bridge behaviour pre-, during and post-intervention. In the short term, it was used to avoid traffic closure while awaiting reinforcement and to measure structural effects associated with repairing. In the long term, it monitored structural response evolution, facilitating more efficient condition-based maintenance instead of traditional time-based methods.

The SHM system was designed to monitor both static and dynamic behaviour in continuous. It consists of MEMS biaxial clinometers and triaxial accelerometers, located near the edges of the bottom surface of the slabs. Sensors are wired and connected to a gateway per carriageway for the collecting and the pre-processing of the data before their storage into a cloud system. The layout of the SHM system is shown in Figure 6: for each span, 5 clinometers and 5 accelerometers (for a total amount of 90 sensors per carriageway) are positioned at the quarters, the thirds and the midspan. Accelerometers sample at 100Hz along three orthogonal axes: Z-axis (vertical), Y-axis (longitudinal in the plane of the deck), X-axis (transversal in the plane of the deck). Clinometers, instead, acquire when queried from the gateway according to a polling cycle and have only the two axes laying in the horizontal plane (X-axis and Y-axis).

## 4.1 Monitoring history

The system installed before of retrofitting intervention allowed to control the structural response changes during and after the activities both from static and dynamic point of view. Figure 7 and Figure 8 summarize an overview of the main results obtained analysing the data collected by sensors:

- Clinometers detected a sudden rotation shift following the application of external prestressing. Starting from the measured rotations, it was then possible to reconstruct the deformed shape due to external prestressing by calculating the midspan camber and comparing it with the one predicted by the designer to evaluate the effectiveness of the intervention. Notably, the intervention was executed without any traffic closing on the viaduct, enabling the sensors to capture deformations caused by moving vehicles. Figure 7 shows tilt measurements in the middle-span.

- Accelerometers data were used to assess the deck natural frequencies pre- and post-maintenance. Figure 8 displays the Power Spectral Density (PSD) curves for X (transverse), Y (longitudinal), and Z (vertical) directions. It can be noted an increase of the frequency values observed especially in the Y and Z axes, reflecting the stronger influence of prestressing on the Y-Z plane.

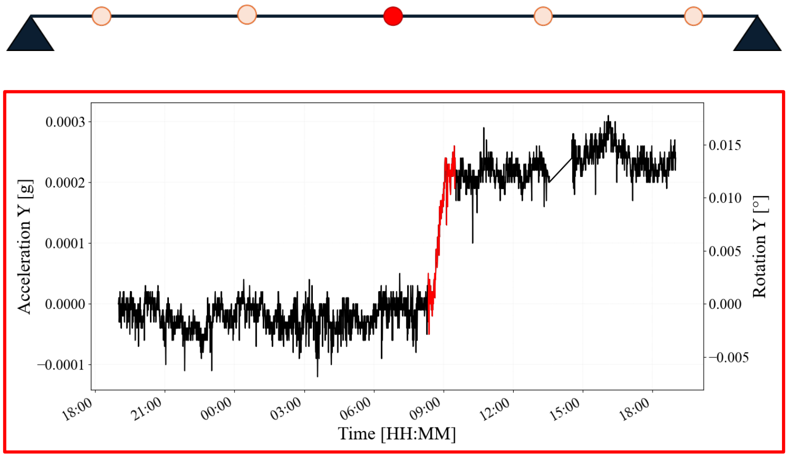

*Figure 7: Case study 3 - static response after the retrofitting intervention.*

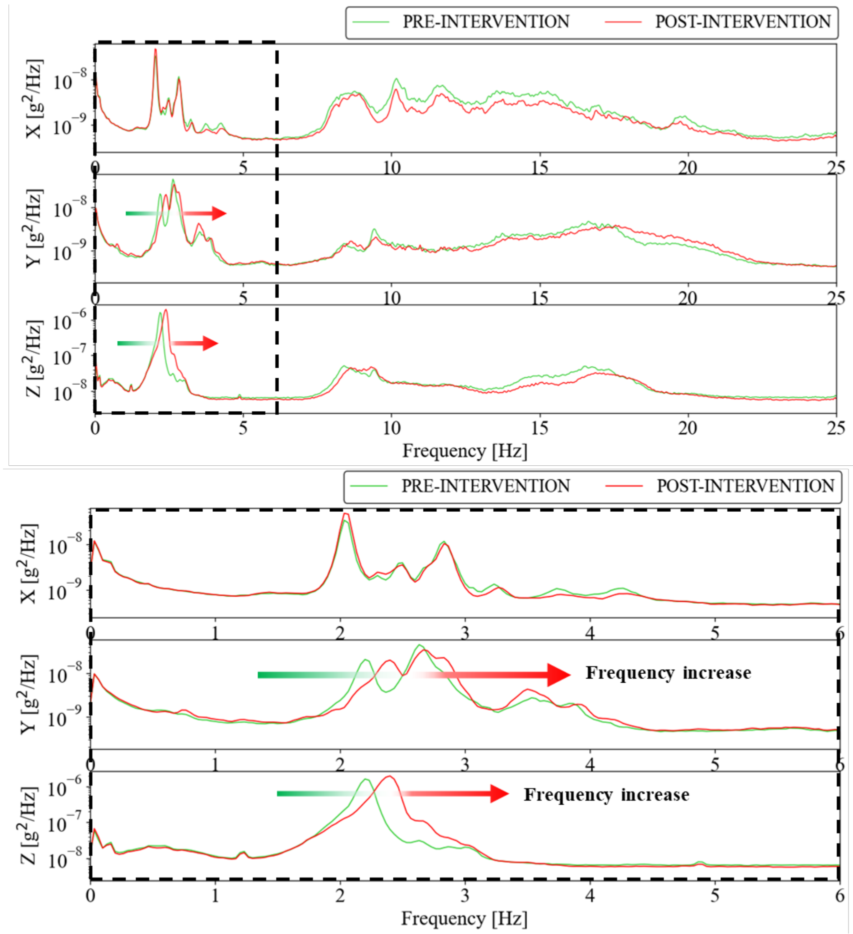

*Figure 8: Case study 3 - dynamic response after the retrofitting intervention.*

From an overall analysis of the response, it emerged that, following the retrofitting intervention, the safety levels of the structure were restored in accordance with the provisions of the current regulations. The change in behaviour was observed significantly both from a static perspective (clinometers) and dynamic perspective (accelerometers). This allowed for a near real-time confirmation of the effectiveness and proper execution of the planned interventions, increasing confidence in the repaired structure.

## 5 Conclusions

Many infrastructures in Europe and around the world have reached or are close to reaching their designed lifespan. This situation presents a challenge for Road Administrators to find a reliable strategy for managing these aging structures, ensuring safety levels, and planning retrofitting interventions when needed. One possible solution is to install monitoring systems on the most critical infrastructures to continuously track any unfavourable trends in their behaviour.

Following this concept, this paper presents some real-life examples of how powerful the application of a Structural Health Monitoring (SHM) system can be in obtaining useful information about the behaviour of structures, aiding in their management. The paper focuses not only on the primary damage detection objective but also on all the benefits that can arise from the application of a permanent monitoring system. This idea is supported by three different case studies, which respectively highlight how monitoring was effective in triggering ordinary maintenance interventions, evaluating the efficacy of a retrofitting intervention, and gaining comprehensive knowledge of the structure. This is indispensable to prevent misclassification problems and to correctly identify deviations from a baseline that might not be unique but variable under different external thermal conditions, as demonstrated in the second case study proposed in the paper. The benefits of adopting a monitoring system are even greater if a Model-Driven approach is utilized. This approach aids in interpreting the results of monitoring, setting damage scenarios on the relevant performance indicators, and identifying the real causes of anomalies detected by the system, discerning damage from all other possible causes of changes in the system behaviour.

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