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New advanced monitoring systems of Bridges with Actionable Real Time Sensor Data

R. Romanello[a]*, E. Miraglia[a], G. Miceli[a], S. Gazzo[b], L. Contrafatto[b], M. Cuomo[b], S. Scalisi[b]

[a]*ETS S.r.l., Via Benedetto Croce 68, Rome 00142, Italy*
[b]*University of Catania, Via Santa Sofia 64, Catania 95124, Italy*

Abstract

The reliability of structures and the preservation of the built environment are issues with a decisive role in the field of civil engineering as well as in the public eye. The existing heritage surrounding human beings is varied and fragile because of its inherent characteristics and the environment in which it is inscribed. These elements are found and emphasized when dealing with special facilities, by constitution and by public utility. This case study analyzes innovative approaches and IoT tools for defining an operational procedure for the proper Life-Cycle management of infrastructure works through a Digital Twin approach. This methodology provides key elements for the proper planning of structural rehabilitation and reinforcement strategies and techniques with innovative interventions and methods, starting with a careful investigation/monitoring campaign to assess its safety condition. This monitoring activity involves the assessment of the real robustness and safety of large structures by acquiring the general principles of signal analysis and the traditional technologies currently available for diagnostics and monitoring (accelerometers, inclinometers, deformometers, strain gauges, etc.). The case study under consideration monitoring activities go through a static type of monitoring that involves the acquisition of absolute and relative displacements, and through a dynamic structural monitoring that is based on the analysis of natural and traffic-induced vibrations using triaxial accelerometer transducers. The latter case of structural monitoring makes it possible to derive the dynamic properties of the structure and ensure the reliability of the finite element model; in addition, the variation in dynamic characteristics over time is an indicator of ongoing degradation in the structure due to damage phenomena. By means of a dense network of sensors (IoT devices) operating completely wirelessly that are able to communicate in real time through a LoRaWAN telecommunication technology, it is possible to create a digital, living and interactive copy in constant update of the physical object. In addition, the system includes implementation of a Real Time notification system called "recognized call," which consists of automatically making a phone call, to numbers specified by the managing body of the work, whose content includes indication of the location, type of alarm threshold, actions to be taken. The objective of this study is to investigate the possibility of using Digital Twin-based systems associated with structural health monitoring of infrastructure works through real-time data analysis.

Keywords: bridges, structural monitoring, infrastructure maintenance, structural identification, vibration analysis, OMA

* R. Romanello. Tel.: +39 3398874015; *e-mail address: raffaella.romanello@etsingegneria.it*

1. Introduction

The safety management of structures and infrastructures represents one of the main engineering challenges in Italy. Their preservation constitutes a strategic asset that countries cannot ignore. The tragic collapse of the bridge over the Polcevera River in Genoa, Italy, in 2018 has made evident the need for a change in the approach to the surveillance and maintenance of infrastructure, generating a strong impulse toward the development of more efficient control strategies. In this context, ***Structural Health Monitoring (SHM),*** is crucial as a valid means of predictive maintenance to assess the condition of structures and their need for preservation over time. SHM represents the set of activities related to the characterization of existing structures, using a dense network of sensors, with the goal of identifying some of their properties. The final goal of SHM is to guarantee that the safety level of the structure under investigation do never fall below a certain threshold.

1. Structural Health Monitoring

Structural Health Monitoring (SHM) is a process that involves a series of techniques designed to assess the conditions of structures such as bridges, buildings, and infrastructure. The aim is to ensure their safety and efficiency by identifying the early onset of damage that may not be visible on the structure.

Structural monitoring is mainly divided into two types:

- *Static monitoring*, that regards the measure of displacements and deformations due to slow actions, like dead loads or slowly varying loads, and involves the use of inclinometers, topographic instruments, strain gauges etc.;
- *Dynamic monitoring*, which is based on the measurement of vibrations through accelerometers, aiming to derive the dynamic properties of the structure.

In addition, structural monitoring can be divided into occasional, meaning periodic for a limited duration, or continuous with permanent installations and readings for a long duration. The first case it aims to obtain the dynamic properties of the structure for creating FEM models, while the second case aims to identify the onset of damage over time.

The phases of monitoring include:

- Preliminary study of the infrastructure, including geometry and historical information;
- Design of the monitoring system, which must define the type of instruments to be employed and their location in the structure;
- Installation of the monitoring system, which must be carried out with the utmost care to avoid problems during measurements;
- Calibration of the monitoring system and data acquisition methods;
- Validation of the acquired data, necessary to determine the proper functioning of the instruments;
- Data management, which must allow the treatment of a large amount of data in the simplest way possible.

Therefore, SHM is a complex engineering practice generated by the combination of various technological tools (hardware and software), consisting of the following systems (figure 1):

- a wired or wireless sensor network, mounted directly on the structure under study, for detecting significant physical quantities of structural response, actions, and environmental conditions;
- a data acquisition system from the sensors;
- data transmission systems to local or remote processing units;
- software components, more or less complex, for pre-processing, analysis, and interpretation of data (damage identification), evaluation of residual life, and decision support;
- a decision-making and alert system for managing emergency situations.

2. Case Study: Steel structure bridge

The analyzed case study consists of a steel road bridge located in central Italy. The goals of the monitoring are focused on acquiring all the necessary information in real-time to understand the current conditions of the bridge and be aware of its structural behavior under static and dynamic actions, in order to ensure an adequate level of safety for public safety.

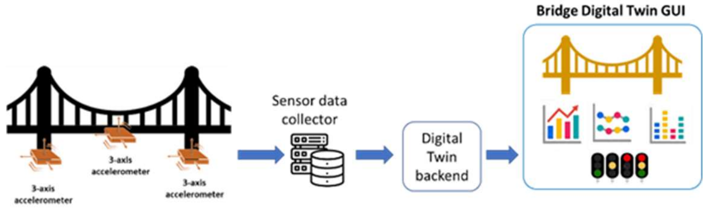


Figure 1 Conceptual architecture of the monitoring system.

2.1. Phase 1 - Basic information acquisition

Through the study of the original project, on-site inspections, and the examination of survey results, it was possible to characterize the structure in question from both a geometric and material standpoint. Figure 2 shows a BIM rendering of the structure. Specifically, the structure under examination consists of 9 arches (7 central full-core arches and 2 lateral reticular arches) hinged at the ends with variable spacing between 1.75 m (between the central full-core arches) and 1.5 m (between full-core arches and reticular arches). Each arch has a span of 25.47 m, a rise of 1.68 m, and a development of 25.76 m. The central arches are constructed using nailed composite sections, while the two outer arches are reticular structures; they are connected to each other by lattice diaphragms and braces placed at the level of the lower flanges. The overall width of the structure is 14.5 m, and the supports, which create a hinge system, are made of cast steel. The deck is constructed with a slab poured on Zores Steel and is supported by a series of struts that connect it to the arches. The masonry abutments are inclined at about 16° relative to the roadway axis, causing the 9 arches to be staggered. The bridge is currently traversed by the municipal road with three lanes.

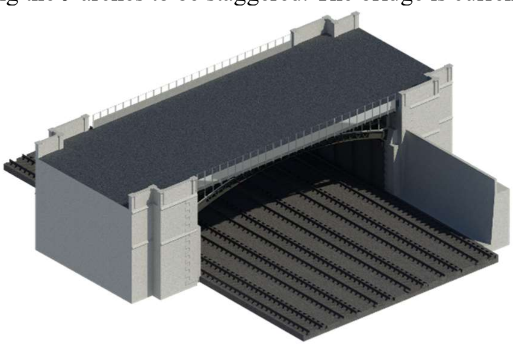


Figure 2 Completed BIM model

Figure 3 Point cloud

This geometric characterization was made possible through measurements with a laser scanner, from which the "*point cloud*" was obtained, (figure 3). The results obtained from the laser scanner were used to create the external outlines of the structure at various elevation levels, for the cross-sections, and for the generation of orthogonal metric elevations. Meanwhile, the mechanical characterization of the various structural elements that make up the structure under examination was carried out based on the information acquired from the investigative campaign conducted on the structure

2.1. Phase 2 – Structural monitoring project

The project of the monitoring system was implemented through preliminary analyses on a provisional finite element model of the bridge, from which the dynamic and deformation properties of the bridge were obtained.

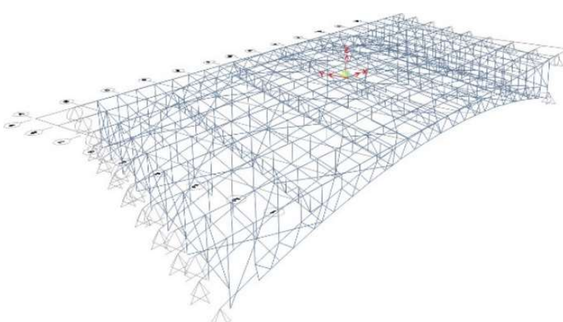


Figure 4 FEM model

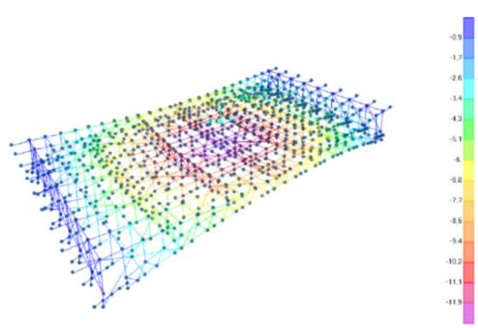


Figure 5 solution of the FEM model

Particularly, the most significant modes were evaluated: the first mode deduced by the preliminary model is a transversal mode with a frequency of 2.36 Hz and 82% of participating mass in the Y direction. The first global vertical mode is the sixth with a participating mass of 63% and a frequency of 5.14 Hz. Longitudinal modes lye in frequency ranges well beyond 10 Hz (figure 6,7,8). The analysis of these most significant modes allowed to determine the location of the accelerometers in order to identify the relevant vibration modes. In addition, transient analyses were performed in order to evaluate the amplitude of the expected acceleration and be able to set the required sensitivity of the instruments, and the confidence limits of the measurements.

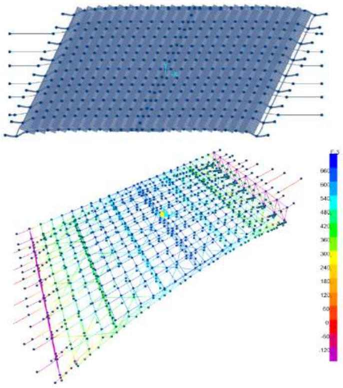


Figure 6 Mode n.1 dir Y

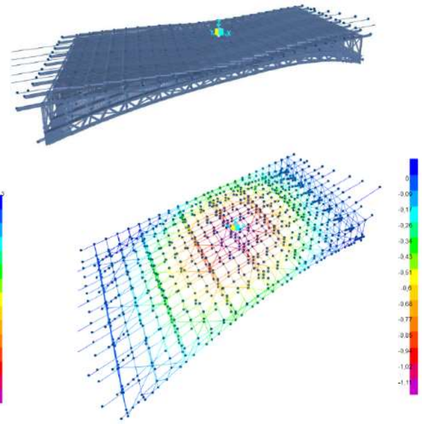


Figure 7 Mode n.6 dir Z

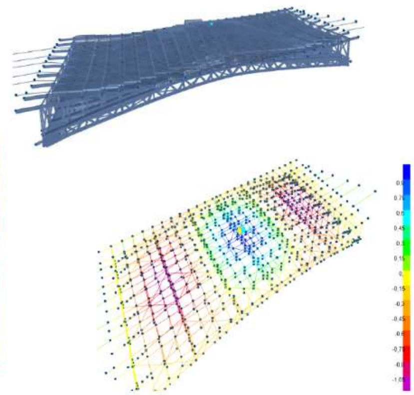
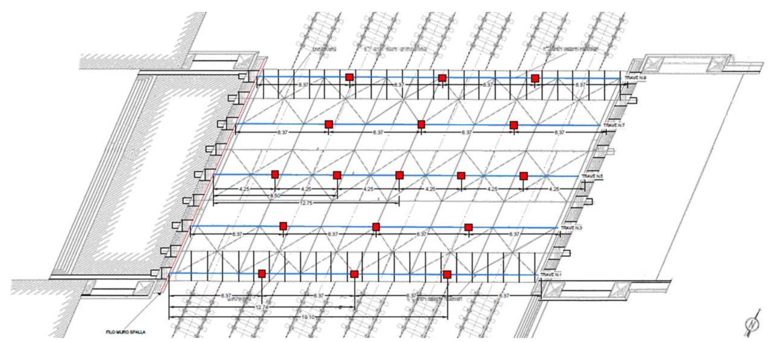


Figure 8 Mode n. 11 dir Z

Seventeen triaxial accelerometers were located as illustrated in figure 9.



Truss number	Sensor count per beam
1	3
2	0
3	0
4	0
5	5
6	0
7	3
8	0
9	3
Tot Dev.	**17**

Figure 9 accelerometers position

A further instrumentation for static measurements was installed on the bridge. Inclinometers were used for the continuous indirect determination of the vertical displacement of the arches. The inclinometers were placed only on beam three, which experiences the highest deformation. Other two inclinometers were positioned on the shoulders of the bridge to verify the absence of absolute rotations of the shoulder and relative rotations between the shoulder and the bridge support (figure 10). In addition, 20 train gauges were placed on the arches in order to measure the axial and bending stresses in the elements. The strain gauges were placed on the lower wing and on the web, in baricentral position.

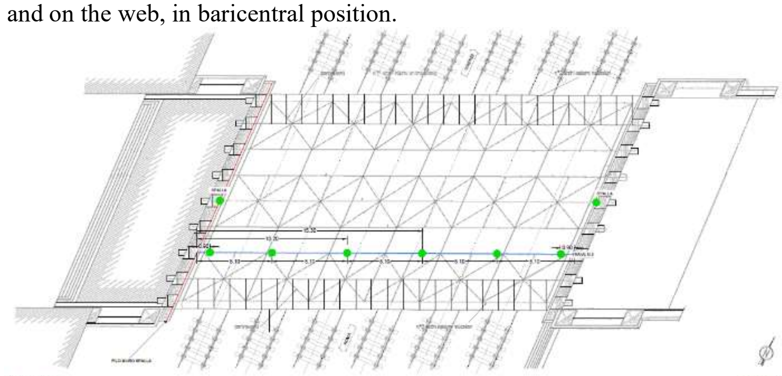


Figure 10 inclinometers positions

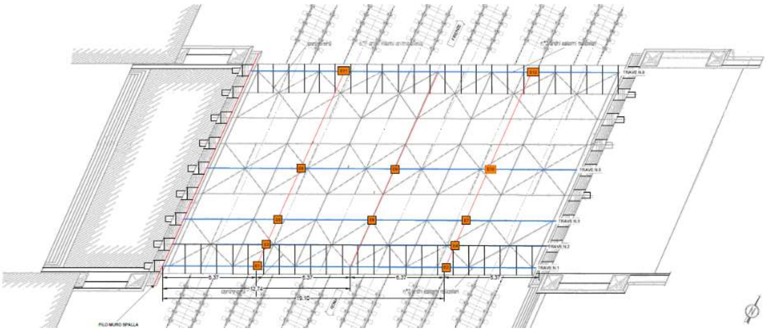


Figure 11 strain gauges positions

Truss number	Sensor count per beam
1	2
2	5
3	6
4	0
5	6
6	0
7	0
8	0
9	2
Tot Dev.	**20**

The monitoring system was completed with the installation of a topographic fixed total station for measuring absolute displacements (figure 12).

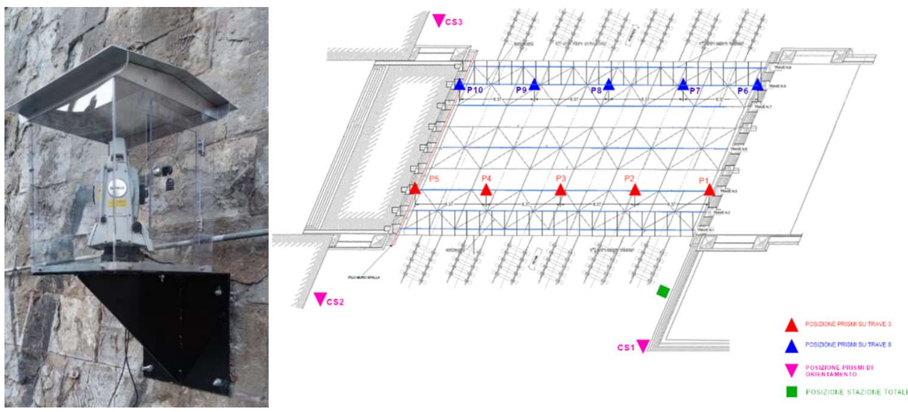


Figure 12 to the left automated total station, to the right prisms, cornerstones and total station locations

2.2. Phase 3 – Installation of the monitoring system

The installation of the monitoring system must guarantee the absence of disturbs and the accuracy of the measurements. Tio this aim stiff supports and connections were designed, so that the dynamic measurements could be free of spurious frequencies.

2.3. Phase 4 - Calibration of the monitoring system

The calibration has been carried out through various comparisons:

1. Analysis of static and dynamic measurements obtained from static and dynamic load tests with known actions. The load test is necessary both for fine-tuning the instrumentation and for acquiring data for comparison with theoretical predictions.
2. Monitoring of vibrations over a selected period of time.

Specifically for the purpose of calibrating the instrumentation installed on the bridge, static and dynamic tests were carried out. The static load test was designed, programmed, and executed to test part of the instrumentation installed on the bridge and evaluate the elastic behavior of the bridge and any residual deformations upon unloading.

Figure 13 instrumentations installed on the bridge

Figure 14 dynamic acceptance test

The dynamic load test was performed for testing part of the instrumentation installed on the bridge (accelerometers), and evaluating the dynamic response of the structure (natural frequencies). For this purpose, wooden listels of 5 and 10 cm were attached to the structure, placed in different positions on the bridge. Heavy trucks were let fall from the wooden listel so to induce forced vibrations on the bridge. Each recording was examined in order to check the correct response of the instrumentation. Through a Fourier analysis have been obtained the first vibration frequencies and modes of the structure, and compared with the expected ones. Particularly, it was observed the absence of local irregularities of the vibration modes, that could suggest the presence of local imperfections or damages in the structure (figure 14).

2.4. Phase 5 – Validation of acquired data

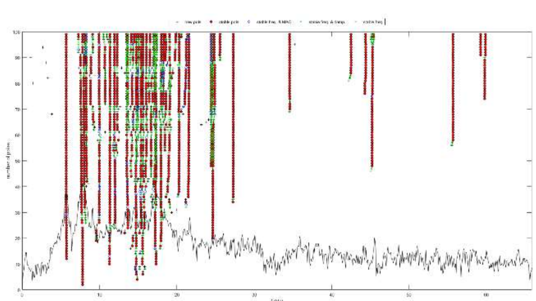
Once the correct functioning of the instrumentation is ensured, we can move on to the data validation phase, which mainly involves analyzing the data obtained from the accelerometers. Two months of recordings were studied using Operational Modal Analysis (OMA) techniques. OMA allows obtaining the dynamic properties of structures and infrastructures solely from output data, i.e., accelerations, velocities, and displacements. Preliminary to the put in service of the system it is necessary to calibrate the instruments. Indeed, every signal is affected by noise and instrumental errors that must be adequately filtered out in order to ensure the correctness of the data. Accidental action, electrical malfunctionings, environmental conditions may all affect the data, and the user must be able to separate the real data from the spurious ones.

The methods for that are based on error analysis of the theory of signals, which require in any case to set a series of criteria and thresholds that change from case to case, the determination of which is one of the goals of the validation phase. In particular, high-fidelity identification techniques belonging to Stochastic Subspace Identification were used, allowing the automatic extraction of frequencies, damping ratios, and modal shapes. Criteria have been developed to automatically distinguish between real and non-real modes using stabilization diagrams, which distinguish between stable and unstable modes through criteria based on frequencies, damping ratios, and modal shapes, enabling the comparison of modes and potentially excluding repeated ones.

After defining the stability diagrams, we move on to a clustering phase that allows grouping stable modes with common characteristics, enabling the automatic comparison of modes with similar features. The criteria for automatic identification include:

- Frequency criteria (multiplicity criterion): this involves the number of frequencies repeated within the same analysis. If this number exceeds a certain threshold, the frequency is accepted; otherwise, it is excluded, figure 15.
- Damping criteria: modes with excessive dispersion of values or unrealistic values compared to expected values for the analyzed structure are rejected, figure 16.
- Modal shape criteria: All modal shapes are compared to obtain the Modal Assurance Criterion (MAC), indicating whether two modal shapes are equal or not. In this case, frequencies with two identical modal shapes, i.e., a value greater than 0.8, are rejected, figure 17.

In the case study of the bridge, two months of recordings were analyzed, using recordings made at the same time of day. This is because it has been observed that, especially for steel structures, thermal expansion due to temperature variations throughout the day leads to significant changes in the results. The first three significant frequencies were found to be approximately 5, 8, and 11 Hz, and the modal shapes associated with these frequencies are all in the vertical direction. Future developments in this field involve further analysis of recordings at different times of the day and a comparison to understand the daily range of frequency variations, setting thresholds beyond which it can be hypothesized that the structure has suffered damage. Once the analysis phase with OMA techniques is complete, the results obtained are compared with the FEM model to improve and update the FEM model.



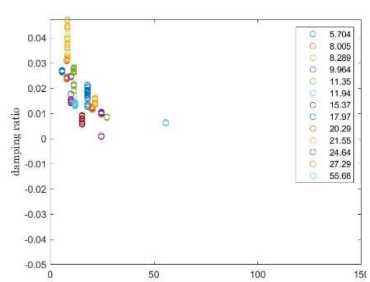


Figure 16 damping ratio

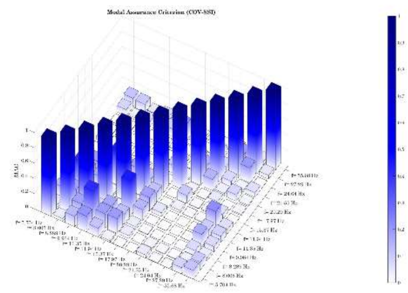


Figure 17 MAC matrix

2.5. Phase 6 – Data management

The operation of the 'recognized call' system has been implemented thanks to the fact that the Gateway, already present in the data communication infrastructure, will send sensor data (accelerometers, inclinometers, extensometers) to a real-time event management and distribution platform. At the core of this data architecture is a complete event management and streaming platform that enables data transformation through the adoption of an Event-Driven architecture. Real-time data movement is managed through Event Brokers connected in an event mesh. An 'Event Mesh' is a configurable and dynamic infrastructure optimized for event distribution among applications, cloud services, and devices asynchronously. The mesh makes event management governable, flexible, reliable, and fast. Essentially, an Event Mesh consists of a network of interconnected brokers. In other words, an event mesh is an architecture that allows events from one application to be dynamically routed and received by any other application, regardless of where these applications are deployed (on-premise, private cloud, public cloud). Among the features of the PubSub+ and Event Broker system are event routing, publish-subscribe, guaranteed delivery, native cloud implementation, high-performance streaming APIs, low latency, and the use of market standards including AMQP, MQTT, JMS, REST, and others. The proposed technical solution involves directing sensor data directly to a real-time event management system using Event Streaming architecture with a configurable telephone alerting system for alarm thresholds. Additionally, the solution will provide the managing entity with an interface to extract historical data with basic visualization functionality for signal values (figure 18).

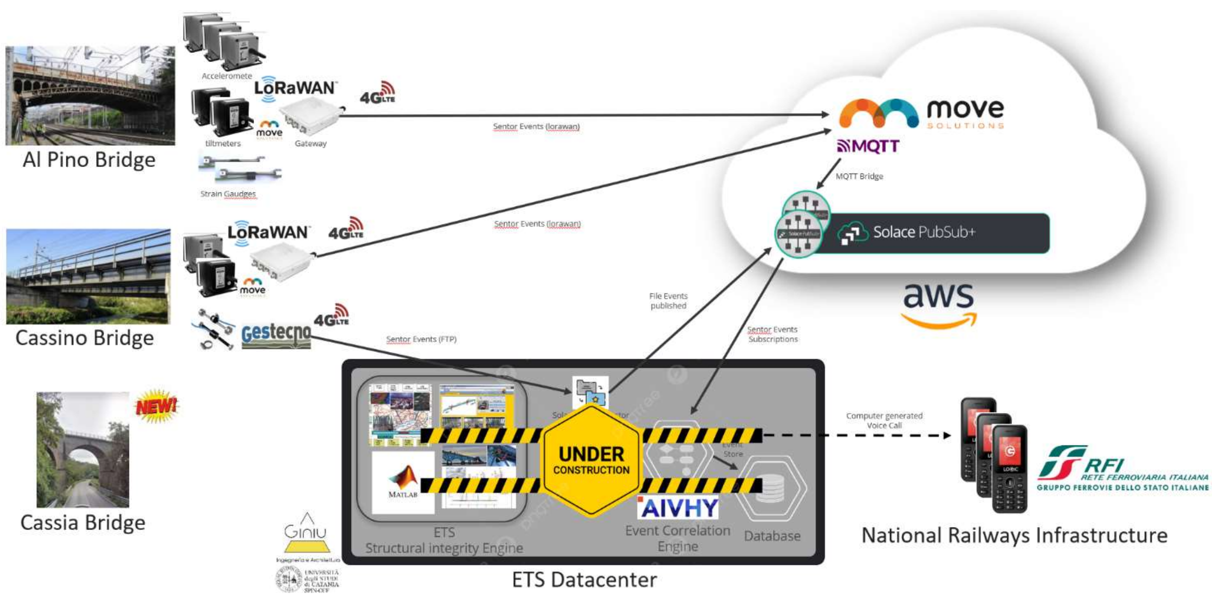


Figure 18 Architecture diagram-Use Case Monitoring Ponte Al Pino (To be)

3. Conclusions

The design, implementation and analysis of a remote monitoring system for a steel bridge has been described. Particularly, it has been underlined that a critical aspect is the validation of the system, that requires a series of operations and analyses in order to assess the correctness of the acquired data. Based on the described procedures, it is possible to implement an intelligent system of calibration of a complex monitoring system. This implementation is object of current studies.

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