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Structural monitoring of a historic masonry bridge

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Abstract

Structural Health Monitoring (SHM) aims to develop autonomous integrated systems allowing inspection and detection of damage with minimal human intervention. It thus represents a process of implementing a damage identification strategy through which, by periodic observation of the structure, it is possible to arrive at an assessment of certain characteristics of the system, as well as to define its current state of health. The case study under consideration describes a new static and dynamic monitoring system of a five-arch masonry railway bridge, realized by a network of sensors installed according to a placement strategy. The general objective of monitoring is the acquisition of all the information concerning the current condition of the bridge and thus the structural behaviour under static and dynamic actions to ensure an adequate level of public safety. Any change in the dynamic characteristics over time is indeed an indicator of ongoing degradation in the structure, due for instance to material damage phenomena, or geometrical. The collected data are visualized in real time with the help of the Web Platform where various operating parameters including sampling rates, resolution, trigger thresholds, alarm thresholds, etc. can be set. The data are finally analysed following a scheduled plan or upon reaching pre-established alarm thresholds.

Keywords: Structural Health Monitoring, railway bridge, masonry bridge, monitoring plan, structural assessment, damage, safety

1. Introduction

Structural monitoring is currently one of the most important engineering fields in which theoretical research combines with the development of new technologies, see Farrar and Worden (2012), Mishra et al. (2022). The many catastrophes that have struck diverse areas of the planet, and Italy in particular, have increased public attention on the complex concept of structural health. In the field of civil engineering, methods for structural identification are of fundamental importance as they allow for the estimate

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resonant frequencies, damping coefficients and modal forms. Once these characteristics are known, it is possible to predict the dynamic behaviour of the structures under study. Dynamic identification is the basis of *Structural Health Monitoring (SHM*), one of the most important methods for monitoring and assessing the health of structures (see Farrar and Worden (2012)). Existing identification methods fall into two broad categories: experimental modal analysis (EMA), and operational modal analysis (OMA). The former requires knowledge of the structural excitation that induces the measured response. OMA, on the other hand, enables identification of dynamic characteristics without knowledge of the structural excitation in question.

Prerequisite for achieving the objectives of any type of monitoring, is the design and implementation of the monitoring network. A monitoring network consists of hardware, comprising devices and sensors for acquisition and storage of information, and software for managing and processing the resulting data. Digitalisation and rapid transfer and processing of data (accelerometer readings, video, etc.) are tools used by designers and operators, in a process characterised by feedback, to check the health of the structure and, together with the owner or manager of the structure, apply measures to safeguard the structure and avoid or limit any possible incidents. This paper presents a structural monitoring strategy applied to the real case of a multi-span masonry bridge undergoing seismic retrofitting, as described in Compagnone et al. (2023). The monitoring plan contains the selection of the sensors and their positioning. The system enables both pre-design evaluation of the structure, in order to diagnose the bridge's current state of health and calibrate the numerical structural analysis models, and post-design verification of the seismic retrofitting works implemented on the bridge. Finally, the system allows the post-intervention health status of the bridge to be monitored in the long term.

2. Structural Monitoring

Structural monitoring is aimed at automatically acquiring, managing, and processing, using specific software, data about structural damage and defects before they become concretely evident (see Avci et al. (2021)). Furthermore, according to the Guidelines on Structural Monitoring in Italy (UNI-TR, 2016), monitoring enables:

- better correlation between loads/stresses acting on the structure, the resulting deformation and the technical assumptions of the design; in other words, a more reliable understanding of the structure's behaviour
- more precise modelling, more efficient sizing criteria and better safety assessment, also in relation to construction
- early detection of anomalies in the structural response, thus yielding information for possible reinforcement work and/or restrictions on use, especially resulting from the decay of the structural properties. Damage can be detected from the observation of the response to cyclic loads (fatigue) or occasional load paths, such as those due to earthquakes or environmental and anthropic agents
- the identification of strategies to extend the expected service life of the structure
- better management of the construction
- collection of statistical data as an input to regulations, also about the effects of climate change

Monitoring may be occasional (i.e. periodic, of limited duration) or continuous (with permanent installations). In the first case, the objective is to acquire information on the evolution of known phenomena, or to assess the effectiveness of extraordinary maintenance or structural interventions. In the second case, the procedure aims to monitor the work continuously and to trigger alarms if specific predefined thresholds are exceeded. Monitoring actions are based on a monitoring plan, which provides the design of specific measurement and information management systems. A possible monitoring strategy is presented in the next section with reference to a case study. Although innovative monitoring methods using Internet of Things (IoT)-based real-time wireless sensors have been proposed, as extensively summarised in Mishra et al. (2022), the strategy follows a traditional approach with wire-based sensor for reasons related to the duration of the monitoring itself and the need to guarantee service continuity with greater reliability.

3. Case Study: multi-span masonry arch bridge

3.1 Geometrical and mechanical properties

The case study under consideration is a five-span railway bridge in masonry, located in Italy. The spans are characterised by rounded arches with a net span of approximately 12 m, consisting of 75 cm thick solid brick and lime mortar masonry. The central arch overpass a stream bed, while the second and fourth overpass two roads.

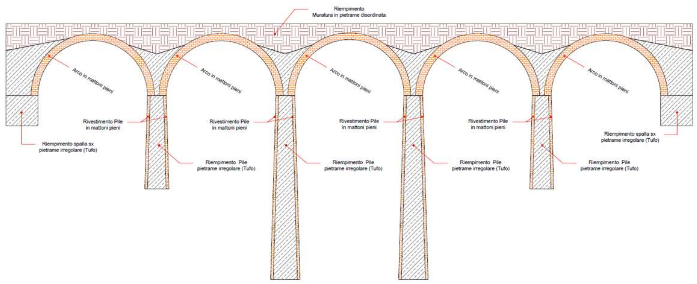


Figure 1. Longitudinal cross section

The two abutments consist of a 3.5 m thick core of loose stone (tuff) bonded with mortar, covered with 30 cm of solid brick and lime mortar masonry. The two central piers consist of a loose stone core (tuff) bonded by mortar, covered by solid brickwork and lime mortar. Core drilling revealed a core thickness of 2 m at the connection to the vaults, and a thickness of 3.2 m at the foundations. The two side piers consist of an irregular stone core (tuff) bound by mortar, covered with solid brickwork and lime mortar. Core drilling revealed a thickness of 2 m at the connection to the vaults, and a thickness of 2.6 m at the foundations. Core drilling of the spandrel revealed a gable thickness of 30 cm, and a type of masonry in solid brick and lime mortar. Figure 1 shows a longitudinal section. The stiffness and mass properties pre/post intervention of the materials are: 1) cladding of the piers and abutments E=1250/1250 N/mm^2 w=18kN/m^3; 2) Arches E=1250/1875 N/mm^2 w=18 kN/m^3; 3) Buttresses and cores of the piers and abutments E=900/1260 N/mm^2 w=14.5 kN/m^3; 4) backfill E=725/725 N/mm^2; w=19 kN/m^3.

3.2 Monitoring strategy

The monitoring system is designed to operate continuously. This type of monitoring provides information on the overall condition of the bridge and allows warning thresholds to be set in the event of ductile failure of the structure.

The monitoring plan is organized into the following main steps:

- Acquisition of geometric and mechanical survey data and construction of the FEM model of the bridge
- Selection of the hardware and software components of the monitoring system
- Installation of monitoring devices, implementation of the software system, acquisition, and data processing
- Testing of instrumentation
- Calibration of the FEM model based on monitoring data and model updates
- Initial (pre-works) assessment of the health status of the bridge
- Acquisition of the results of vulnerability analysis ad design of maintenance and structural reinforcement works
- Validation of the effectiveness of retrofitting intervention (post-works)
- Calibration of the warning thresholds used to trigger alarms in the event of structural anomalies
- Periodic assessment of the state of conservation of the bridge

The acquired data are divided into:

- data from Static monitoring, which involves the measurement of deflections by means of an automated total station
- data from Dynamic monitoring, which analyses natural and traffic-induced vibrations using three-axis accelerometer transducers
- environmental data (temperature, humidity, wind and pressure)

The calibration of the numerical model is carried out by analysing two sets of data:

- static and dynamic measurements obtained from static load testing with known loads. The static load test serves both to fine-tune the instrumentation and to acquire data for comparison with the FEM numerical prediction of the bridge response under the same loading condition
- data from long-term monitoring of vibrations. This set is used to evaluate the dynamic parameters of the structure (resonant frequencies, damping factors and modal shapes), averaged over time in order to eliminate contingent deviations. The dynamic properties are compared with those predicted by the numerical model

The assessment of the effectiveness of the seismic retrofitting intervention is pursued by comparing the initial and post-intervention global stiffness, and the dynamic properties of the bridge.

In order to guarantee long-term operativity of the sensors without interruption, they are installed with a continuous cabled power supply. The data are transmitted via a gateway to a cloud platform, thus enabling them to be analysed and reviewed at any time. Various operating parameters can be set in the web platform, including sampling frequencies, resolutions, trigger thresholds, alarm thresholds, etc.

Structural identification is achieved by applying OMA technique to identify the resonant frequencies and fundamental modes of vibration, see Li Rosi et al. (2023), Imposa et al. (2023). These depend on the intrinsic characteristics of the structure (masses, stiffnesses, damping, boundary conditions, etc.) and not on the magnitude and/or type of applied loads; therefore, if the structure of the bridge does not change (due to structural damage, for instance), its dynamic behaviour will remain unchanged over time.

The flow of monitoring actions is shown in **Errore. L'origine riferimento non è stata trovata.**. Three warning thresholds have been established, to be set based on the analysis of data acquired over a minimum period of three months:

- GREEN: regular service the behaviour
- YELLOW: the structure requires the attention of the manager
- RED: the structure requires works (e.g. bridge closed to traffic)

The thresholds relate to the occurrence of abnormal events, compared to normal conditions. The definition of the thresholds depends on the type, intensity, and frequency of the abnormal events in question. The violation of a given threshold does not in itself imply the existence of a risk. Further analysis is required. For example, violating the yellow warning threshold requires the monitoring authority to analyse the dynamic data in order to check for changes in the dynamic response of the bridge, and to check the deflection measurements. Violation of the red threshold, on the other hand, demands urgent inspection and/or the status of out-of-service structure.

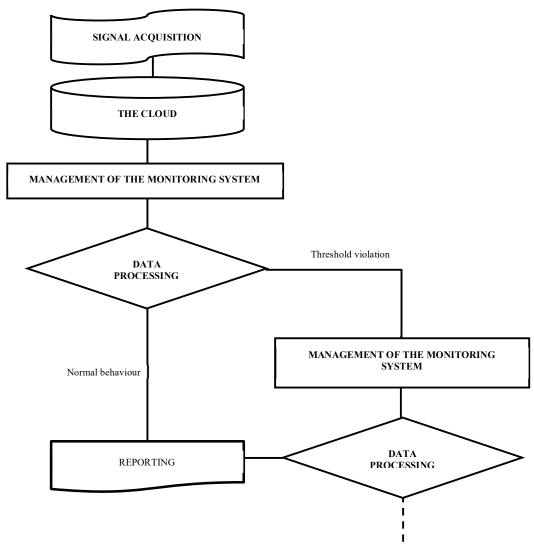


Figure 2. Flow chart of the monitoring process

3.3 Sensors placement

The monitoring devices were chosen and positioned in consideration of the predicted dynamic properties and modal deflections of the bridge (numerical model). A detailed model of the structure was developed with the Midas FEA NX software. Table 1 gives the three frequencies in the three dominant modes in the directions x, y, z and the corresponding modal mass.

Table 1. Fundamental modes and frequencies obtained from the FEM model

Direction	Vibration mode	Frequency Hz	Period s	Ux	Uy	Uz
	5	3.12	0.31	46.94 %	0.00 %	0.00 %
x	7	4.30	0.23	17.45 %	0.00 %	0.00 %
	12	5.27	0.18	1.32 %	0.00 %	0.00 %

	1	1.02	0.97	0.00 %	50.90 %	0.00 %
y	3	2.52	0.39	0.00 %	15.03 %	0.00 %
	8	4.38	0.22	0.00 %	5.59 %	0.00 %
	11	5.02	0.19	0.00 %	0.00 %	26.81 %
z	15	6.37	0.15	0.00 %	0.00 %	28.14 %
	19	7.92	0.12	0.00 %	0.00 %	10.14 %

The frequency analysis shows that in the X-direction (longitudinal axis of the bridge) the frequencies corresponding to modal participation factors with significant masses are in the range 3.12 to 5.27 Hz. On the other hand, in the Y-direction (transverse direction of the bridge) and in the Z-direction (normal to the bridge deck) the dominant frequencies range from 1.02 to 7.92 HZ. Considering the modal deformations corresponding to the modes in the X, Y and Z directions shown in Figures 3 to 6, one can determine the points of maximum modal deflection, where the instrument can be positioned to enable reconstruction of the modal form with the OMA dynamic identification technique. No advanced Optimum Sensor Placement algorithm is used as in Meo and Zumpano (2005).

The positioning of the instruments, deduced from the modal deflections, is shown in Figure 7. Eighteen Triaxial Micro Electro-Mechanical System (MEMS) accelerometers are chosen to be part of the monitoring system.

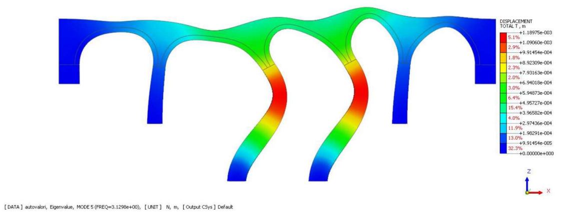


Figure 1. Mode No. 5, X axis (f=3.12 Hz)
Modal deflections X (Mass 46.94%)

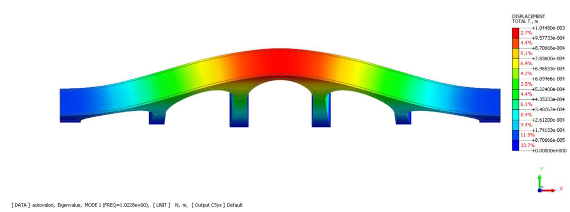


Figure 2. Mode No. 1, Y axis (f=1.02 Hz)
Modal deflections Y (Mass 50.90%)

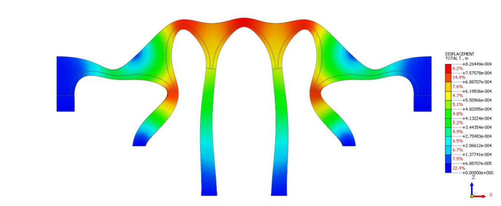


Figure 3. Mode No. 11, Z axis (f=5.02 Hz)
Modal deflections Z (Mass 26.81%)

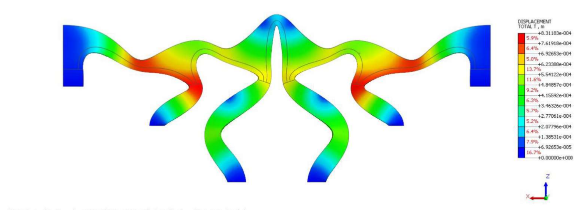
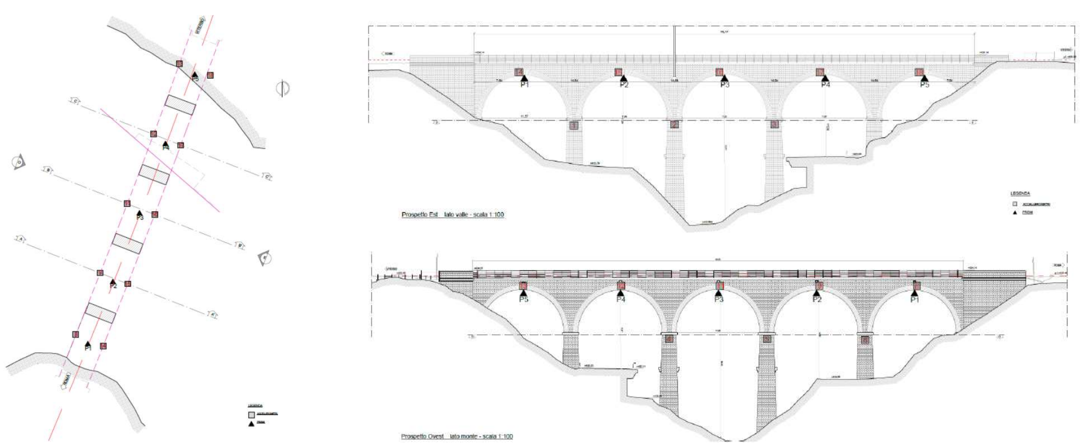


Figure 4. Mode No. 15, Z axis (f=6.37 Hz)
Modal deflections Z (Mass 28.14%)



(a) (b)

Figure 7. Accelerometer layout (a = plan, b = elevation)

In order to verify the chosen positions and to ascertain whether the accelerometers were sufficiently sensitive to capture accelerations due to the passage of railway vehicles, a linear dynamic analysis of the Time History type was run to simulate the dynamic effects of the passage of the train over the bridge. The load train used in the simulation is the D4 train from the RFI design manual. The time history analysis confirmed that the instruments are correctly positioned, as can be observed in figures 8 and 9.

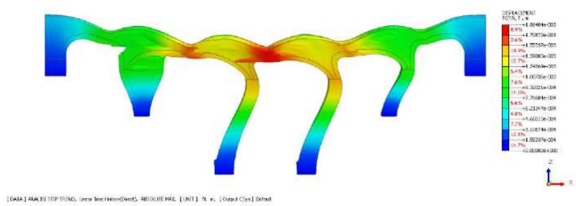


Figure 8. Total displacement

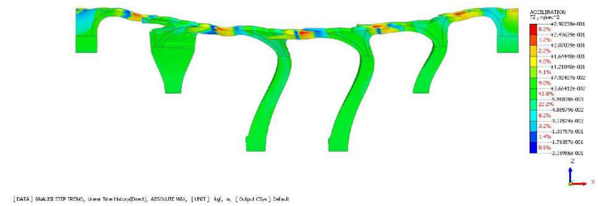


Figure 9. Acceleration Z

Static monitoring is done with a very high precision automated total station and topographic sensors. The total station is positioned inside a fixed case to be protected from possible shocks and connected to a router with data SIM card for remote control of the system. Power is supplied by a buffer battery connected to photovoltaic panels installed in the immediate vicinity. The sensors were also positioned in consideration of the maximum modal deflections, at the intrados of the five spans. Figures 7a and 7b show planimetric and altimetric positioning of the accelerometers and of the 5 prism total station reflectors. Figure 10 reports a typical installation of the total station.

Figure 10. Installation of the total station

3.4 Anchor system

The accelerometer measurements are affected by the method of fastening to the support. For this reason, the anchoring supports of the accelerometers are custom designed. The design ensures separation of the supports' own vibrational frequencies from those of the monitored structure, as well as the proper installation of the instruments. The steel reinforced L-shaped brackets are therefore designed with a known vibrational frequency, at least two orders of magnitude higher than the frequency of the structure and greater than the instrument's sampling frequency. Figures 11 and 12 show some details of the design and of the FEM model.

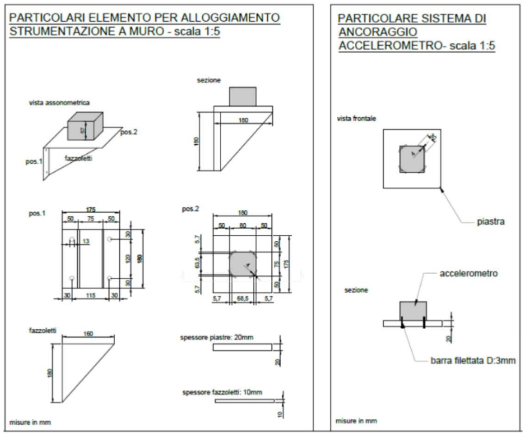


Figure 5. Structural detail of the accelerometer anchor plate

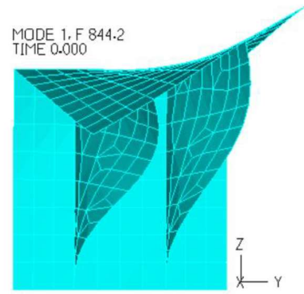


Figure 6. Finite element model of the plate

4. Conclusions

The work is a comprehensive example of the typical contents of a monitoring plan, according to current standards. The example relates to the continuous monitoring of a five-arch masonry railway bridge in need of seismic improvement. The illustrated sensor positioning methodology is of an engineering type, suitable for use in professional context regardless of more performing and optimized methodologies which are however more complex to use. In the transitional phase prior to the execution of the works, the bridge, where damage phenomena are present, is monitored in order to check its health and ensure its operating conditions. Both static and dynamic measurements are used to calibrate the FEM numerical model, which is then used in the design phase of the reinforcement works. In the post-intervention phase, monitoring simultaneously serves to verify the effectiveness of the reinforcement works by re-evaluating the dynamic properties of the structure and comparing the pre- and post-intervention elastic and inelastic structural response. In the long term, the monitoring system constitutes a surveillance system for the state of the bridge.

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