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Structural Health Monitoring of transport infrastructures: preliminary experimental calibration of the numerical model of "Ponte della Musica – Armando Trovajoli"

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Abstract

Considering the high vulnerability of existing structures and infrastructures, mainly due to deterioration of building materials, to the exposure to cyclic and seismic loads and environmental factors, one of the main challenges of recent years in the field of structural health monitoring is the development of systems capable of integrating satellite data with on-site sensor measurements in order to obtain more reliable information on structural safety conditions for the structures at different scales: from the local to the territorial one. However, this enormous potential is counteracted by some limitations of the common satellite techniques used to obtain displacement along the LOS (line of Sight) that can lead to the loss of information in the case of particular flexible infrastructures, as confirmed from recent studies. The bridge "Ponte della Musica Armando-Trovajoli" in Rome, made by a steel arch structures with a underlying prestressed concrete deck, considered as case study in this work, represents an example in which the satellite images do not allow to obtain useful information on the displacement, at least for the central and more deformable portion of the deck, and therefore also on the possible pathological movements. In the attempt to interpret of this phenomenon, this paper focuses on a dynamic identification campaign carried out on the bridge using ambient vibration measurements, to suitably calibrate a SAP2000 3D structural numerical model of the bridge to be considered for successive numerical evaluation of thermal deformations useful to better understand the link between physiological deformations and limits of satellite techniques.

Keywords: Structural Health Monitoring; Differential SAR Interferometry; Numerical Modelling; Dynamic Identification; Transport Infrastructures, Model Calibration

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1. Introduction

The resilience of the built environment is a key issue in European regions, particularly for 20th century reinforced concrete structures which are undergoing ever more rapid material deterioration. Enhancing the knowledge about new strategies for structures and infrastructures health monitoring can significantly contribute to improve their assessment and to facilitate the planning of interventions for risk mitigation. The persistent structural health monitoring of strategic structures and transport infrastructures, plays a crucial role to satisfy code provisions criteria over time and provide an effective support to make decisions about ordinary and non-ordinary maintenance program.

Significant progress has been made in the field of structural health monitoring and dynamic identification, based on different approaches and techniques. Bao et al. (2019) and Serlenga et al. (2021), analysed various engineering algorithms and applications of data acquisition, data diagnosis and reconstruction of the structural health. Different studies were performed on dynamic identification based on the analysis of the variations of wave propagation, as reported by Picozzi et al. (2010), Ditommaso et al. (2015), and on the techniques operating in the time-frequency domain, as reported by Ditommaso et al. (2012a and 2012b), Michel et al. (2018), Iacovino et al. (2018). It is well known that the presence of structural damage can change the dynamic characteristics of the structural system. Several methods for damage detection and localization on framed structures, based on the evaluation of the variation of modal or non-modal parameters and on the evaluation of the modal curvature evolution over time were developed, such as by Ponzo et al. (2010), Snieder et al. (2006), Dinh et al (2011), Pandey et al. (1991), Ditommaso et al. (2021).

Remote sensing can provide valuable information of natural and anthropic hazard scenarios thanks to its synoptic capability. Recently, the satellite Differential Synthetic Aperture Radar (SAR) interferometry (DinSAR) technique, already consolidated for the detection of ground displacements, is becoming one of the most innovative methodologies also for structures displacement monitoring in urban areas (Manzo et al. 2012). The technique is based on the exploitation of the phase difference (i.e., interferogram) between two temporally separated SAR images that, following the phase unwrapping operation (Fornaro et al. 1997), permits information on the detected displacements to be retrieved, projected along the radar sensor Line of Sight (LOS), that occurred between the two acquisition times, with an accuracy in some cases less than one centimeter.

In recent years, new technologies have been developed (mainly in the field of electromagnetic sensing and ICT) capable of completing the analysis methods of civil engineering, able to integrate the satellite data with on-site sensor measurements, providing precise information on dynamic characteristics, Cuomo et al. (2018) and Cuomo (2020).

This has led to the development of integrated systems for early warning, monitoring and quick damage assessment of the built environment and critical infrastructures. Several examples of this integrated approach, focusing on its suitability for long-term monitoring of transport infrastructure, were applied in Soldovieri et al. (2014) and Proto et al. (2010). Recent studies demonstrated the potential and limitations of multi-temporal DinSAR techniques applied for the structural monitoring and assessment of constructions affected by different external actions, as reported in Talledo et al. (2022).

An experimental campaign, with the aim of setting up new protocols to merge information retrieved from the DInSAR measurements and accelerometric data for the monitoring of strategic infrastructure was carried out within the WP6 “Structural Health Monitoring and Satellite Data” 2019-21 Reluis Project, developed under the framework of the Italian Civil Protection Department agreement. The selected case study was the “Ponte della Musica Armando-Trovajoli” bridge located in Rome described by Ponzo et al. (2021).

In the first stage of observation, the remote-sensing DInSAR measurements provided information about the long-term deformation status both of the structure and of the surrounding soil. The analysis results of satellite data relating to both the ascending and descending orbits showed that there were no measuring points detected by the satellite on the deck as reported by Ponzo et al. (2021). Same measurements performed on other masonry arch bridges with the piles in the riverbed located close to the Ponte della Musica and characterized by higher stiffness and, shown data both on the support and on along the deck. In the case of “Ponte della Musica” bridge monitoring, the associated displacements are continuously varying in time due to temperature and traffic loads. However, the combination of heavy traffic loads, strong wind, temperature changes and other second-order events may lead to large unexpected deformation effects on this specific bridge typology, which sometimes jeopardize the correct retrieval of displacements associated to the investigated bridge or some parts of it.

In a second stage two experimental ambient vibration measurements campaign have been performed on October 2020 and November 2021, integrated with a visual survey of the bridge. The vibrational-based data obtained by velocimetric data, described in Ponzo et al. (2021), and by accelerometric data were analysed to provide information about the main eigenfrequencies of the bridge and their possible variation over time.

Some further investigations to detect the possible causes (e.g., sudden temperature variations, strong winds) of this lack of coherent DInSAR measurements on the bridge deck of Ponte della Musica, need to be further deepen, by means of experimental and numerical analyses. In this work the preliminary results of the numerical calibration of the 3D model developed in Sap2000 are presented and compared with the main results of the experimental dynamic identification, based both on velocimetric and accelerometric data.

2. The "Ponte della Musica-Armando Trovajoli" case study

The "Ponte della Musica - Armando Trovajoli" is a shallow arch bridge for pedestrians/cyclists crossing the River Tiber in Rome with a single span (Fig. 1). The bridge is almost 190 m long and is 20 m wide, so that it is one of the widest pedestrian bridges ever built. The bridge has main span of approximately 130 m and two side spans of about 30 m (Fig. 2). The bridge comprises two outwardly inclined arches made of fabricated 'tear drop'-shaped tubular steel supporting stiff transverse frames positioned at 8.5 m intervals. The arches rise 10.6 m above the crown of the deck at midspan, giving a span-to-rise ratio of about 12:1, Liaghat (2015). Construction began in 2008 and it was inaugurated in May 2011.

Fig. 1. "Ponte della Musica Armando-Trovajoli" in Rome.

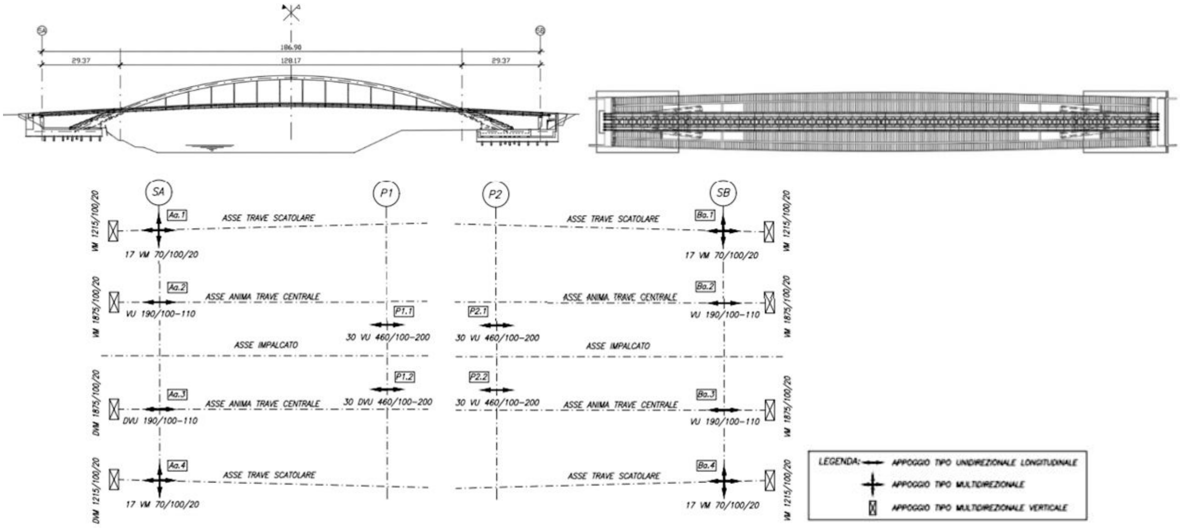

Fig. 2. Structural scheme of the investigated bridge and constraint conditions (Design documentation provided by Ing. Stroveglia)

A pile foundation has been adopted due to the local geological and geotechnical setting of the subsoil, as reported in Ponzo et al. (2021). This foundation is composed by 54 piles (Φ 600) inserted into two concrete plinths, 1620 m^3 the right one and 2785 m^3 the left one. As described in Liaghat (2015), during design development, a fundamental change to the structural scheme of the bridge was defined, from a true arch to a tied arch, in order to avoid the inclined mini-piles solution.

3. In-situ testing

Two in-situ testing campaign of ambient vibration measurements were carried out in order to evaluate the main eigenfrequencies of the bridge, based on different type of sensors: i) the first campaign was performed using one three-directional velocimetric stations and ii) the second one was performed using six three-directional accelerometric stations.

In October 2020, the first experimental campaign was carried out acquiring data on the span at L/2, both at the centre and on the east edge, at L/4 on the east edge and on the abutment (more details in Ponzo et al., 2021). This experimental campaign was performed using stations characterized by a dynamic range equal to 144 dB, a digitizer characterized by a resolution equal to 24 bit, a sensor characterized by a frequency equal to 0.5 Hz.

In November 2021, the second experimental campaign was carried out, based on the installation of six tri-directional accelerometric stations synchronized and distributed along the bridge as depicted in Fig. 3a and Fig. 3b.

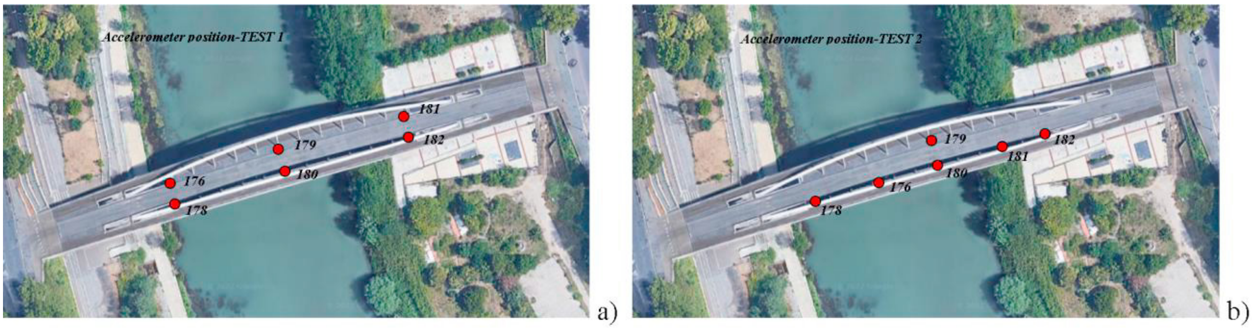

Fig. 3. Plan view of the November 2021 ambient vibration recordings - a) Sensor Configuration n.1; b) Sensor Configuration n.2.

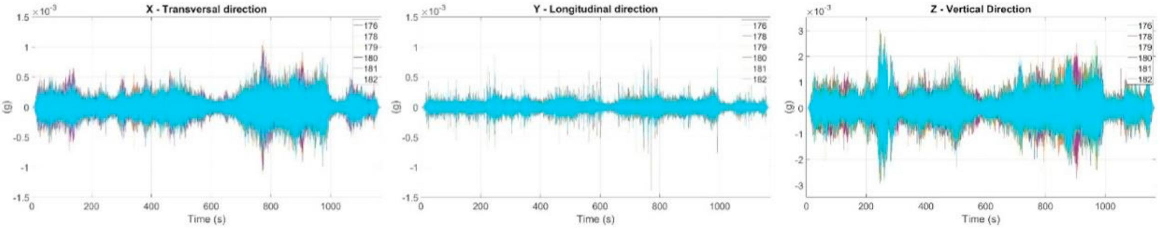

Fig. 4. Accelerometric acquisitions

Within the second experimental campaign three one hour duration tests have been performed using a 250Hz sampling frequency. During the first two tests the sensor configuration illustrated in Fig. 3a was used, while for third test the geometric distribution of the sensors illustrated in Fig. 3b was applied. Force-balanced accelerometric sensors equipped with a 24-bit digitizer and a wide dynamic range have been used.

The analysis of the accelerometric data obtained from the configuration of the sensor of Fig.3a allows to observe that along the transverse and longitudinal directions the maximum accelerations are quite similar, while the vertical components of the acceleration histories are completely different both in terms of content of frequency and maximum acceleration values. Some preliminary results recovered from the more accurate second experimental campaign are provided in Section 5. In any case, they confirmed by and large the outcomes obtained during the first test campaign.

4. Numerical model

A finite 3D element numerical model of “Ponte della Musica – Armando Trovajoli” was implemented in Sap2000 software, CSI (2014), based on a detailed representation in 3D Cad. The irregular geometry sections of the arches, the central beams, the edge beams and the curbs were not available in the SAP library and were opportunely defined and implemented in Sap2000 and modelled as one-dimensional frame elements. In particular, fig 5a shows the central beams section modelled as one-dimensional frame element with open Z section S355 steel grade. The longitudinal axis is straight in plan and parabolic in the vertical plane. In fig 5b is represented the section of the tubular section of the arch, modelled as one-dimensional frame of S355 steel grade, with a shape called "asymmetrical drop", 1837.5 mm wide, whose orientation, for aerodynamic reasons, foresees the curved part facing the outside and the cusp of the drop towards the inside.

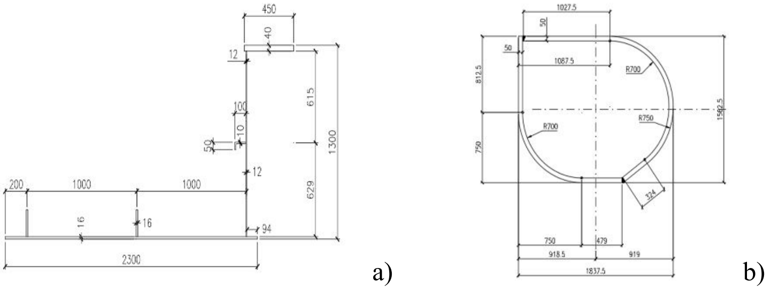

Fig. 5. (a) Central beam section and (b) steel arch section.

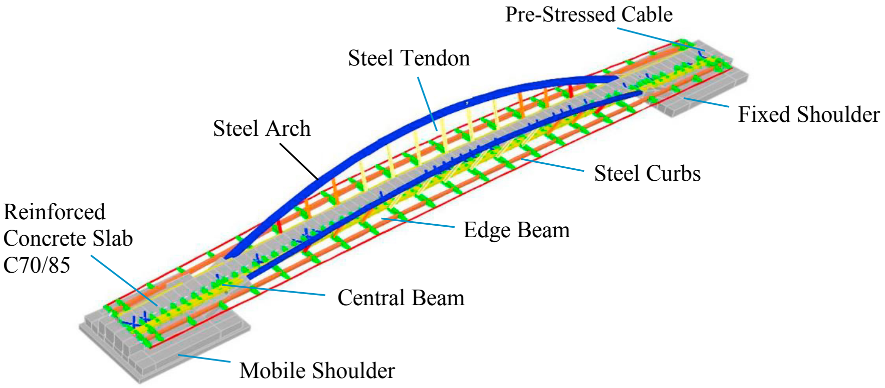

Fig. 6. 3D numerical model of the bridge.

The section of arches is also rotated by 21.2496°, to be orthogonal to the axis of the hangers, which are also rotated by the same angle with respect to the vertical. The configuration of the arches appears curved, but it is a series of short straight elements, 4.5 m long, welded together.

The six pre-stressed cables were modelled as a tendon element with an 0.0495 m^2equivalent section. The shoulder and the support rafts were defined as two-dimensional shell type elements of C70 / 85 reinforced concrete, for the slab a "shells thick" type element with a thickness of 0.18 m was defined. The abutments shell elements were discretized according to the intersections between central beams and crosspieces. The masses of the bridge were opportunely defined taking into account of dead load and permanent load, including the masses due to the road pavement. The simulated conditions are representative of load conditions during the experimental campaign. In order to simulate the boundary conditions of the real structure, in this preliminary phase, pin supports were considered (which simulate the effect of friction for low levels of stress) at the edges of the deck and fixed supports at the base of the arches and abutment.

4.1. Preliminary dynamic identification using accelerometric data

Data recorded during the second experimental campaign on the bridge have been acquired in stationary condition with good weather conditions. For the preliminary analyses the stochastic subspace identification method (Reynders, 2012; Rainieri and Fabbrocino, 2014) has been used to characterize the main structural eigenfrequencies of the monitored bridge. From Fig. 7 it is possible to appreciate the difference in terms of level amplitudes of each peak along the different components representative of different motion component of the bridge for each eigenfrequencies.

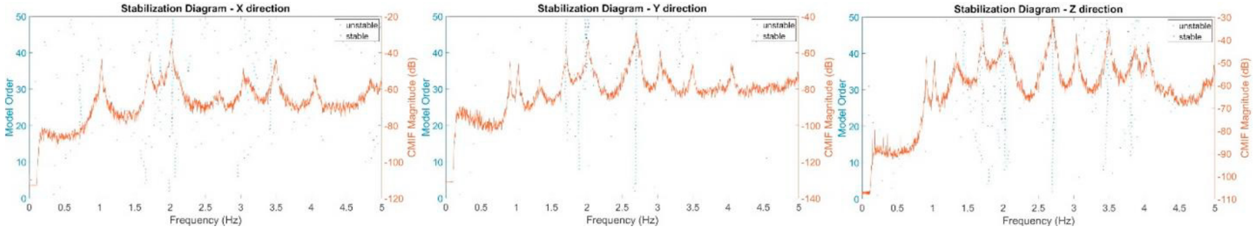

Fig. 7. Stabilization diagram of the monitored bridge obtained by accelerometric stations.

Consistent with results retrieved using velocimetric stations, the main structural experimental eigenfrequencies are those represented in the first second column of Table 1, further analyses are necessary to provide information about mode shapes and related equivalent viscous damping factors.

4.2. Calibration of numerical model: preliminary results

For a proper calibration of the model, various constraint conditions of the bridge were analysed, such as pinned base constraints at the shoulder connection, or pinned and roller constraints, or link elements, in order to take into account various constraint conditions depending on the external force levels. Among the possible configurations, this paper presents the most appropriate for the stress conditions considered (ambient noise). In particular, a model with joints at the base of the foundations and linear links for modelling the sliding support devices have been considered (Fig. 8). Table 1 shows the comparison between the experimental and numerical characteristics of the bridge in terms of the main frequencies. A good correspondence between numerical simulation and on-site experimental results has been observed.

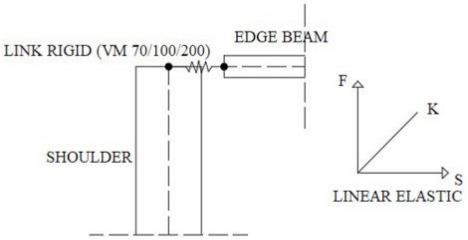

Fig. 8. Linear link element connecting deck-abutment

Table 1. Main experimental and numerical frequencies of the bridge

	Experimental	Numerical	Percentage Difference
Mode number	Frequency [Hz]	Frequency [Hz]	Rate [%]
Mode 1	0.92±0.01	0.92	0±0.1
Mode 2	1.01±0.01	1.07	5.94±0.1
Mode 3	1.33±0.01	1.49	12.03±0.1

5. Discussion

One of the mail goals of 2019–2021 DPC-Reluis Project was setting up new protocols to merge information retrieved from satellite data and on-site measurements. The "Ponte della Musica–Armando Trovajoli" bridge has been selected as a test site. In this paper, a preliminary discussion about the modal calibration of the numerical model of the bridge has been presented. Particularly, the numerical calibration was based on the minimization of the difference among retrieved experimental eigenfrequencies and numerical ones.

The calibration process was mainly based on the variation of mechanical characteristics of external constrains (taking into account foundation-support devices-structure interaction). Mechanical and geometrical characteristics of the elements have been retrieved from the design documentation. Further analyses on the acquired data are necessary to evaluate experimental mode shapes and related equivalent damping factors. All these information will be used to improve the accuracy of the numerical model taking into account also this other kind of information and to better calibrate nonlinear boundary conditions. Once the calibration phase of the model has been completed, new numerical linear and nonlinear analyses will be performed in order to understand the amount of lateral and vertical displacement due to air temperature variations and solar radiation. The last goal will be to understand the possible role played by thermal effects on bridges and their correlation with the coherence of interferograms retrieved from satellite over time.

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