In-Operation Experimental Modal Analysis of a Three Span Open-Spandrel RC Arch Bridge

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Abstract. This paper presents the results of the dynamic tests conducted on a historical reinforced concrete arch bridge located in the Tuscan-Emilian Apennines, in the province of Parma (Italy). The design of the sensors location was determined in order to investigate the possible separation into bodies operated by the joints between the different spans. The ambient vibration data allowed the dynamic characterization of the 3-span arch bridge with the total length of 146 m and 18 m in width. The interpretation of the main global modes, distinctly detected through time domain identification methods, indicates that the horizontal response is governed by the deformability of the joints. The results show that the obtained modal features provide a reliable reference for the subsequent updating of the bridge FE model.

Keywords: Experimental modal identification, RC Arch Bridge, Dynamic tests, Bridge joints, Stochastic subspace identification.

1 Introduction

Bridges are critical elements of the transportation systems, particularly exposed to various phenomena of failure, which are to be kept safe and functional for a very long time through an effective maintenance system [1]. The performance of existing bridges, though at the time of their design their operation limit was set for long period, is usually inadequate. This is due to various factors, such as the traffic conditions, vehicles load and speed, and the progressive request to adequate the safety standards to the updated codes. Moreover, in the long-term, the condition and performance of a structure inevitably change, so that the material properties and boundary conditions are very different from the initial stage of construction. In this regard, reliable assessment procedures represent a fundamental step to identify possible vulnerabilities and consequently plan the best intervention procedures.

Dynamic tests are a useful tool to assess the health state of a structure, especially when combined with calibrated Finite Element Models (FEM) in order to obtain predictive models. When using FEM codes, some of the parameters like structural geometry, material properties, boundary condition, etc. are simplified [2]. It is hence expected that the measured response of a structure and the response from its model do not generally match. In this regard, FEM updating has become an effective and widely used tool to improve the correlation between test data and computational prediction [3]. In recent years, quite a lot of research work has been produced on model updating, including many applications to historical structures [4].

The proper design and performance of dynamic tests play a decisive role in the process of model updating. Farrar et al. [5] summarized that vibration tests can be categorized in: forced vibration tests (FVT) and ambient vibration tests (AVT). AVT is applied in normal conditions with non-controllable and non-measurable ambient load like traffic and wind loadings, while FVTs are only performed with controllable and measurable ambient loads applied by shakers, droppers or exciters. Consequently, FVTs usually need more expensive equipment and controlled operation condition [6].

The modal parameter identification techniques can be classified based on the analysis domain into three categories: frequency domain, time domain and joint time-frequency domain identification methods. In recent years, time domain techniques have been pursued rather successfully, also thanks to the great spectral resolution offered in the analysis of complex systems, and thanks to their modal uncoupling capability [7]. Contrary to classical methods, subspace algorithms do not suffer from the problems caused by a-priori parametrizations and non-linear optimizations. The singular value decomposition and QR decomposition techniques are used in the calculation, which greatly improves the calculation efficiency. The Stochastic Subspace Identification (SSI) is an efficient system identification method and is widely used in the modal parameter identification of structures [8]. One of the main shortcomings of these methods is that they often produce spurious modes, whose true nature, however, can usually be ascertained by means of simple modal form correlation indicators, or, as an alternative, with the aid of numerical models.

The objective of the present work is to study the dynamic behavior of a historical reinforced concrete arch bridge located in the Tuscan Emilian Apennines, province of Parma (Italy), in order to assess its health state and highlight its vulnerabilities. The measurement setups were determined based on a preliminary FE model of the investigated structure. Subsequently the main global modes of the bridge were identified from AVT signals by using SSI techniques.

2 Description of the RC arch bridge

The Lamberti bridge on the Ceno river was built in 1933 on the road connecting the towns of Varsi and Bardi, in the province of Parma and it represents an important infrastructure for local mobility. The bridge, entirely made of reinforced concrete, is constituted by three spans of 38 meters long each, which are supported by three arches each (Figure 1a). As documented by the photographic report made during the inspection of September 2018, the spans of the structure are disconnected at the level of both the deck and the vertical elements: in Figure 1b is possible to notice a joint between the spans. The first available documentation on the bridge dates back to 1984 and relates to the executive project of an intervention for the existing deck, which was not yet equipped with a waterproofing system for the slab.

Fig. 1. Lamberti Bridge on the Ceno river (a); joint connecting two spans (b).

3 Dynamic tests

The dynamic tests were performed on the 21th and 22th of November 2018. The accelerometers used for the dynamic tests were of the capacitive type and the acquisition system was composed of 20 mono-axial piezoelectric accelerometers, and 8 Linear Variable Displacement Transducers (LVDT) for dynamic displacement measurements (Figures 2a and 2b). LVDTs are highly sensitive electromagnetic devices that are used to measure slight displacements that vary over time.

Fig. 2. mono-axial accelerometer PCB (a); LVDT (b).

Four acquisition setups were designed and performed; however, in this paper only Setup 1 and Setup 2-bis are presented, since they were the ones useful to characterize the global behavior of the bridge and maximizing the spatial resolution of the experimental modal shapes. The layouts of the two main setups are represented in Figure 3. The LVDT had been used in Setup 1 and were positioned in correspondence of the joints between the different spans in both the horizontal directions of the deck, in order to measure the relative displacements at the joints. The signals, lasting approximately

45 minutes, were acquired in the presence of the regular vehicular traffic with a sampling frequency of 512 Hz.

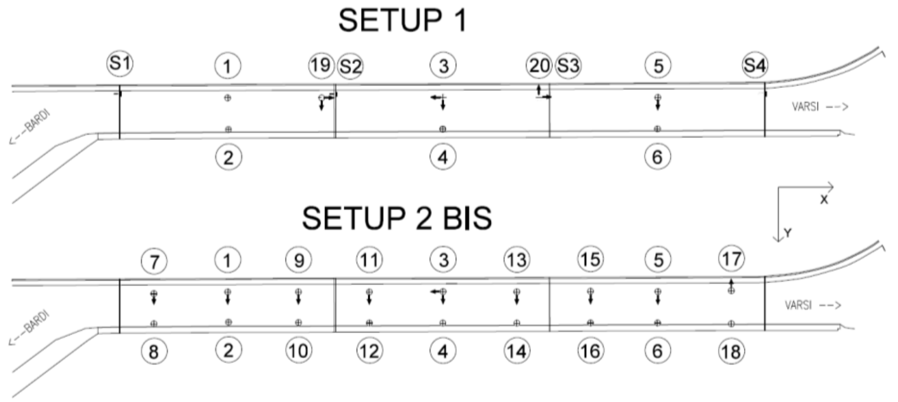

Fig. 3. Acquisition Setups

By observing the acquired signals (Figure 4), it is possible to distinguish the peaks produced by vehicles of low mass, which present fluctuations of the order of 10^{-3} m/s^2, from those related to vehicles with a medium-high mass, whose peaks exceed 0.3 m/s^2. In Setup 2-bis, instead, the records are only constituted by accelerometric data. In Setup 1 the displacements detected by the LVDTs (Figure 5) were analyzed separately with respect to the accelerometric data, in order to finally check the consistency of the results obtained from different sensors.

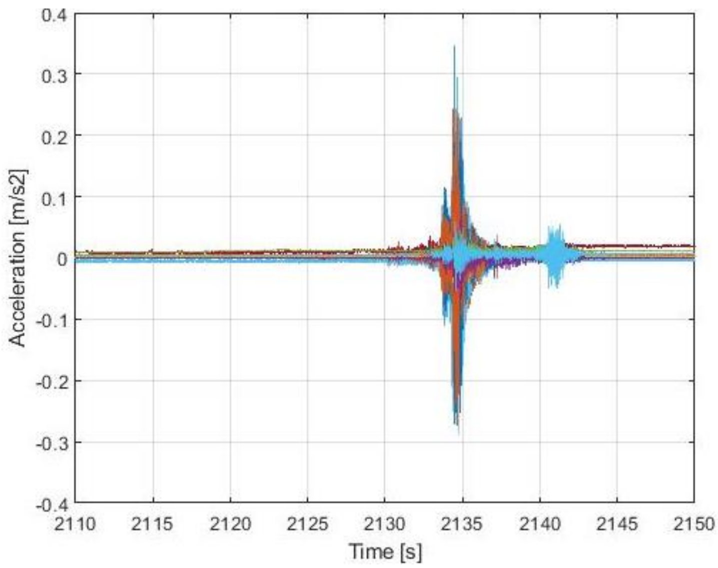

Fig. 4. Signals recorded by accelerometers

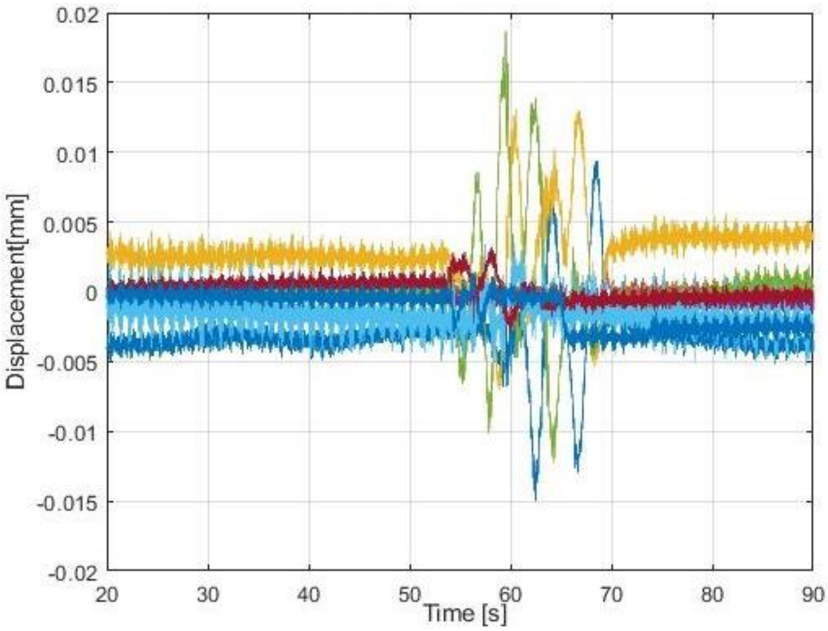

Fig. 5. Setup 1: Displacements recorded by LVDT

Table 1 summarizes the values of the maximum absolute and relative displacements, measured along the X, Y and Z directions; the absolute displacements were obtained by numerical integration of the accelerometric values, while the relative displacements were recorded directly by the LVDTs positioned on the joints.

Table 1. Maximum displacements recorded during the test campaign

Position	Direction	Displacement [mm]	
1	Z	-0.759	Absolute (accelerometers)
20	X	0.021	
11	Y	0.525	
S3	X	0.527	Relative (LVDT)
S3	Y	0.975	

3.1 Results of the time domain dynamic identification

The dynamic identification of the structure was performed in the time domain, in terms of frequencies, modal shapes and damping. In particular, an algorithm of the SSI family was used. In order to improve the reliability of the results obtained with the *output-only* methods, a statistical analysis of the results obtained in the identification sessions was carried out, as well as on the stability of the modes by changing the system order.

The identification procedure was performed by segmenting the entire length of the signals. All the signals have been filtered with Butterworth, a 4th order band-pass filter, with an interval between 0.2 and 25 Hz, and then decimated up to 128 Hz. The filter was applied in order to remove of any kind of linear trend, including the average. In the identification process, all modes with equivalent viscous damping identified as less than 1% and above 8% were neglected, as they were considered spurious for this kind of structure. Referring to the analyzed acquisition sequences, it was possible to plot the diagrams of Power Spectral Density (PSD) and detect peaks corresponding to frequencies with higher energy content. The PSD diagrams are generally shown in the background of the stabilization diagrams in order to highlight the overlap between peaks and identifications relating to the stable modes. The identification occurred mainly through the setup 2-bis, while the setup 1 was used to confirm the results and to obtain additional information regarding the vertical vibration modes of the structure. For brevity, only the diagram corresponding to the stable components of the setup 2-bis is shown in Figure 6, i.e. those that show a certain stability when the system order changes.

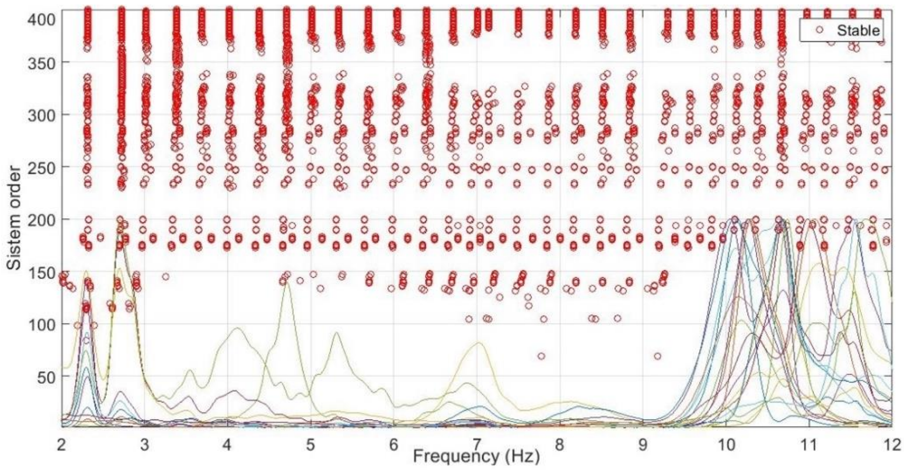

Fig. 6. Stabilization diagram Setup 2-bis: stable identifications in 2-12 Hz range.

The clustering diagram referred to the setup 2-bis is also reported (Figure 7), by means of which it is possible to discriminate the modes with a nearby frequency, and associate the corresponding damping obtained as the average of the values within the several clusters. Finally, in Figure 8, the first four modal shapes identified are graphically represented. It is important to keep in mind that they refer only to the three spans on which the sensors were placed and to the instrumented movements. The phases of the modes, generally complex, have been forced to the values 0 or π by phase alignments, so as to make the representation intuitive. Furthermore, the modal shapes are appropriately expanded to the non-instrumented positions with polynomial laws, separately for each of the three portions of the bridge.

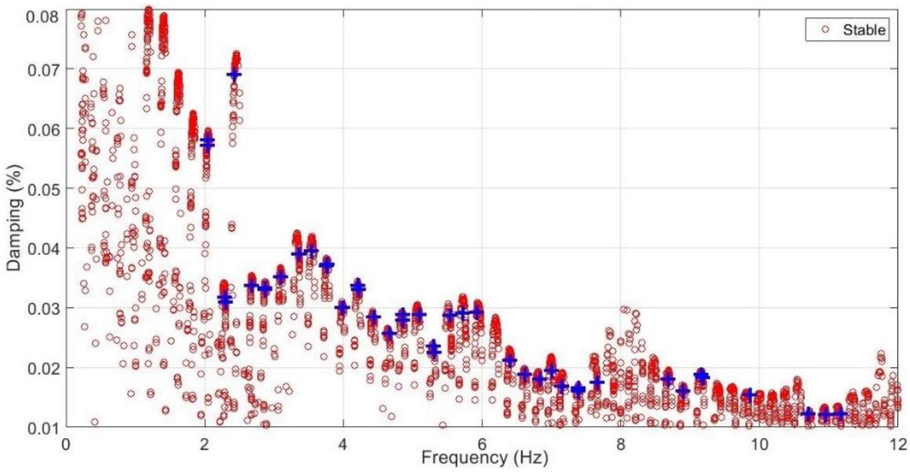

Fig. 7. Setup 2 bis: clustering diagram.

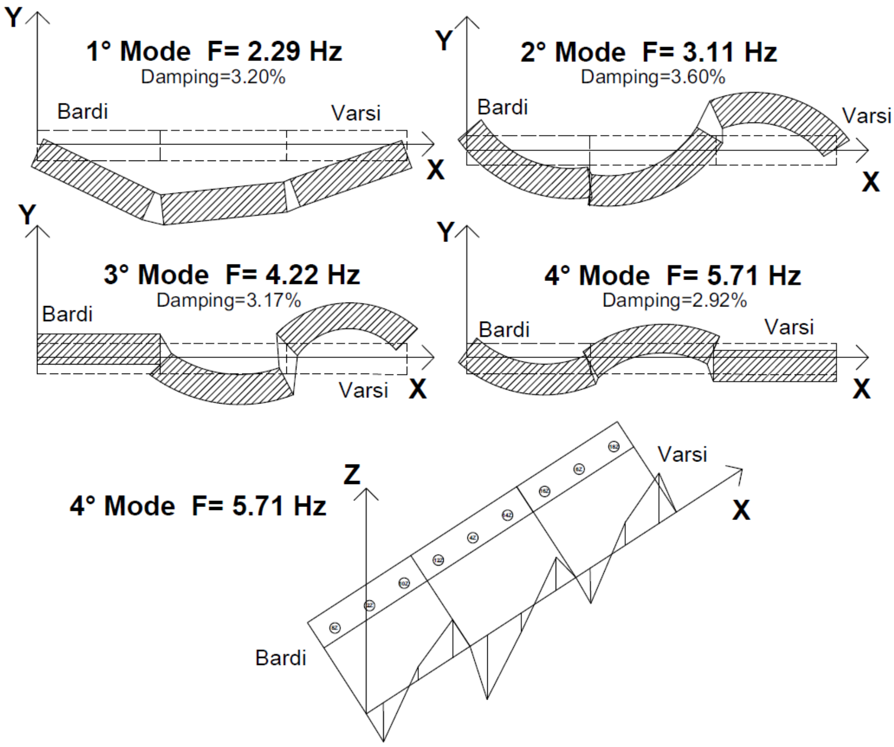

Fig. 8. Schematic rrepresentation of the first 4 modal shapes.

4 Conclusions

This paper describes an ambient vibration testing campaign performed on an historical RC arch bridge. The observed complexity in the dynamic behavior of the Lamberti bridge is to be ascribed to several factors, including: i) the presence of multi-connected elements and the consequent local dynamics; ii) the uncertainties related to the rigidity of restraints and connections; iii) the presence of joints between the different arch spans; iv) the apparent degradation state of the materials. These factors cause difficulty in classifying the multitude of observed modal components. However, the test setup design has led to the detection of 4 modes, allowing the following observations:

- The first horizontal vibration mode, identified at 2.29 Hz, is governed by the deformability of the joints, which prove to be effective in separating the transverse dynamic behavior of the deck in three parts, corresponding to the three arches. The disconnections at the deck raise some concerns about the transverse seismic response.
- The first two horizontal modes are markedly asymmetrical, which indicates deviations in the dynamic behaviour of the three arches.
- The damping has relatively high values, around 3% on the main vibration modes.

Acknowledgement

The research was conducted under a contract with the Road and Infrastructure Service of the Provincia di Parma.

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