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The dynamic characterization of a multispan prestressed concrete bridge

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ABSTRACT

This paper presents and discusses results of the dynamic tests performed on the Moscosi Bridge in Cingoli (Italy). The main scope of the tests is to evaluate the dynamic parameters of the bridge, such as the eigenfrequencies, the mode shapes and the relevant modal damping ratios, in order to characterize the structural behaviour before the execution of some required restoration works, providing (*i*) useful information for the development of the numerical model for the design and (*ii*) a benchmark for the evaluation of the retrofit effectiveness, by repeating tests after the retrofit. The dynamic characterization is obtained through the measurements of ambient vibrations, which are processed with the Covariance-driven Stochastic Subspace Identification. In addition, the dynamic response of the bridge subjected to a vehicle passages is registered and compared to that induced by the ambient excitations. First considerations seem to reveal the presence of the observed structural damage at the base of one pier.

1. INTRODUCTION

The dynamic structural identification and monitoring are the most efficient methods to characterize the behaviour of the structures, especially in the case of strategic constructions of great importance and/or in the case of structures characterized by not-common and complex dynamic behaviour. As for bridges, the monitoring provides numerical data which are not affected by the presence of non-structural elements, thus, the monitoring of the dynamic properties also represents a useful tool for the intrinsic structural health evaluation, being their changes over time strictly related to degradation

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of the structural integrity. The presence of damages resulting from the occurrence of extreme events, i.e. earthquakes, or from degradation phenomena can be recognized as a reduction in the stiffness of the structure, and results in a decrease of natural frequencies and a modification of the mode shapes.
The dynamic control is usually based on the experimental identification of the modal parameters that, in case of massive structure or big constructions, can be most easily obtained with Operational Modal Analyses (OMA) procedures, based on ambient vibration measurements.
This paper deals with the dynamic structural characterization of the current state of the Moscosi Bridge located in Cingoli, in the centre of Italy. Interventions on the viaduct are planned in order to restore the integrity of the structure after the Italian seismic events of the recent years (August 2016, 24th and aftershocks). The presence of a spreading cracking condition on the whole bridge, and in particular at the base of one of the supporting piers, makes necessary the execution of retrofitting works on the entire structure (i.e. the strengthen of piers, the recovery of structural joints between spans, the substitution of bearings) according with the Italian Standards. First, the main structural characteristics of the viaduct are described; then, tests and data processing methods are presented. The global dynamic response of the structure is checked by means of different placement configurations of accelerometers with the aim of highlighting two specific dynamic aspects: *i*) the flexural-torsional behavior and *ii*) the transverse one of the deck. The processing of the tests data is carried out with the SSI-Cov method, then the PoSER technique is adopted to merge results of different configurations and to finally identify the global behavior of the structure. Furthermore, the dynamic response of the bridge subjected to a vehicle passages is also registered to evaluate the bridge response when subjected to actions with higher intensity than that induced by the ambient excitations. The aim of these tests is to attempt a damage identification by comparing results of the tests with those obtained through ambient vibration measurements.

2. DESCRIPTION OF THE MOSCOSI VIADUCT

The bridge is constituted by 14 spans of 31.6 m (except for the first and the last ones, which are 30.6 m) laying on 13 reinforced concrete circular piers of variable heights. The deck has a curved shape as reported in Fig. 1. It is formed by 3 prestressed concrete box girders, of 3.6 m spacing, 1.8 m height, with 3.09 m, 0.85 m and 0.14 m superior width, inferior width and web thickness, respectively. The box girders are connected by end cross beams. The slab is 0.2 m thick, with a total width of 10.7 m (hosting a carriageway of 8.6 m). The pier bents have rectangular cross sections of 3 m width, 9 m total length and variable height from 0.8 m to 1.55 m. The deck is supported by 84 fixed both mono and multi-directional bearings of 0.8x0.8 m (6 on each pier and 3 on each abutment). The piers have a circular cross section with a variable diameter from 2.6 m to 4.0 m from the top to the base. The foundation is constituted by squared-plan plinths of 1.8 m height with variable dimensions (7.6x7.6 m, 8.5x8.5 m, 9.3x9.3 m), while the abutments are 4.2 m high, 1.2 m thick, based on a 1.2 m height foundation.

Fig. 1 Aerial view of the Moscosi Bridge deck (from Google Maps) and actual state of the Moscosi Bridge

3. AMBIENT VIBRATION TESTS AND MEASUREMENTS

The Operational Modal Analysis uses the dynamic response of a structure under its operating conditions to identify its modal parameters. OMA is performed without measuring, nor explicitly applying forces, but assumes that the sources are broadband random (ambient forcing with approximately white noise characteristics).
In this paragraph, some details of the experimental tests performed on July 2017 are reported, discussing firstly the characteristics of the equipment used, the test configurations and then the modal parameters obtained from the numerical elaborations.
To measure the ambient vibrations the following instruments have been used:
(i) 10 single-axis piezoelectric accelerometers PCB model 393B31 characterized by a sensitivity of 10 V/g, a measurement range of +/– 0.5 g, a frequency range 0.07÷300 Hz and a broadband resolution of 1 μg r.m.s.,
(ii) 1 USB chassis NI cDAQ 9178 equipped with 3 NI 9234 4-channel dynamic signal acquisition modules (24-bit),
(iii) 1 laptop and
(iv) coaxial caves.
Part of the equipment is reported in Fig. 3.
The vibrations were generated by microtremors and a very low wind acting during the whole day. The air humidity and temperature conditions have been stable, within a range of ±3 °C around the average temperature (27 °C). From the obtained results, the

ambient excitation reveals to be sufficient to identify the modal parameters of the viaduct.

(a) (b)

Fig. 2 (a) PC and signal acquisition modules; (b) 2 accelerometers positioned

Eight different test configurations have been adopted to catch the effects of the structural joints between adjacent spans on the behaviour of the bridge. In detail:

- the configurations P2, P3, P7 and P8 mainly allow the evaluation of the transverse behaviour of the viaduct, and thus the accelerometers were positioned only on one side of the deck with transverse measurement direction, on both the left and the right side of each joint (Fig. 3);
- the configurations P1, P4, P5 and P6 allow the evaluation of the flexural and torsional behaviour of the deck; in this case, the measurement direction is the vertical one and the accelerometers were located on both the deck sides (Fig. 3);

For each configuration, 2800 seconds long records, sampled at a rate of 2048 Hz (the minimum for the used equipment), are acquired. This time length provides enough data to obtain modal parameters with a good accuracy, as reported in (Cantieni, 2005). The eight configurations are reported in Fig. 3. The numbering and the position of sensors follows that of the piers (red labels).

The identification of the modal parameters is performed with the Covariance-driven Stochastic Subspace Identification (SSI-Cov) technique, operating in time domain. The SSI-Cov is one of the most powerful OMA methods and uses a stochastic state-space model to describe the dynamic problem (Juang, 1994; Peeters, 2001). This permits the use of a first-order system of differential equations, instead of the usual second-order system of differential equations, to describe the dynamic system. Within the OMA context, such technique is widely recognized for its low computational time, accuracy of the identification of closely spaced modes and suitability to be automated (due to its algebraic nature). The application of SSI-Cov method for the analysis of ambient vibrations on bridges is common in the literature (e.g. Gara, 2016; Dezi, 2016; Ubertini, 2013).

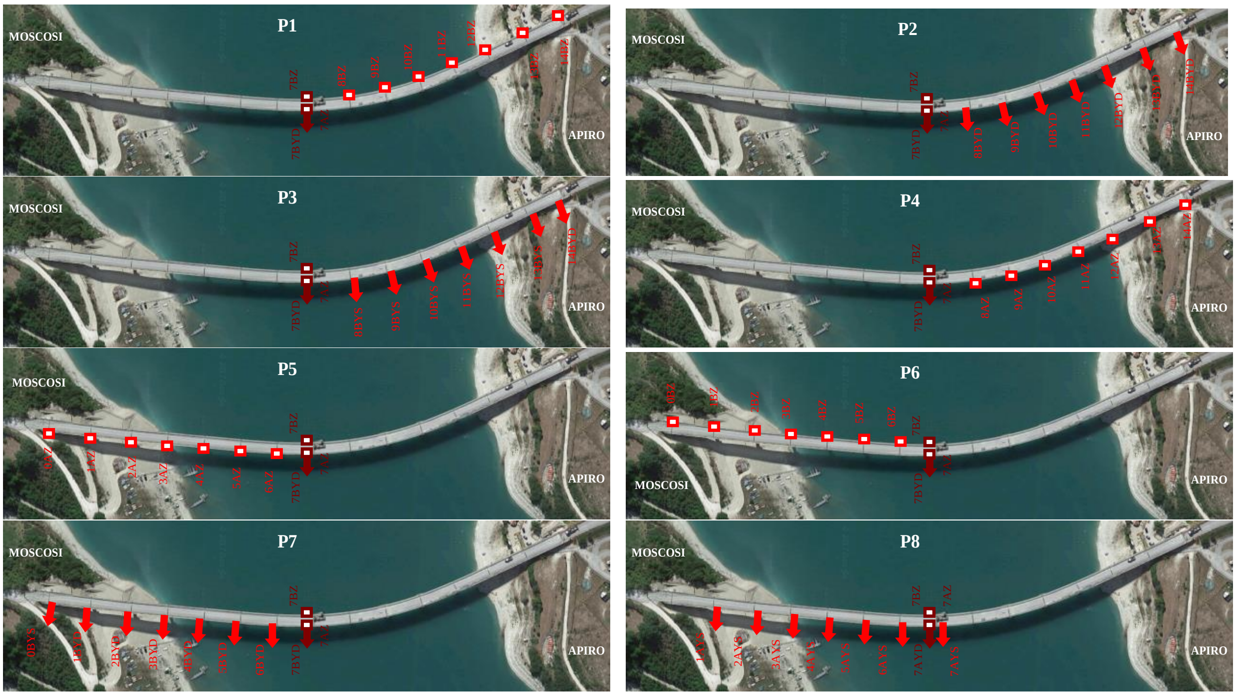

Fig. 3 Sensor configurations for the ambient vibration tests

In order to obtain the correct scaled modal shapes from the different configurations, a data merging procedure is needed. For the actual case, the PoSER technique (Post Separate Estimation Re-scaling) is adopted, which consists in the modal identification in each measurement configuration and the successive modal component scaling (Reynders, 2009). The method considers the matrices of the modal coordinates of every configuration (collected in vector ϕ) and minimizes the difference between the reference sensors through the coefficient α:

$$\alpha_i^{j\rightarrow k} = \frac{\left(\phi_i^{j,ref}\right)^H \left(\phi_i^{k,ref}\right)}{\left(\phi_i^{j,ref}\right)^H \left(\phi_i^{j,ref}\right)} \quad (1)$$

where k is the benchmark configuration, I is the vibrational mode and j is the number of the current configuration. Once α is determined for all the modes in each configuration, the normalized modal shapes are calculated:

$$\phi_i^k = \alpha_i^{j\rightarrow k} \cdot \phi_i^j \quad (2)$$

In this case, the reference sensors are located in the position 7 (dark-red marks in Fig. 3). The adopted PoSER procedure is schematically represented in Fig. 4.
Tab. I shows, for each mode identified, and for each test configuration, the frequencies obtained with the SSI-Cov method. The results have been summarized and combined through the PoSER technique to identify the global behavior of the bridge. Tab. II shows for each identified mode, the average frequency value, its standard deviation, the average damping ratio and its standard deviation.

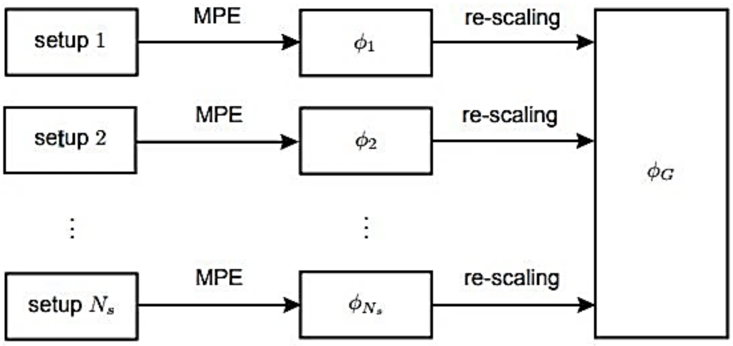

Fig. 4 The PoSER approach: merging partial mode shape estimates ϕ_k, k=1,...,N, into a global mode shape estimate ϕ_G. (MPE stands for Modal Parameter Estimation)

Mode	P1		P2		P3		P4		P5		P6		P7		P8	
	f [Hz]	ξ [%]	f [Hz]	ξ [%]	f [Hz]	ξ [%]	f [Hz]	ξ [%]	f [Hz]	ξ [%]	f [Hz]	ξ [%]	f [Hz]	ξ [%]	f [Hz]	ξ [%]
1°	0.96	4.53	0.93	4.08	0.97	3.99	0.98	3.62	0.91	1.94	0.91	1.64	0.91	1.76	0.92	4.08
2°	1.14	5.83	1.14	4.58	1.15	7.73	1.14	6.97	1.14	2.93	1.14	3.30	1.14	2.48	1.11	3.10
3°	1.35	5.22	1.35	0.38	1.36	1.61	1.35	0.84	1.34	0.72	1.42	12.69	1.34	0.92	1.35	1.37
4°	1.65	2.98	1.63	2.01	1.64	2.51	1.67	4.07	1.67	3.74	1.64	1.31	1.64	1.97	1.62	2.17
5°	1.96	1.18	1.97	1.33	1.97	1.62	1.97	3.42	1.98	1.48	1.93	3.79	1.97	1.04	1.98	1.74
6°	2.36	2.77	2.37	1.42	2.36	0.62	2.37	1.28	2.36	3.01	2.35	1.56	2.36	1.81	2.36	0.91

Tab. I Modal frequencies and equivalent viscous damping ratios from SSI-Cov

Modo	*f* [Hz]	*Δf* [%]	ξ [%]	Δ ξ [%]
1°	0.94	3.54	0.03	1.51
2°	1.13	6.81	0.02	6.85
3°	1.35	1.05	0.04	5.94
4°	1.64	2.33	0.02	1.19
5°	1.97	1.92	0.02	0.99
6°	2.37	1.79	0.01	0.86

Tab. II Modal parameters – PoSER

In Fig.5 the first 6 mode shapes identified are reported; the transverse components and the vertical components of the modal displacement are depicted in Fig. 5a and Fig. 5b, respectively; in Fig.5a the red circle denotes Pier 10 (where a damage has been observed).
Finally, the autoMAC values (Pastor, 2012) related to the identified modal shapes are reported in the classical matrix form of Fig. 6. It can be noticed that the identified modes are mainly decoupled, hence they represent the first 6 proper modes of the structure.

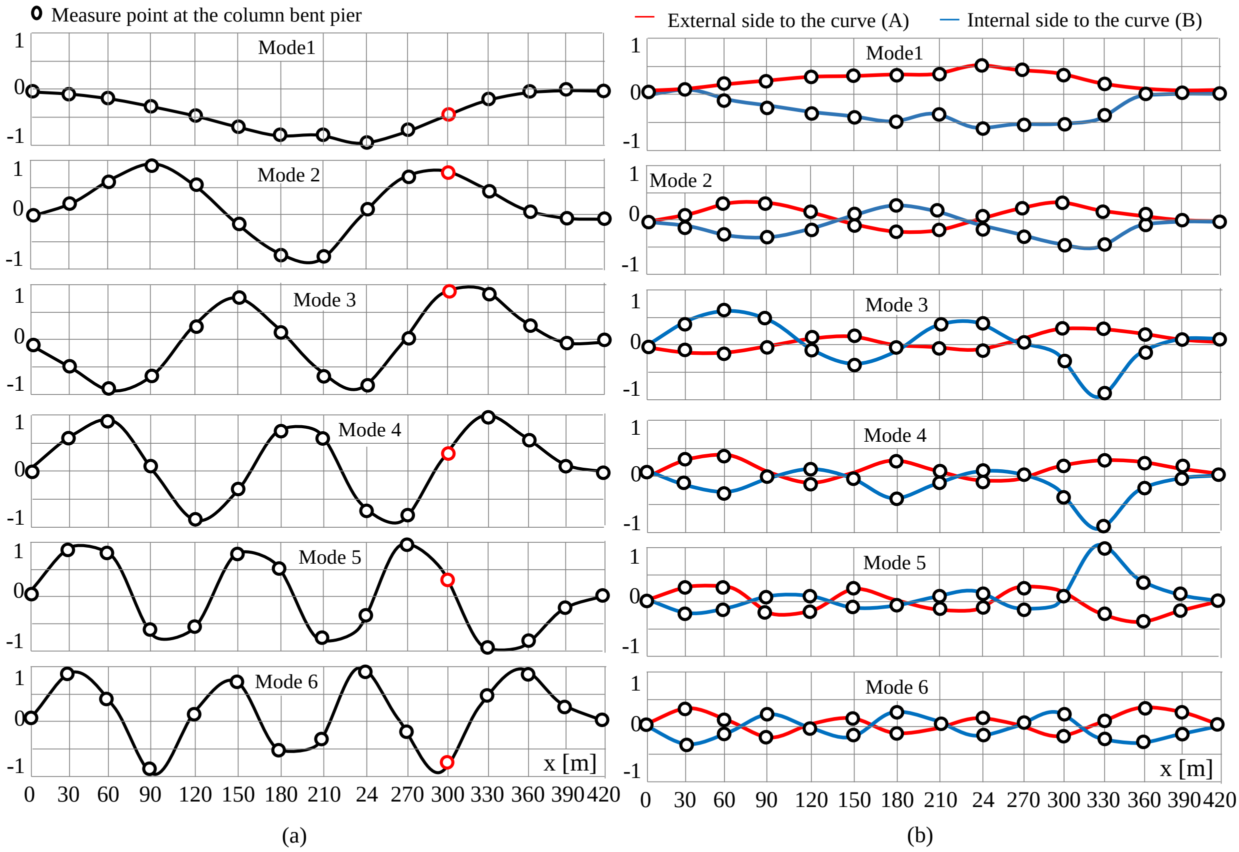

Fig. 5 (a) transverse and (b) vertical components of the first six mode shapes identified

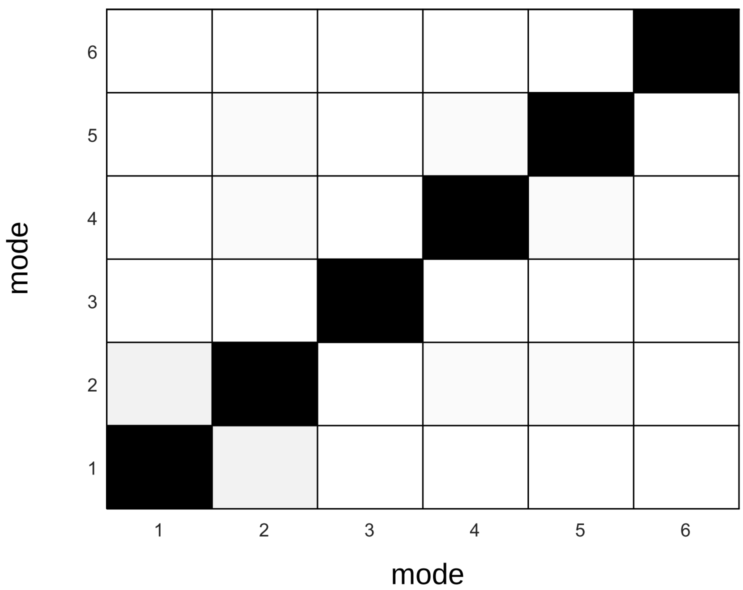

Fig. 6 AutoMAC matrix of the 10 identified vibrational modes

An integration of the experimental data from ambient vibration tests is provided by a second set of measurements derived from the use of a truck transiting on the deck in eccentric position, at low velocity. The position of the truck is chosen to induce bending moments in the piers and consequently displacements in the transverse direction of the deck. The test configurations used are the same of Fig. 3. The new input, characterised by a higher intensity than the ambient vibration one, is asked to highlight the presence of a visible damage at the base of Pier 10, detected during a survey of the structure before the retrofitting works. First results are herein presented, but further investigations are needed to judge the effectiveness of the performed tests to highlight the presence of the damage.
The Stockwell Transform (Stockwell, 1996) of the signal captured on the transverse direction by the configuration P2 is reported in the Fig. 7. It is worth noting a variation of the peak corresponding to the third vibrational frequency (1.35 Hz from the SSI-Cov procedure), and in particular the change to the lower value of about 1.20 Hz, at the truck transiting time above the cracked pile, which is attained at about t=40 s. This first analysis of the test results may confirm the presence of the observed damage at Pier 10.

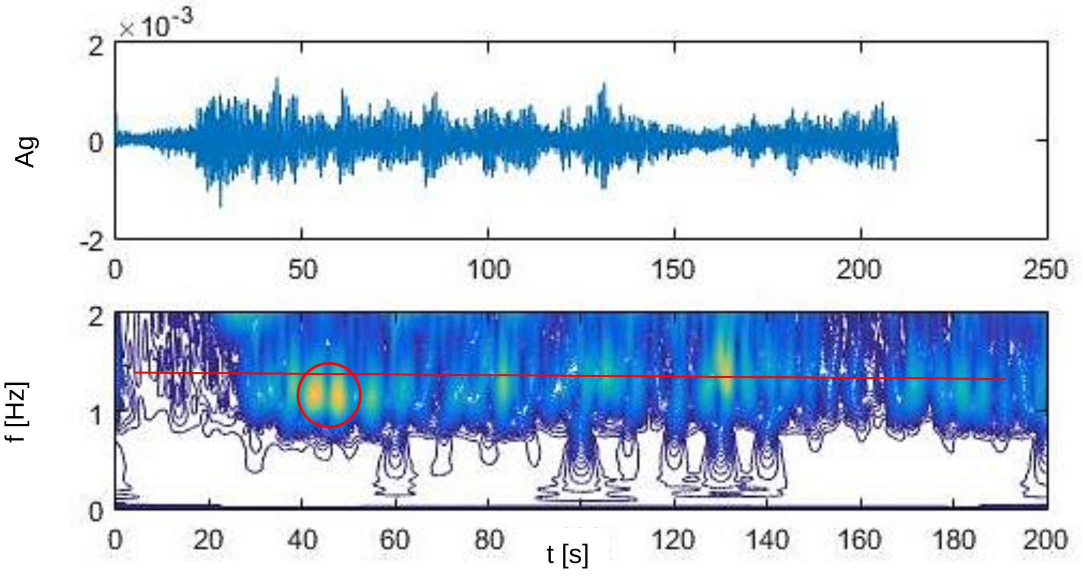

Fig. 7 Stockwell Transform from the P2 configuration signal. The red line represent the frequency of the proper third vibrational mode, while the red circle highlights the lower peak corresponding to the truck transit on the cracked pile

4. CONCLUSIONS

Ambient vibration tests carried out on the Moscosi Bridge have been reported and commented in this paper. Tests are oriented at determining the modal parameters of the bridge before the execution of some required restoration works, providing (*i*) useful information for the development of the numerical model for the design and (*ii*) a

benchmark for the evaluation of the retrofit effectiveness, in the framework of a structural health monitoring program. Fundamental periods, mode shapes and the relevant damping ratios are identified, processing results of different sensor configurations to capture both the flexural-torsional behavior and the transverse one of the bridge. The recorded data are processed with the Covariance-driven Stochastic Subspace Identification (SSI-Cov) technique in conjunction with the PoSER method to merge results of different configurations. In addition, the dynamic response of the bridge subjected to a vehicle passages is registered in an attempt to identify a visible damage at Pier 10, through the analysis of the bridge response subjected to actions with higher intensities with respect to the ambient vibration ones.
The autoMAC matrix reveals that the first 6 vibrational modes of the structure are properly identified. The Stockwell Transform of the signal provided by the accelerometer on the cracked pier reveals a reduction of the vibrational frequency, in agreement with the lowering of the local structural stiffness.

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