First Middle East Conference on Smart Monitoring,
Assessment and Rehabilitation of Civil Structures
8 – 10 February 2011, Dubai, UAE

SMAR 2011

Dynamic testing and structural identification of two R.C. arch bridges

K. Islami [1], C. Modena [2], F. Da Porto [3], F. Casarin [4] , M. Dalla Benetta [5]

[1] PHD Student, Dept. of Structural and Transportation Engineering (DSTE), University of Padua, Padua, Italy
[2] Full Professor, DSTE, University of Padua, Padua, Italy
[3] Assistant Professor, DSTE -University of Padua, Padua, Italy
[4] PhD, Research collaborator, DSTE, University of Padua, Padua, Italy
[5] PhD, Research collaborator, DSTE, University of Padua, Padua, Italy

ABSTRACT: To reduce the risk associated to seismic events it is necessary to preliminarily study in depth the causes of damages of infrastructures and in particular of bridges, as well as their seismic vulnerability. In the context of the project sponsored by the Regional road managing authority of Veneto Region of Italy (Veneto Strade), two concrete arch formed bridges were subject of experimental and analytical investigation to assess their mechanical and dynamic characteristics. Both are composed by a lower arc with or without vertical columns and a set of longitudinal girders bearing a thin slab. Due to their similarity, as a first step the bridges were subjected to the same investigation methodology (sensors and data gathering) with the aim of performing their Operational Modal Analysis (traffic and wind induced vibrations). Multiple non-simultaneously recorded measurement setups were applied. By using this identification method, the first principal natural frequencies were identified. Finite element models were updated and adjusted in order to tune the numerical natural frequencies and mode shapes to the experimental ones.

1 INTRODUCTION

In the field of dynamic testing of bridges, it is feasible to use very portable and user-friendly equipment to measure the structural response under dynamic loads and obtain very accurate estimates of the most relevant modal parameters. Dynamic tests are performed to validate the analytical model of a bridge, but some discrepancies arise between the experimental results, usually expressed in terms of natural frequencies and mode shapes. After extracting this information from the experimental data, they can be used to modify and update the model in order to improve it. Output-only identification technique, which is performed by just measuring the structural response under ambient excitation, is becoming the most commonly used procedure to get information from the structures without exciting them on purpose, action which may cause non negligible inconveniences. During the acquisition campaign the traffic was not interrupted, but on the contrary it was used to excite the structure – besides other sources of excitation as wind - in order to capture all the possible significant number of modal contributions in the response. Vibrations were measured with high sensitive piezoelectric accelerometers that can register in the range of 0-100 Hz. The data acquisition and storage of dynamic data requires the use of an analog-to-digital (A/D) converter in the measurement chain. At last using a large number of output-only modal identification techniques available in the literature, going from the Peak Picking (Bendat and Piersol, 1993) technique to the Frequency

Domain Decomposition (Brinker and Zhang, 2000) and Stochastic Subspace Identification methods (Peeters and De Roeck, 1999), data can be processed used for FE model updating.

This work is part of a project developed in collaboration with Veneto Strade S.p.A., the Regional road managing authority of Veneto, in the North of Italy. The aim of the research is to develop guidelines for engineers who will deal with bridge retrofitting in the region. As a first step two reinforced concrete arch bridges were subjected to ambient vibration testing and several others destructive and non-destructive tests as pullout, ultrasonic pulse wave, rebound hammer and core sampling techniques were executed to characterize the mechanical characteristics of materials on site and in the laboratory. Both arch bridges were constructed in the beginning of the twentieth century. One of them, the S. Giustina Bridge has inside the concrete structure, the frame of the old steel bridge of S. Giustina erected in 1888 (Fig.1) That is, the old steel bridge was incorporated inside the new bridge in a reinforcement intervention in 1960. The particularity of this bridge was taken into account in numerical modeling. From the different models developed has been demonstrated that the presence of the steel structure inside the concrete has no influence in the dynamic analysis due to the huge geometrical difference of the cross sections.

The analysis was completed by the development of 3D F.E. models based on the built drawings and the on-site material and geometrical survey. The material characteristics, used in the F.E. models were related to the numerous cores taken in different parts of the structure.

2 DESCRIPTION OF THE BRIDGES

The bridge of S. Giustina is a 68,0m single arch span, two-lane reinforced concrete valley overpass. The main characteristics and general layout are shown in Fig. 2.

The bridge is supported by two tapered arches (open spandrel arcs) linked together by several r.c. beams. The height of the section of the arch is 2,50m at the basis of the arch and 1,80m at the key position. Along the length of the arch there are 16 vertical concrete columns that connect the arches with the slab forming a rigid frame. All the columns are connected together with cross struts; the outer and higher columns are also transversally braced by X-shaped steel (Fig. 3). The deck of the bridge is 9,00m wide for two traffic lanes and two pedestrian walkways and consists of a cast in place r.c. slab supported by 6 longitudinal girders and 17 transversal beams. The bridge is fixed to the foundations at the basis of the arches and left free to move on the abutment's supports. Foundations at the beginning have been modeled as fixed in the Finite Element Model but as will be shown later some sensitivity analysis has been developed changing the rotational stiffness of the foundations.

The Roverè bridge is a 76,0m single arch span, two-lane reinforced concrete valley overpass. The main characteristics and general layout are shown in Fig. 4.

The bearing structure is realized by four r.c. tapered arches that do not support in a complete manner the deck (as in the case of usual arc structures), but provide support to the central part of the roadway, and a second part of deck is built with the traditional Gerber technique. The height of the section of the arch is 0,75m at the basis of the arch and 1,40m near the key position. Near the basis of the arches there are supporting walls rising up and connecting with the deck to hold the first span of the bridge deck and the second part obtained by a saddle in a cantilever area. As shown in Fig. 4, the first span of the deck is supported by the abutment and the intermediate elevation walls that also create a cantilever where the second part of the deck will lie down. The arches go up and form a seat for a small part of the deck and a second Gerber cantilever, so to create almost 7 expansion joints in total. The roadway has a difference in level of 6,0m from the entrance section and the exit one, namely a 7,9% slope.

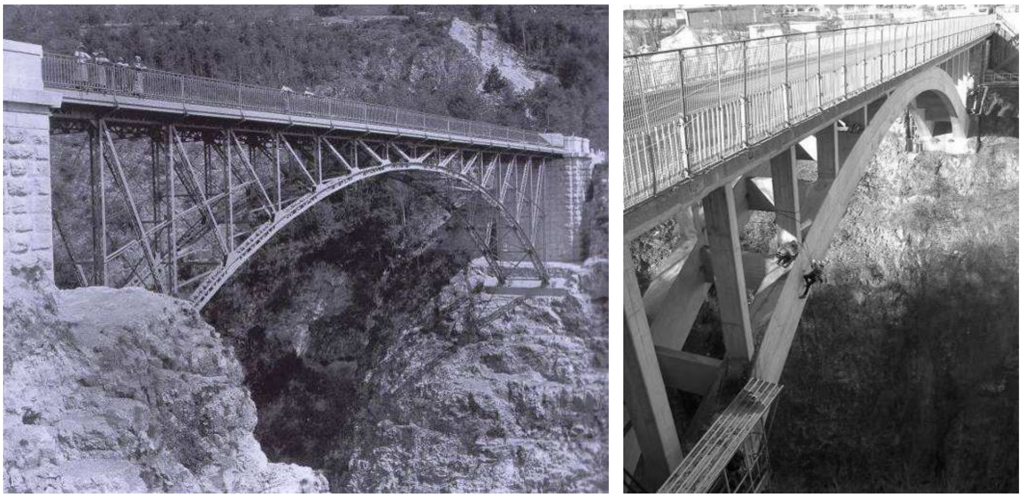


Figure 1. S.Giustina bridge: (a) original bridge - year 1888; (b) reinforced bridge-year 2010.

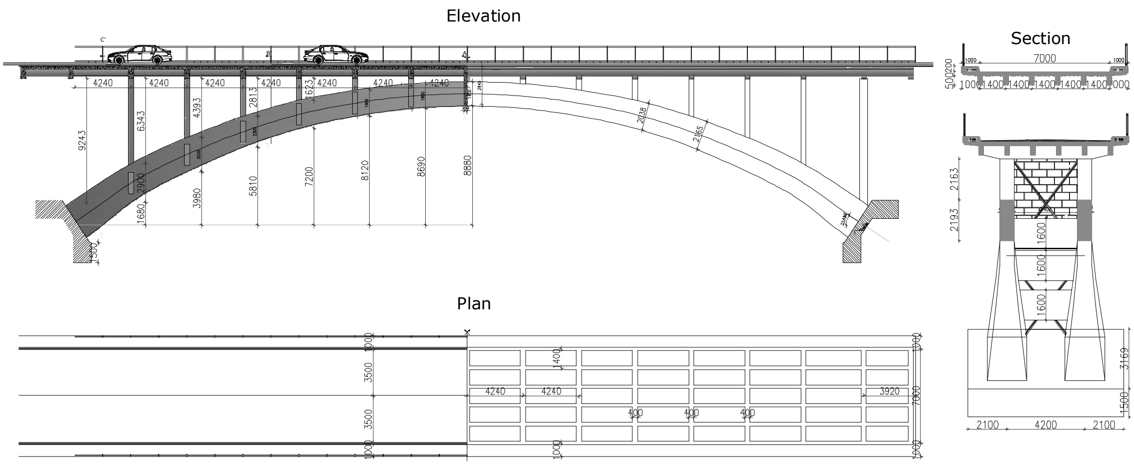


Figure 2. S.Giustina bridge: plan, elevation and cross-sections.

3 AMBIENT VIBRATION TESTING AND MODAL IDENTIFICATION

3.1 Equipment and Test Procedures

The dynamic ambient response is captured by one or more reference sensors at fixed positions and with a set of roving sensors at different measurement points along the structure and in different setups. The number of points used is conditioned by the spatial resolution needed to characterize appropriately the shape of the most relevant modes of vibration (according to preliminary-finite element modeling).

Figure 3. Roverè bridge: (a) view of the bridge; (b) test on the aches of the bridge.

The acquisition campaigns were carried out in November 2009 and in January 2010. During the 2 day tests for each bridge generally low temperatures were detected and for this reason increasing values in the natural frequencies because of the formation of ice inside the concrete and in the road pavement were expected.

Piezoelectric accelerometers with vertical axes were used to measure the bridge's response. Three accelerometers were placed as a reference in the middle of the bridges and eight other accelerometers were simultaneously moved to cover the entire area of the bridge (Figure 5). The sensors, which have a resolution of 6 μg m/s^2, were connected by coaxial cables to a computer equipped with the data acquisition board. The ambient accelerations time series were recorded for nearly 11 minutes with sampling frequency of 100 Hz.

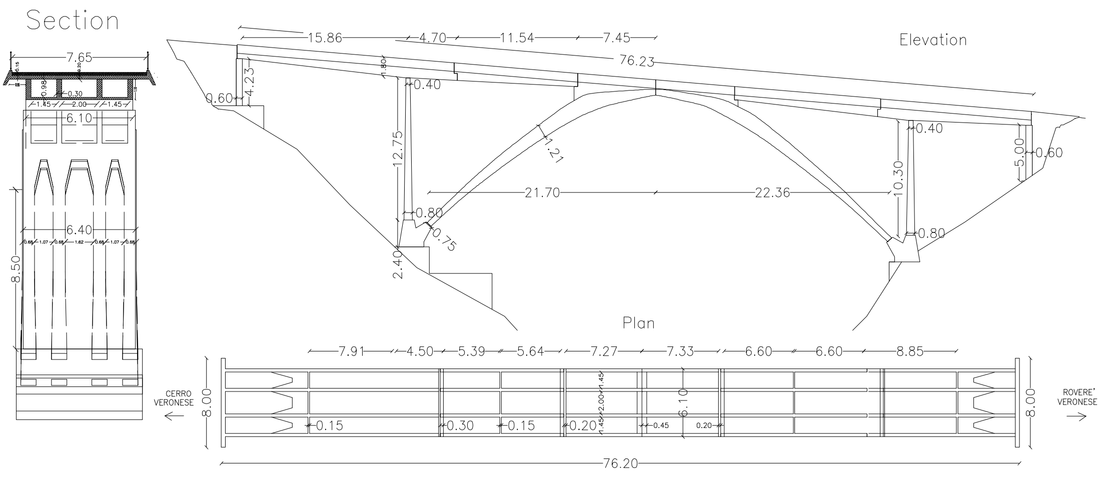


Figure 4. Roverè bridge: plan, elevation and cross-sections.

3.2 *Identification of modal parameters*

The extraction of modal parameters from ambient vibration data was carried out by using the Frequency Domain Decomposition (FDD) developed by Brincker et al. (2000).

In the FDD identification, the first step is to estimate the power spectral density matrix. Then the Singular value decomposition (SVD) of G (1) at each frequency is calculated:

$$\widehat{G}(j\omega_i) = U_i S_i U_i^H \quad (1)$$

where the matrix U is a complex matrix containing the singular vectors as columns and the superscript H denotes complex conjugate matrix transpose and the S_i is a diagonal matrix holding the scalar singular value s_{ij}. Near a peak corresponding to the *k*-th mode in the spectrum this mode will be dominating. Thus, the first singular vector is an estimate of the mode shape and the correspondent singular value is the auto power spectral density function of the corresponding single degree of freedom system.

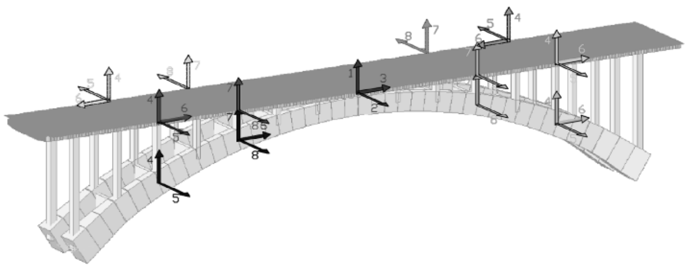


Figure 5.Sensor locations and directions for the S. Guistina bridge tests.

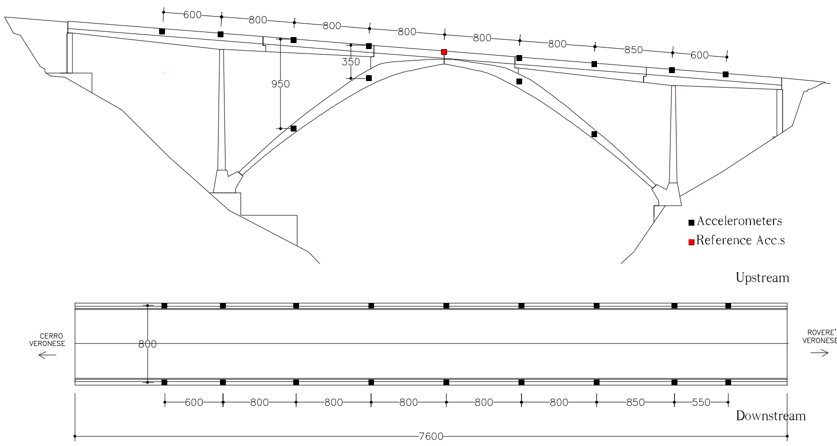
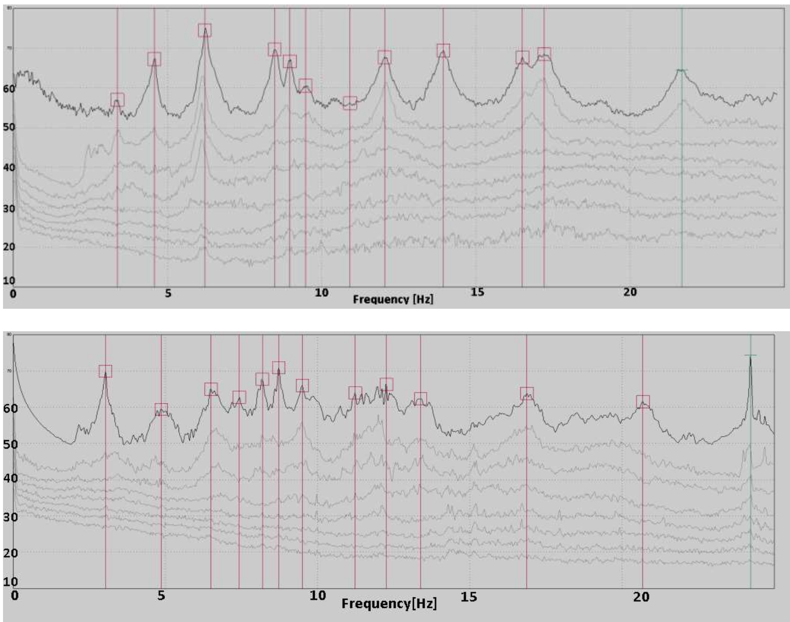


Figure 6. Sensor locations for the Roverè bridge tests.

4 MODAL IDENTIFICATION RESULTS

As expected the principal natural frequencies were identified between 0 and 15 Hz. In Fig.7 are shown the singular values and the mode identification. It can be seen that the two graphics present similar features and the first six modes are in both cases are included in the range 0-10 Hz.



(a)

(b)

Figure 7. Singular value and identification of natural frequency: (a) S. Giustina Bridge;(b) Roverè bridge.

Fig. 8 shows as first mode is a transversal mode, second mode is a vertical mode and third one is a torsional mode. As easily can be observed these modes have the same form in both bridges.

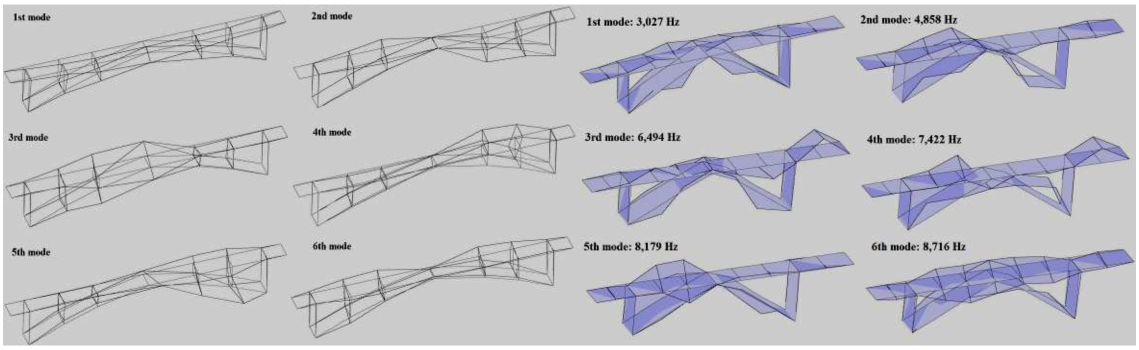


Figure 8. Experimental mode shapes: (a) S. Giustina Bridge;(b) Roverè bridge.

5 COMPARISON BETWEEN EXPERIMENTAL DATA AND F.E MODELS

The modal identification of bridges and other civil structures is required for validation of finite-element models used to predict static and dynamic structural behavior either at the design stage or in case of structural strengthening. The correlation of modal parameters can be analyzed both in terms of identified and calculated natural frequencies and by corresponding mode shapes using correlation coefficients or MAC (modal analysis criteria) values.

For the first bridge it has been created two different F.E models with two different software (Straus7, HSH computing, Padova and Midas, Cspfea, Este, Italy). The materials used in the model were determined by laboratory tests from core samples taken from the S.Giustina bridge. Elastic moduli of 25300 Mpa and 37100 Mpa were considered respectively for the vertical columns and the arches. Arches, columns, and girders have been modeled with *beam* elements, while the deck slab is modeled with 4-node *shell* elements. The arch footings and the outer columns footings were considered as fixed at the beginning.

The second bridge has been modeled using *beam* elements for arches and girders, *plate* elements for deck slab, *wall* elements (implemented in Midas/Gen) for the vertical walls. At the Gerber cantilever bearings have been modeled with elastic springs for transversal and longitudinal displacements and rigid links for vertical displacements. Regarding the materials, concrete for walls has a modulus of 34000 Mpa, arches 36500 Mpa and girders 37200 Mpa.

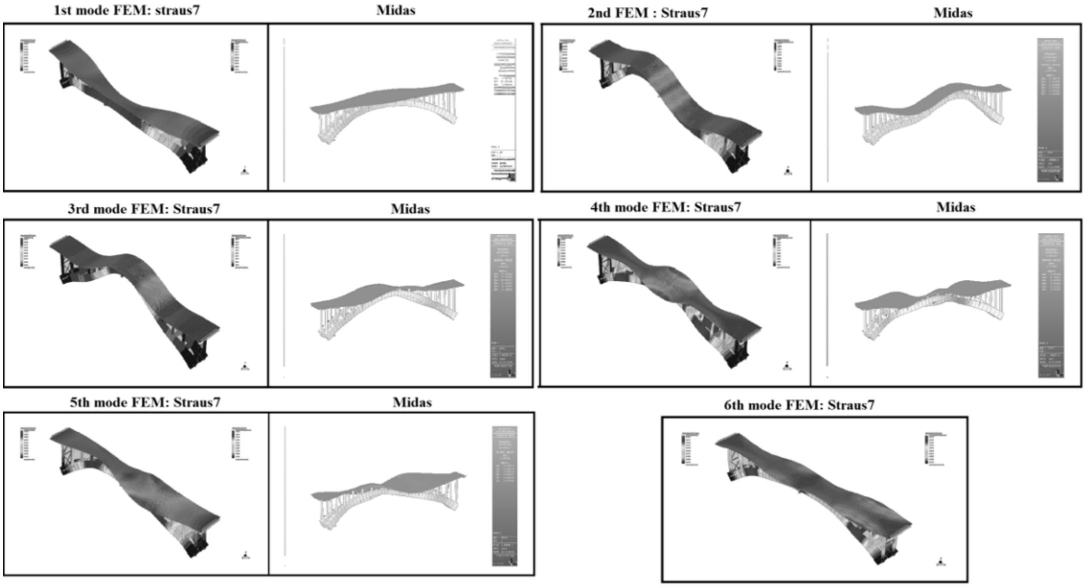


Figure 9. F.E.M. mode shapes of S.Giustina bridge.

Table 1. Correlation between numerical and experim. modal behavior of S.Giustina and Roverè bridge.

Mode	FDD f (Hz)	Model 1 (Straus7)			Model 2 (Midas/Gen)	
		f (Hz)	Δ (%)	MAC	*f* (Hz)	Δ (%)
1	3.369	3.402	1.039	0.967	3.312	-1.692
2	4.565	4.952	8.478	0.843	5.057	10.778
3	6.201	5.636	-9.111	0.645	6.068	-2.145
4	8.472	8.332	-1.653	-	8.852	4.485
5	8.96	9.187	2.533	-	-	-
6	10.91	10.520	-3.575	-	10.324	-5.371
7	12.04	12.540	4.153	0.610	-	-
8	13.94	13.630	-2.224	-	-	-
9	16.5	14.800	-10.303	0.287	-	-
10	17.21	17.050	-0.930	0.347	17.931	4.189
11	21.68	20.550	-5.212	0.521	-	-

Mode	FDD f (Hz)	Model (Midas/Gen)	
		f (Hz)	Δ (%)
1	3.027	3.007	0.665
2	4.858	4.683	3.737
3	6.494	-	-
4	7.422	7.320	1.393
5	8.179	8.025	1.919
6	8.716	-	-
7	9.497	9.384	1.204
8	11.23	-	-
9	12.26	-	-
10	13.38	13.333	0.353
11	16.87	-	-

A sensitivity study (Fig. 10) was performed on the S.Giustina Model Bridge, varying the stiffness of the elastic springs simulating the boundary conditions at arch basis and the Young's modulus of elasticity of reinforced concrete elements. It can be observed that natural frequencies doesn't vary consistently in the range of 25-95 kg/cm^3 and thus the decision of considering the constraint fixed at the arch basis is suitable for the F.E. analysis.

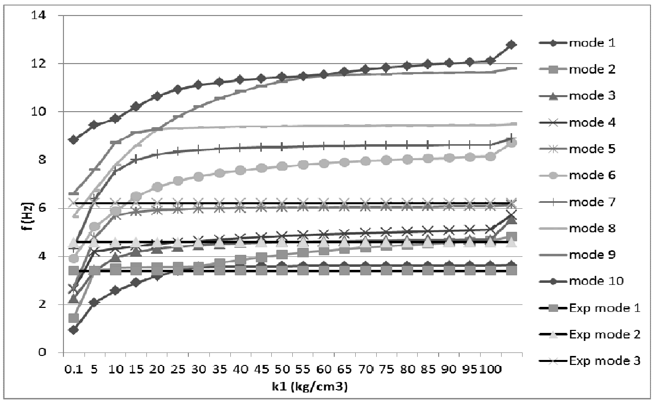


Figure. 10 Sensitivity analysis: spring stiffness at the foundation at the basis of the arch.

6 CONCLUSIONS

In this paper a structural identification procedure based on dynamic data is applied in two arch r.c. bridges. 3 vertical, 2 lateral and 3 torsional modes were successfully identified using the FDD method. From the analysis emerges that the choice of the correct structural parameters is very important for the accuracy of the modeling. A good match was found between F.E. models and experimental data shown by the low percentage of difference (Tab. 1), in terms of natural frequencies. Only for the first frequencies the relatively high MAC values indicate a good correlation in terms of mode shapes, in the case of the S. Giustina bridge. Finally, based on the parametric sensitivity analysis it was demonstrated that after a certain value of soil stiffness the structure reveals the same dynamic characteristics with close values to the choice of modeling as fixed the constraints at the arch basis. Models were then validated on the basis of experimental evidences, and then ready for assess the static and seismic response of structures.

7 ACKNOWLEDGEMENTS

The authors would like to express their gratitude to engineers Umberto Guglielmini and Davide Ferrarese for their valid contribution in the execution of the activities related to the experimental campaign and numerical simulations.

8 REFERENCES

Cunha, A, Caetano, E, 2005 Experimental Modal Analysis of Civil Engineering Structures, FEUP

Cunha, A, Caetano, E, and Magalhã F, 2003, Output-only dynamic testing of bridges and special structures, Proceedings of the institute of Civil Engineering,135-148

Brincker, R, Zhang, L, and Andersen, P, 2001, Modal identification of output-only systems using FDD

Morassi, A, Tonon, S, 2008, Dynamic Testing for Structural Identification of a Bridge, Journal of Bridge Engineering, ASCE, 573-585

Gentile, C, Bernardini, G, 2008, Output-only modal identification of a reinforced concrete bridge from radar-based measurements, NDT&E international, Elsevier

Gentile, C, 2006, Modal and structural identification of a R.C. arch bridge, Structural Engineering and Mechanics, Vol 22,No.1 53-70

Aktan, A, Catbas, N, Tuner, A, Zhang, Z, 1998, Structural identification: analytical aspects, J. Struct. Eng. 124(7) 817-829

Allemang, R.J and Brown, D.L, 1983, Correlation coefficient for modal vector analysis, Proc. 1st Int. Modal Analysis Conf. (IMAC)