# Efficient operational modal testing and analysis for design verification and restoration baseline assessment: Italian case studies

B. Peeters
*LMS International, Leuven, Belgium*

G. Sforza, L. Sbaraglia
*Essebi, Roma, Italy*

F. Germano
*LMS Italiana, Novara, Italy*

ABSTRACT: In this paper some very recent civil engineering experimental vibration assessment projects in Italy are discussed. The objective in a first category of projects is to verify the design of new structures such as bridges and viaducts. During the design of these dynamically loaded structures, the modal parameters have been computed using Finite Element Models. After completing the construction, the structural vibrations under ambient wind and traffic excitation are measured and Operational Modal Analysis is applied to identify the modal parameters from the measurements allowing making comparisons with the calculation models. In a second category of projects, dynamic testing and Operational Modal Analysis is part of the "baseline assessment" of historical structures that will be restored in near future. Also here, comparisons with calculation models are possible and the repetition of the measurements after restoration allows assessing the effectiveness of the restoration.

## 1 INTRODUCTION

This paper highlights the benefits of performing a dynamic test on structures. With a very limited effort and by using the available ambient vibrations combined with powerful data-processing techniques, an entire dynamic characterization of structures is possible. In Cunha et al. (2003), it is demonstrated that the experimental assessment of the dynamics of bridges play a very relevant role during the phases of conception and design, construction, reception, rehabilitation and monitoring (temporary and long-term). In the present paper, two case studies will be presented in which the design of new bridges is verified by means of ambient vibration testing and Operational Modal Analysis (OMA): the *Vacale Viaduct* in Reggio Calabria (Section 4.1) and the *Ponte della Musica* in Rome (Section 4.2).

There is also an increased interest in performing experimental modal analysis on historical structures, especially in seismic regions with a rich cultural heritage such as large parts of Italy. The experimental determination of the modal parameters of these structures is useful in a Structural Health Monitoring context and also allows verifying the structural performance under dynamic loads such as earthquakes. The assessment procedure typically includes a full-scale ambient vibration test, modal identification from ambient vibration responses (i.e. OMA), constructing Finite-Element Models (FEM) and updating of the uncertain FEM parameters based on the experimental results (Gentile and Saisi 2007). Some more examples of OMA applied to historical monuments can be found in Gentile and Gallino (2008) and Ramos et al. (2010). In the present paper, two case studies will be presented in which OMA was used to establish a baseline model before the restoration of historical structures that suffered from damage caused by the April 2009 earthquake in L'Aquila: the *Dome of the Basilica di San Bernardino* (Section 5.1) and the *Tower of the Palazzo Margherita* (Section 5.2).

Essebi S.r.l., established in 1992, is a company involved in experimental diagnosis and monitoring of civil structures and architectural monuments. Since the beginning it operates in Italy and more specifically in the Rome basin, in which many ancient and famous monuments are located. After the very destructive earthquake of L'Aquila, quite some activities took place in that zone with the aim to evaluate the dynamic response of damaged structures.

## 2 MEASUREMENT SYSTEM

Seismic ICP accelerometers are very well suited for Operational Modal Analysis of large and complex civil engineering structures. Relevant sensor characteristics for these applications are the capability to measure very low-frequency components, the high sensitivity and the low broadband noise level. Due to the necessity to employ a large number of transducer during a measurement session, also the low cost is a very important characteristic. Compared to Force-Balance sensors, seismic ICP sensors have almost the same characteristics at competitive costs. Essebi usually uses the PCB 393A03 and the PCB 393B12 models. They are identical in shape (and have the same weight) and have roughly the same technical characteristics.

For all applications, a multi-run setup is implemented to optimize the number of transducers. The idea is that much more locations on the structure can be measured than the number of available sensors, by measuring in multiple runs and keeping 1 or more reference sensors in common to each run. A 24-bit high dynamic range data acquisition system such as the LMS Scadas Mobile is particularly suited for ambient vibration measurements in which the vibration levels cannot be controlled and often high vibration levels are alternated with very low levels. To increase the efficiency, it also possible to use multiple data acquisition systems, synchronized by GPS, at different locations along the structure. This would minimize the (analog) cable lengths between the sensors and the acquisition systems, combining the advantages of lower noise and a more efficient installation procedure. The measurement chain is represented in Figure 1 and some in-field illustrations are given in Figure 2.


Figure 1 : PCB sensor, LMS Scadas Mobile data acquisition system and a Windows mobile PDA.

Figure 2 : (Left) LMS Scadas recorder at the Vacale Viaduct (Section 4.1); (Right) Sensor setup inside the dome of the Basilica of San Bernardino (Section 5.1).

## 3 OPERATIONAL MODAL ANALYSIS

The estimation of eigenfrequencies, damping ratios and mode shapes from output-only vibration measurements is referred to as “Operational Modal Analysis” (OMA). Typical for the output-only case is that the lack of knowledge of the input is justified by the assumption that the input does not contain any information; or in other words, the input is white noise. The theoretical assumption of white noise turns out to be not too strict in practical applications. As long as the (unknown) input spectrum is quite flat, OMA methods will work fine. An overview and comparison of operational modal parameter estimation methods can be found in Hermans and Van der Auweraer (1999) and Peeters and De Roeck (2001). In this paper, the PolyMAX method will be used. It is a particular algorithm which is very successful in classical modal analysis (Peeters et al. 2004) and which was extended to OMA (Peeters et al. 2007). More details on the algorithm and on the optimal pre-processing of the raw measurement data can be found in the above-cited references.

## 4 CASE STUDIES: DESIGN VERIFICATION OF NEW STRUCTURES

### 4.1 *Vacale Viaduct (Reggio Calabria)*

The Vacale Viaduct in Reggio Calabria is curved and has a width of 11 m and a total length of 615 m, divided in 9 spans (Figure 3 – Left). The first and last span measure 51.5 m and 59.5 m; the 7 middle spans have a length of 72 m. are all equal other with a length of 7 to 72 m. The bridge deck consists of 2 continuous steel beams.

The viaduct vibration response under ambient excitation was measured and Operational Modal Analysis was applied. The purpose was to experimentally measure the eigenfrequencies and mode shapes for validating the numerical models that were created during the design. The sensor locations are indicated in Figure 4. The bridge was measured in 4 runs and 2 reference sensors were in common to each run. Figure 3 (Right) shows the power spectra of the same reference sensor during the 4 runs. During the first and the last run, the ambient excitation level was apparently significantly higher. In Figure 5, the pre-processing for OMA is illustrated: from the raw time histories, the correlations are computed; an exponential window is applied and the spectra are obtained by a single DFT of the windowed correlations. PolyMAX was applied to the pre-processed data and in Figure 6 the stabilization diagram is shown as well as the comparison between a measured spectrum and the synthesized one. Figure 7 shows some typical mode shapes: one is a horizontal and the other a vertical bending mode.

Because of the excessive length of the bridge, it was not time- and cost-efficient to have a high density of measurement points. Nevertheless, the results are very encouraging and very close to those predicted at the design stage.

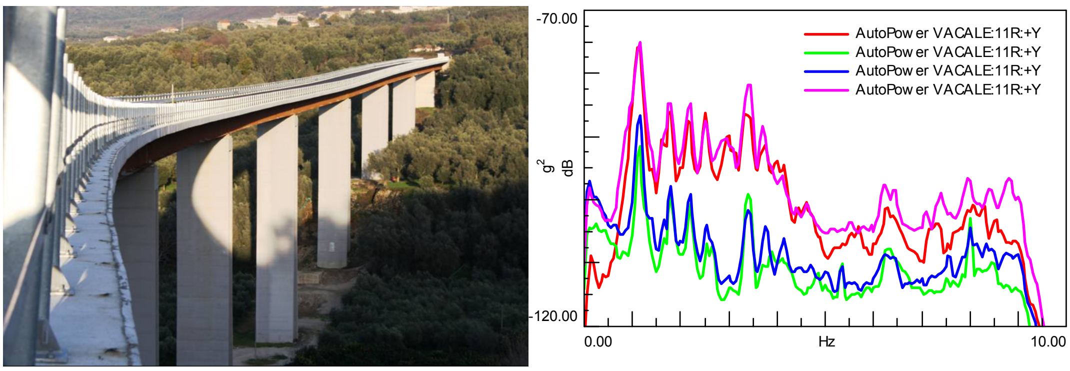


Figure 3 : (Left) Vacale Viaduct in Reggio Calabria; (Right) Power spectra of a reference sensor during 4 different runs.

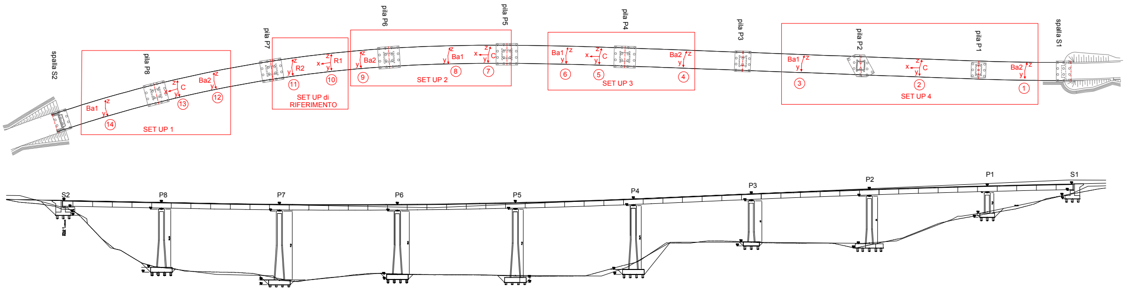

Figure 4 : Sensor locations at the Vacale Viaduct.

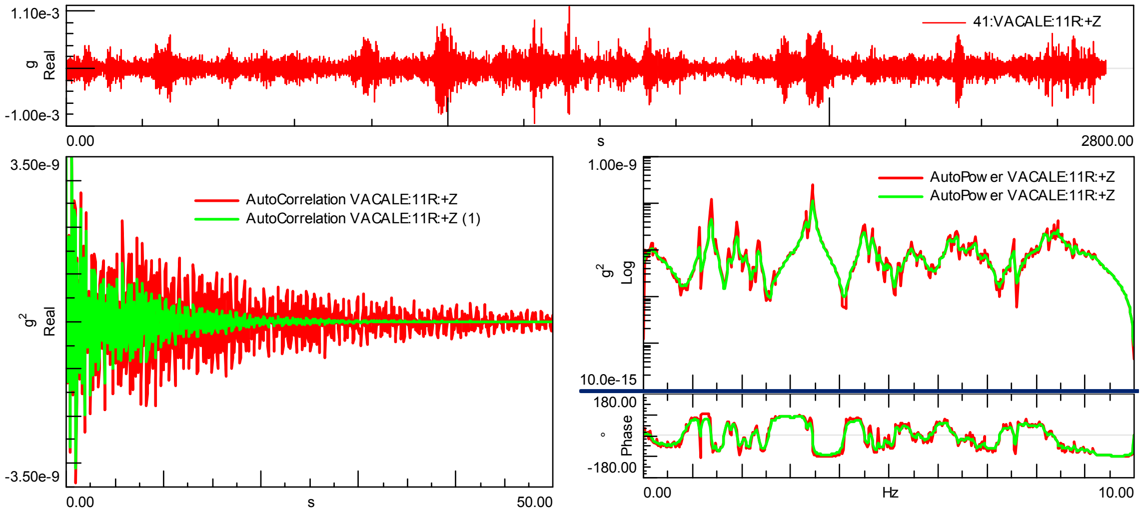


Figure 5 : Illustration of the data pre-processing for OMA. (Top) acceleration time series; (Left) auto-correlation with and w/o exponential window; (Right) Power spectra with and w/o exponential window.

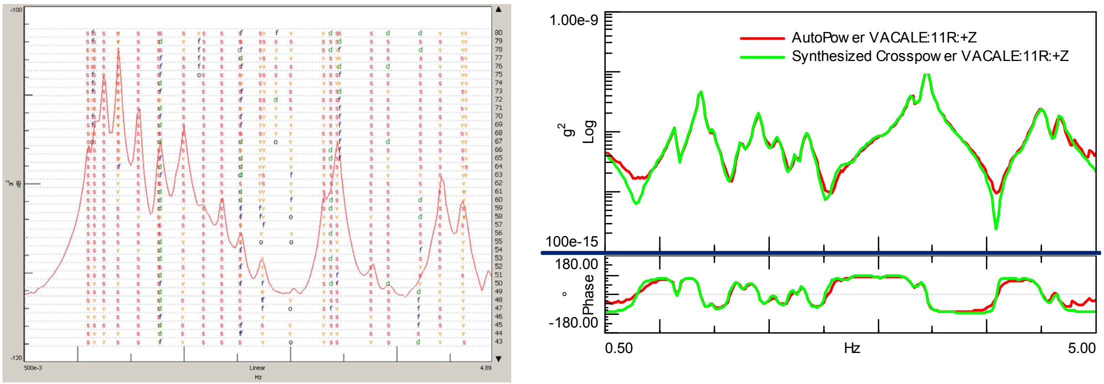


Figure 6 : (Left) PolyMAX stabilization diagram; (Right) comparison between measured and synthesized spectrum.

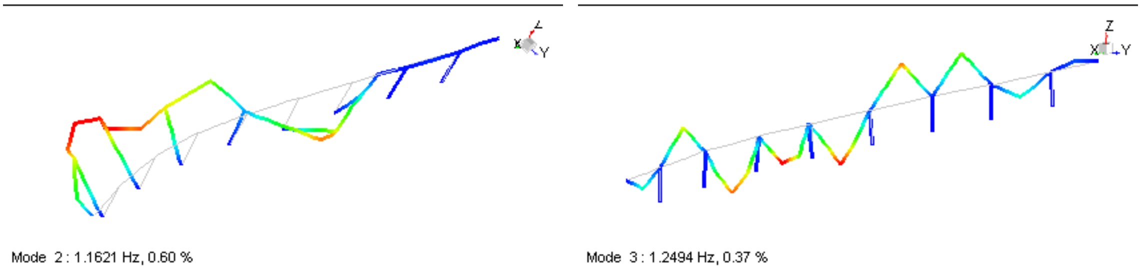


Figure 7 : Mode shapes of the Vacale Viaduct: (Left) horizontal bending; (Right) vertical bending.

### 4.2 *Ponte della Musica (Rome)*

The Ponte della Musica (Bridge of Music) crossing the river Tiber in Rome is an engineering and architectural work of contemporary design, made of steel, concrete and wood (Figure 8 – Left). It connects the Lungotevere Flaminio with the Lungotevere Cadorna, linking the axis of the Auditorium by Renzo Piano and the Maxxi Museum by Zaha Hadid with the Foro Italico sports complex. Originally designed for pedestrian traffic, the bridge has been gradually changed and now also includes the passage of bicycles and public transport. The structure consists of a metal deck supported by two low arches resting on steel reinforced concrete piers that contain the stairs leading to the two banks of the river. The central part of the bridge is paved while the sidewalks are made of wooden slats that rest on the steel structure. It is 190 m long, 22 m wide in the middle and 14 m at the end.

Operational Modal Analysis was conducted as part of the dynamic testing of the structure. The objective of the test is to experimentally determine the modal parameters and to compare them with those coming from calculation models. PolyMAX was applied to the ambient vibration measurements. Figure 8 (Right) compares the measured spectra with the synthesized ones. The high-quality data fit indicates that the identified modal parameters represent the measurements very well. Figure 9 shows some typical mode shapes. Though at 1 side of the bridge, less measurement locations were selected, the mode shape could still be characterized.

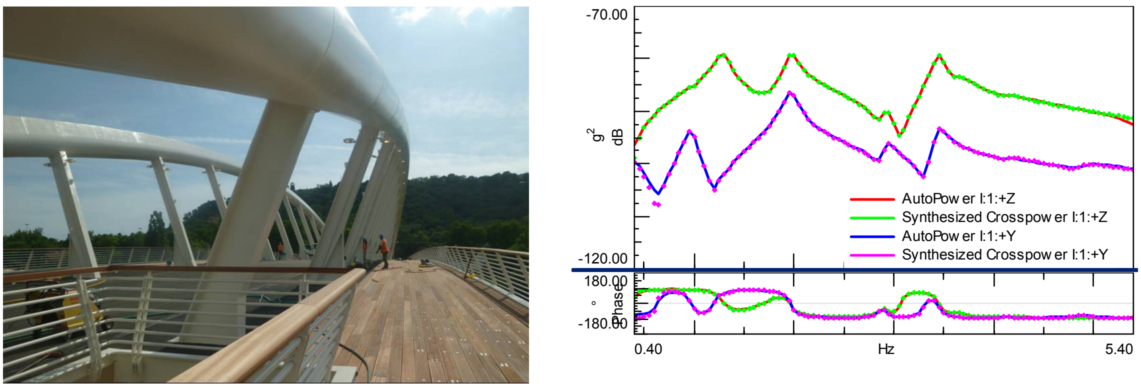


Figure 8 : (Left) Ponte della Musica during dynamic testing; (Right) measured and synthesized spectra.

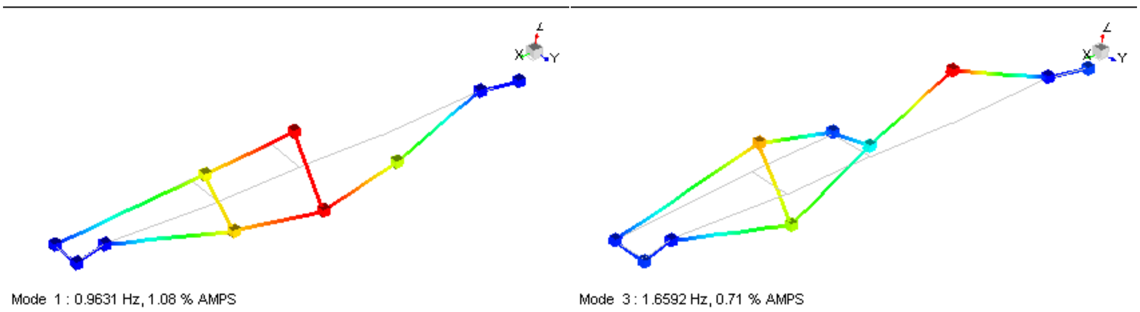


Figure 9 : Measured mode shapes.

## 5 CASE STUDIES: BASELINE ASSESSMENT BEFORE RESTORATION

### 5.1 *Dome of the Basilica di San Bernardino (L'Aquila)*

The Basilica di San Bernardino, one of the monuments of the city of L'Aquila, built between the 15th and 16th century with the citizens' money and therefore still owned by the town, suffered from severe damage following the earthquake of April 6, 2009. In particular, the basic octagonal dome was severely damaged by the impact of the adjacent bell tower that collapsed during the earthquake (Figure 10 – Left). After the initial emergency repairs, a first measurement campaign for Operational Modal Analysis was performed in order to evaluate the characteristic frequencies and detect possible discontinuity of the walls. Restoration works using modern materials such as reinforced plastics are currently in progress. At the end of these interventions, new dynamic measurements will be performed so that the modal parameters of the dome before and after the restoration can be compared. This will allow for an objective evaluation of the effectiveness of the intervention.

The entire dome was measured using 4 different runs. It was possible to combine the mode shape components from the different runs by means of 2 reference sensors that were measured during all runs. Figure 10 (Right) shows the power spectra of the reference sensor that was finally used in the analysis. Because the ambient excitation is not the same during the 4 runs, these spectra are not identical. It is however clear that more or less the same peaks are visible, indicating that the dome dynamics will be correctly identified from the 4 runs. Figure 11 shows some typical mode shapes of the dome, confirming the high-quality results that can be obtained from OMA.

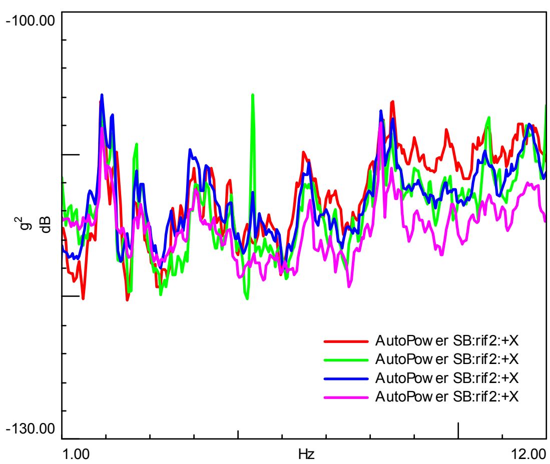


Figure 10 : (Left) Damaged dome; (Right) Power spectra of reference sensor during 4 different runs.

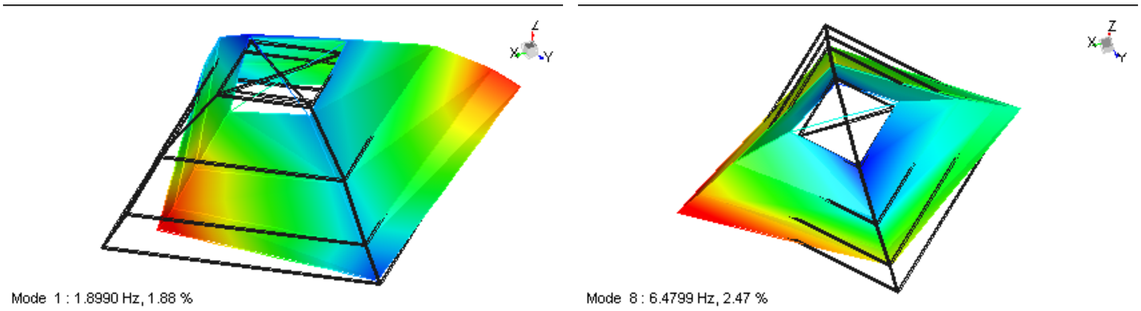


Figure 11 : Typical mode shapes of the dome.

## 5.2 *Tower of the Palazzo Margherita (L'Aquila)*

The tower of the Palazzo Margherita at the Piazza Palazzo, formerly Piazza Sallustio, located at the historical site of the Municipality of L'Aquila, was seriously damaged by the earthquake of April 2009. The aim of this survey was to experimentally determine the dynamic properties of the structure in terms of natural frequencies, damping ratios and mode shapes. The tower, made entirely of brick from local stone, has a square cross section with 5 m internal distance between the walls. The tower shares with the municipal building the wall facing North-East, from street level to the level of the eaves of the building. The total height of the tower is approximately 41 m measured from street level to the top, even though internally, the lower tower level starts at 9.8 m above the ground. Below this level the tower blends with the municipal building. Internally the structure consists of a series of ramps, covered by a wooden staircase, that run straight along the four interior walls.

The tower was measured in 15 locations and at each location the accelerations were recorded in both horizontal directions. Two reference sensors were installed close to the top of the tower. Another 6 sensors were changing location in each run. A total of 5 runs sufficed to measure the tower at the pre-defined locations (Figure 12). Since the tower is quite symmetric, it is not unexpected that the first bending modes have very close frequencies and bend along perpendicular axes. Both modes could be very nicely separated although they are only 0.02 Hz apart (Figure 13).

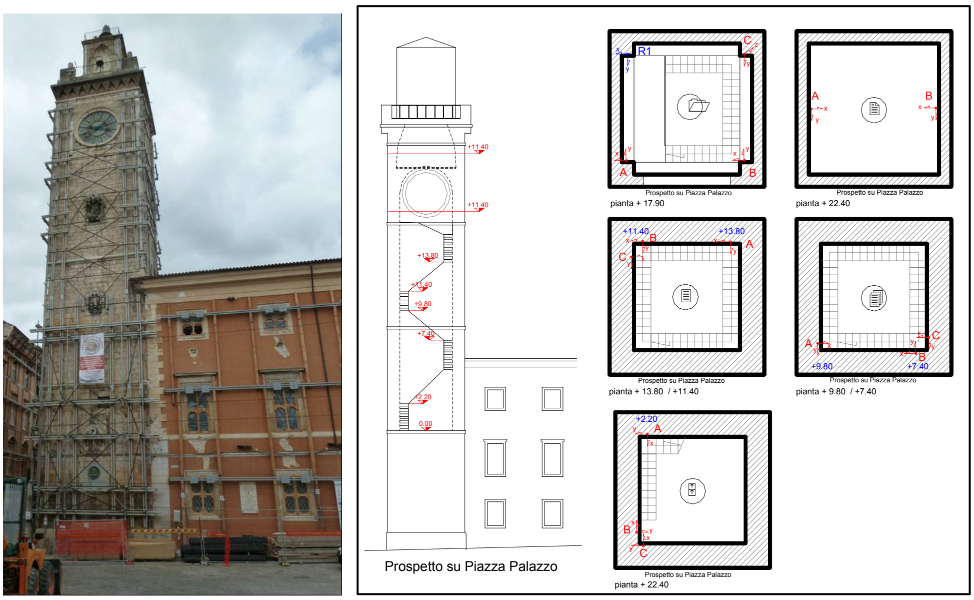


Figure 12 : Tower of the Palazzo Margherita with indication of the accelerometer locations.

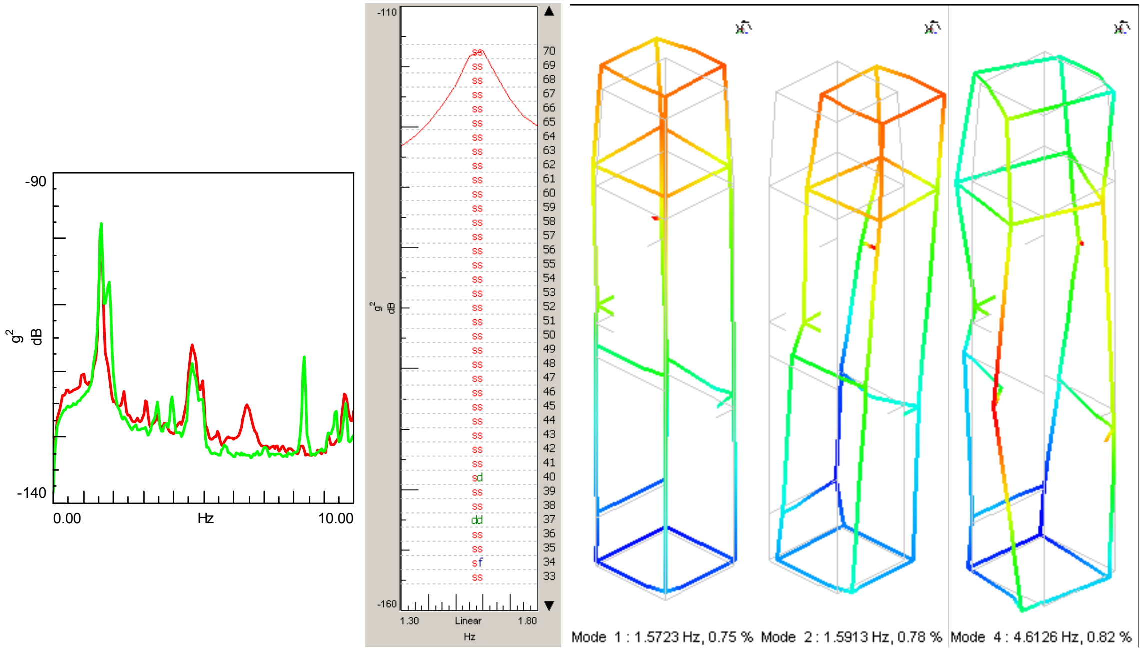


Figure 13 : (Left) Power spectra at reference sensors; (Middle) zoom of stabilization diagram highlighting a pair of closely spaced modes; (Right) mode shapes: 2 bending modes and 1 torsion mode.

## 6 CONCLUSIONS

This paper discussed some very recent and very successful civil engineering experimental vibration assessment projects in Italy, both for design verification of new structures such as bridges and viaducts as well as for the "baseline assessment" of historical structures that will be restored in near future. Ambient vibration testing and Operational Modal Analysis are very time-efficient means to determine the dynamic characteristics of these structures.

## REFERENCES


Cunha, A., Caetano, E., Calçada, R., De Roeck, G., and Peeters, B. 2003. Dynamic measurements on bridges - design, rehabilitation and monitoring. *Bridge Engineering*, **BE156**(3):135-148.

Gentile, C. and Saisi, A. 2007. Ambient vibration testing of historic masonry towers for structural identification and damage assessment. *Construction and Building Materials*, **21**:1311-1321.

Gentile, C. and Gallino, N. 2008. Ambient vibration testing and structural evaluation of an historic suspension footbridge. *Advances in Engineering Software*, **39**:356-366.

Ramos, L.F., Marques, L., Lourenço, P.B., De Roeck, G., Campos-Costa, A., and Roque, J. 2010. Monitoring historical masonry structures with operational modal analysis: Two case studies. *Mechanical Systems and Signal Processing*, **24**(5):1291-1305.

Hermans, L., and Van der Auweraer, H. 1999. Modal testing and analysis of structures under operational conditions: industrial applications. *Mechanical Systems and Signal Processing*, **13**(2):193-216.

Peeters, B., and De Roeck, G. 2001. Stochastic system identification for operational modal analysis: a review. *ASME Journal of Dynamic Systems, Measurement, and Control*, **123**(4):659-667.

Peeters, B., Van der Auweraer, H., Guillaume, P. and Leuridan, J. 2004. The PolyMAX frequency-domain method: a new standard for modal parameter estimation? *Shock and Vibration*, **11**:395-409.

Peeters, B., Van der Auweraer, H., Vanhollebeke, F., and Guillaume, P. 2007. Operational modal analysis for estimating the dynamic properties of a stadium structure during a football game. *Shock and Vibration*, **14**(4):283-303.