MODAL ANALYSIS OF THE TOWER OF THE NATIONS IN NAPLES

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ABSTRACT :
Seismic risk reduction is a fundamental task in earthquake prone regions. It affects also historical structures, which are characterized by a high degree of uncertainty due to their unique structural schemes and to uncertainties about geometry and materials which make accurate structural analyses and assessment of the effective behaviour of the structure in its operational conditions difficult. In the last thirty years several techniques aimed at the experimental evaluation of the dynamic characteristics of structures have been developed. As historical structures are concerned, output-only modal parameter identification techniques are certainly of interest and can prevent damages to constructions and artefacts, because they are fast and cheap and imply a minimum interference with the normal use of the structure. Identified modal parameters, representative of the structural behaviour under operational conditions, can be used to validate or update finite element models. Thus, combination between numerical models and experimental measures offers interesting opportunities in the fields of vibration and seismic protection of strategic or historical constructions. In this paper the main results of dynamic tests carried out in order to identify modal properties of an important historical structure such as the Tower of the Nations, located into the Mostra D'Oltremare in Naples, are reported, pointing out the adopted data processing procedures. Test results are then compared with those ones obtained by numerical analyses.

KEYWORDS:
Heritage structures, Operational Modal Analysis, Automated modal parameter identification

1. INTRODUCTION

Seismic hazard affecting large European areas, especially those located in the South-Eastern regions, requires an increasing knowledge of the dynamic behaviour of structures, particularly in the case of existing buildings and/or historical structures. Uncertainties about geometry and materials make difficult accurate structural analyses and assessment of the effective behaviour of the structure under operational conditions. Therefore, the knowledge of the modal properties of historical structures can be very relevant, in particular for the evaluation of the structural performances in presence of extreme load conditions such as earthquakes. In the last thirty years a number of techniques aimed at the experimental evaluation of the dynamic characteristics of structures have been developed. Beside traditional techniques based on the knowledge of the input source, in recent years increased attention has been paid to techniques for modal parameters identification based on ambient vibrations. As historical structures are concerned, output-only techniques are preferred, because of cheaper and faster test execution and minimum interference with the use and preservation of the structure (Gentile, 2005). The present paper describes the use of Operational Modal Analysis for the evaluation of the modal parameters of an important historical structure such as the Tower of the Nations (Naples). In particular, it is aimed at the discussion of the methods and of the results of an experimental assessment of the dynamic properties of the tower based on environmental vibrations according to a well-established procedure of output-only modal identification, such as the Frequency Domain Decomposition (Brincker et al., 2000), and to a new procedure for automated extraction of modal properties (Rainieri et al., 2008a). Test results are finally compared with numerical evaluation of modal parameters, in order to understand how much the model fit the actual behaviour of the structure under operational conditions.

2. THE TOWER OF THE NATIONS: PRELIMINARY INVESTIGATIONS

The Tower of the Nations is a very representative building located within the area of the Mostra D'Oltremare in Naples. It is a reinforced concrete building characterized by two opposed blind and two completely see-through façades and by a unique scheme according to which, apart from the first, second, and third floor, the remaining part of the building was built so that the user can look from one floor to another (Figure 1). The need to design an appropriate restoration and seismic upgrading intervention, taking into account the intrinsic characteristics of the structure itself, and therefore the need of improved knowledge of the structural characteristics of the building suggested to perform a number of accurate investigations, including dynamic identification tests. Assessment of the building structure has been undertaken evaluating a number of sources of information, in compliance with relevant National (Direttiva P.C.M. 12/10/2007, 2008) and International (EuroCode 8, 2004) Codes concerning seismic evaluation of existing constructions. It has been divided into the following three different phases:

- Geometric investigation, to completely define the geometric characteristics of the structure in terms of structural and non-structural elements;
- Structural investigation, aiming at the definition of the structural scheme and of the steel reinforcement in the structural elements;
- Investigation about materials, aiming at the evaluation of the mechanical characteristics of concrete and steel;
- Evaluation of the structural response in the case of dead loads and under earthquake loading.

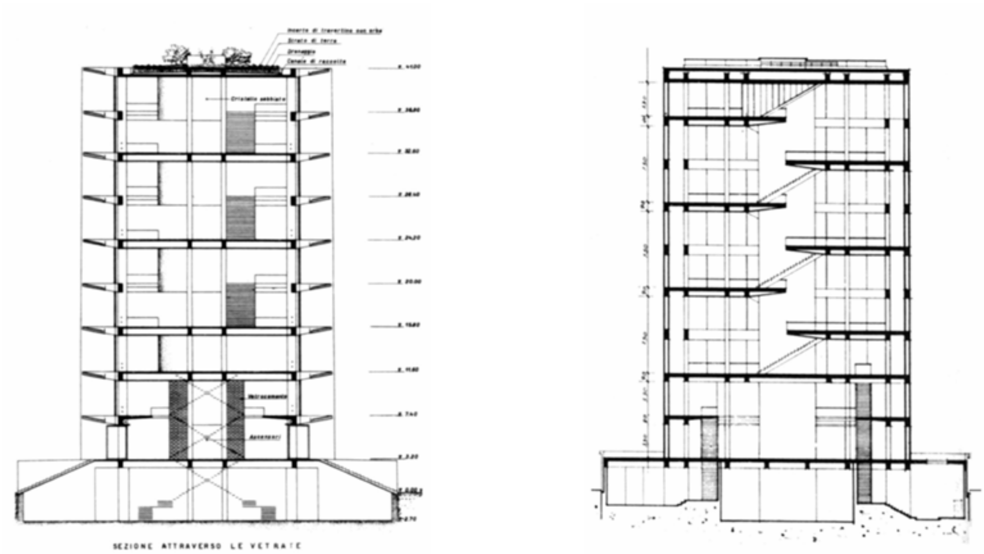


Figure 1 The Tower of the Nations: transversal (left) and longitudinal (right) section

An appropriate investigation has been carried out in order to identify the geometry and the reinforcement of all structural elements. Geometry has been evaluated starting from the examination of structural drawings and then carrying out visual inspection and survey. Destructive and non-destructive tests have been carried out in order to evaluate material mechanical properties and reinforcement details. As regards the beams, the reinforcement has been evaluated in three sections (one at the center and the others at the ends) while, as regards the columns, only a midspan section has been considered. Moreover, geometry of foundations has been assessed: they are made by prismatic blocks on circular piles. The comparison between the results of simulated design of the structure and field investigations has confirmed that the structure was designed to bear only gravity loads. According to Italian seismic code provisions, a 'knowledge level' KL2 has been reached. Combining destructive and non-destructive tests, the mechanical characteristics of materials have been defined. As regards concrete, some logs have been extracted and some SonReb tests have been conducted, to evaluate the compressive strength of the material:

values ranging from 10.64 MPa and 25.98 MPa have been obtained, with a mean value of 15.26 MPa (Rainieri et al., 2008b). As regards the steel reinforcement, some specimens have been extracted by the structural elements, obtaining an average yielding strength of 275 MPa. The bars were smooth and affected by corrosion, in particular at the first level and the roof. All these tests have been carried out to support the numerical model of the building and the development of non-linear static push-over analyses to assess the seismic capacity, besides modal dynamic analyses. Additional details can be found in (Cosenza et al., 2006). Finally, some dynamic measurements have been carried out, in order to get the modal parameters of the structure under operational conditions and perform a model validation.

3. THE MODAL PARAMETER IDENTIFICATION TECHNIQUE

Evaluation of the modal parameters of the structure has been performed in output-only condition through the use of the Frequency Domain Decomposition (FDD) technique. It is an extension of the Basic Frequency Domain technique (BFD), often called the Peak-picking technique (Bendat & Piersol, 1986), since it is based on the Singular Value Decomposition (SVD) of the Power Spectral Density (PSD) matrix. In fact, considering a lightly damped system and that the contribution of the modes at a particular frequency is limited to a finite number (usually one or two), near a peak corresponding to the kth mode in the spectrum the singular value decomposition of the output PSD matrix gives:

$$\hat{G}_{yy}(j\omega_i) = s_i u_{i1} u_{i1}^H \qquad \omega_i \to \omega_k \tag{3.1}$$

The first singular vector at the k-th resonance is an estimate of the k-th mode shape:

$$\hat{\phi}_k = u_{k1} \tag{3.2}$$

In case of repeated modes, the PSD matrix rank is equal to the number of multiplicity of the modes. As a result, modal frequencies can be located by the peaks of the singular values plots. From the corresponding singular vectors mode shapes can be obtained. Not only natural frequencies and mode shapes can be estimated by this method: the Enhanced Frequency Domain Decomposition technique allows also the estimation of damping ratios. To estimate damping ratios, the singular values near the peak with corresponding singular vector having MAC higher than a MAC rejection level are transferred back to time domain through inverse FFT, which is an approximated correlation function of the equivalent SDOF system. From the free decay function of the SDOF system, the damping ratio can be calculated by the logarithmic decrement technique.

4. THE AUTOMATED MODAL PARAMETER EXTRACTION PROCEDURE

Under the assumption that the FRF matrix is dominated by the corresponding term near a resonance:

$$[H(j\omega_r)] = \{\psi\}_r \frac{Q_r}{(j\omega_r - \lambda_r)} \{\psi\}_r^T \tag{4.1}$$

in the bandwidth of a mode, being $\{\psi\}_r$ theoretically constant, the MAC index (Allemang & Brown, 1982) computed at the same frequency line between the two first singular vectors obtained by the SVD of the PSD matrix for two subsequent records should be constant and equal to 1 for a stationary system. It is not the case of actual records since measures are affected by noise: however, specific selection criteria and tolerances can be set. The algorithm starts from the SVD of the output PSD matrix. The latter is the core of the EFDD method, so that the first singular vector at each frequency line is obtained. This step is repeated for a number of subsequent records. Afterwards, the MAC between the two singular vectors at the same frequency line obtained from two different records is computed. In order to reduce the effect of noise, the average MAC vs. frequency plot is computed. Averaged MAC vs. frequency plot can be seen as a coherence function: where a certain mode is located, points are located very close each other and to 1 and a flat shape is obtained as shown in Figure 2. However, the distance between two consecutive points in the averaged MAC vs. frequency plot is strictly dependent upon the number of averages. As a result, noise of measures need to be processed. Identification of the bandwidth of each mode is carried out evaluating the mean and the standard deviation of the MAC value at each frequency line for a given number of processed records. In order to have a good estimation of such parameters at least ten records are generally taken into consideration.

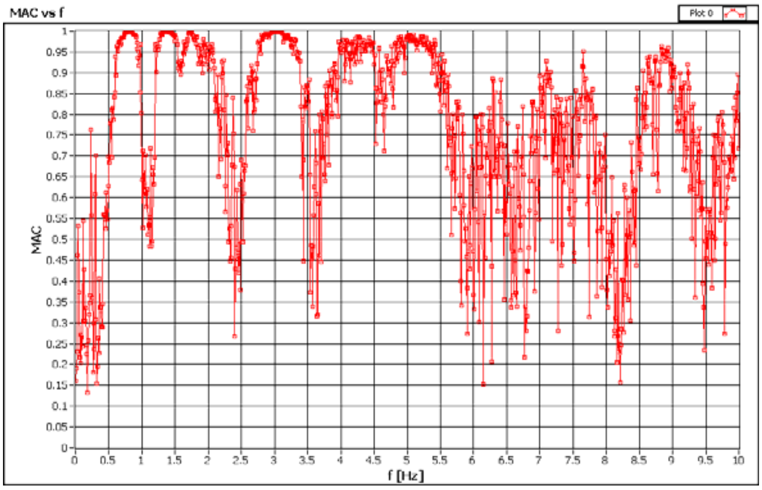
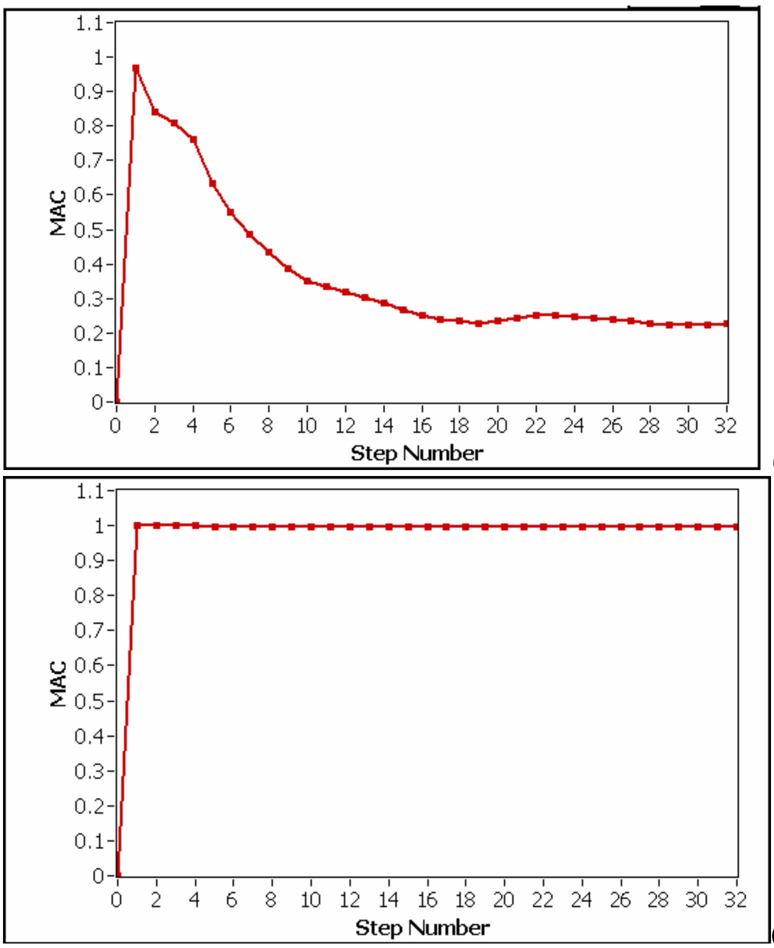


Figure 2 Averaged MAC vs. frequency plot



(a)

(b)

Figure 3 Averaged MAC vs. step number: (a) noise; (b) mode bandwidth

Figure 3 shows the MAC function that is nearby horizontal only at the frequency lines located within a mode bandwidth. It has been assumed that such function is horizontal if mean and standard deviation comply with given limits (Rainieri et al., 2008a). Based on the above mentioned results, the bandwidth of a number of modes can be defined by looking at those frequency lines characterized by a MAC value above a predefined limit (for example, 0.95) and by mean and standard deviation complying with the previously mentioned limits. Within each bandwidth, use of the peak detection algorithm to the corresponding portion of the singular value plot leads to the identification of the natural frequency of that mode.

The corresponding singular vector at that frequency line is a good estimation of the mode shape of the structure. Starting from the SDOF Bell function of the mode (Brincker et al., 2000), damping and natural frequency can be determined in an automated way from the correlation function of the isolated SDOF system using only the function down to a certain decay level, as suggested in (Brincker et al., 2007). A synthesis of the proposed algorithm is shown in Figure 4. It can be used for single applications, in order to define the first modes of the structure under test, or as modal information engine for the tracking procedure described in (Rainieri et al., 2007).

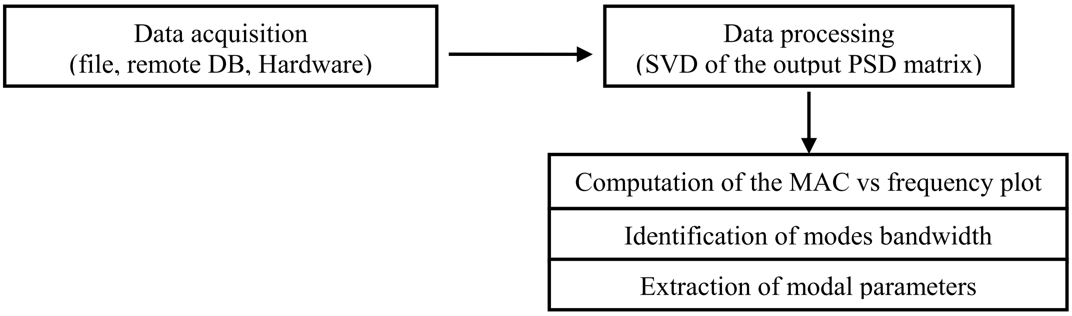


Figure 4 The algorithm for automated modal parameters identification

5. MODAL IDENTIFICATION RESULTS AND CORRELATION WITH NUMERICAL MODEL

The dynamic response of the structure has been measured at the fifth level of the building and at the roof. Each level has been instrumented in three corners: at each corner two Force Balance accelerometers (Kinemetrics EpiSensor ES-U2) have been placed. The accelerometers were placed parallel to the main directions of the building. The sensors have a bandwidth (-3 dB) of about 200 Hz at 1 g, a full scale range of ±1 g and 2.5 V/g as sensitivity.

A Kinemetrics K2 Digital Recorder, characterized by a 24-bit DSP, has been used for data acquisition. Before analyzing the records, a preliminary classification and validation of the data has been performed, aiming at recognize stationarity, presence of spurious harmonic components and the statistical distribution. In particular, a data standardization has been performed to verify that data were approximately normally distributed and that clipping, drop-out did not occur.
Test results obtained by applying the traditional (manual) FDD are reported in Table 5.1, while in Figure 5 are reported the complexity plots of the identified mode shapes, pointing out that the obtained modes are real.

Table 5.1 Results of identification (traditional FDD)

Mode	**Type**	**Frequency** [Hz]	**Damping Ratio** [%]
1	Translational (open side)	0.79	3.3
2	Translational (tuff walls)	1.31	3.8
3	Torsional	1.65	2.5

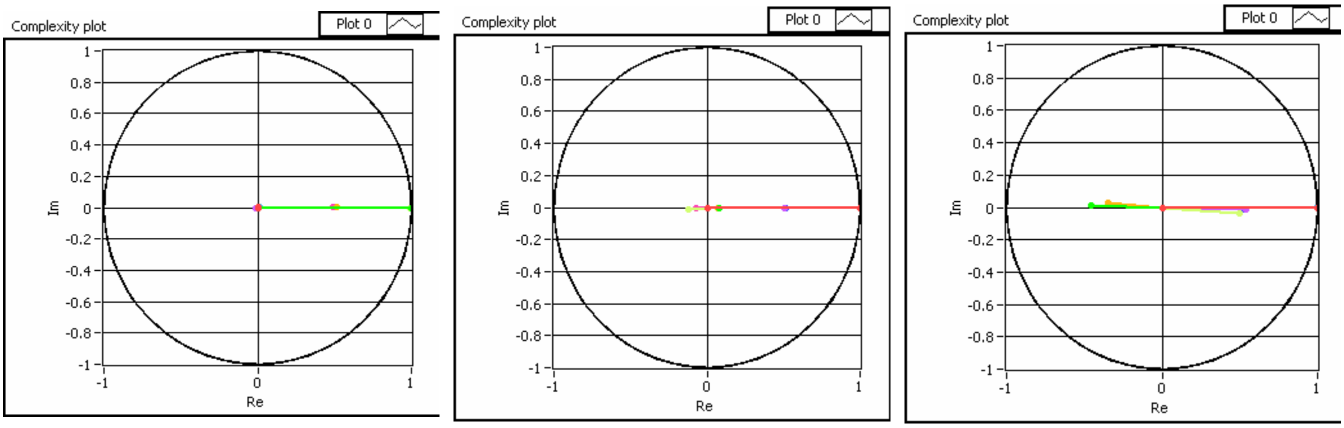


Figure 5 Complexity plots of the identified mode shapes

After the manual identification of modal parameters, a new longer in time dataset has been recorded some months after the first test and used within the automated identification algorithm. The record set was about one hour long, and characterized by a sampling frequency of 100 Hz. In Figure 6 the first singular value plot obtained by the SVD of the PSD matrix has been superimposed to the MAC vs. frequency plot obtained by the automated procedure whose results are reported in Table 5.2: comparison with manual identification results point out the effectiveness of the proposed algorithm.

Results in terms of natural frequencies obtained during the second tests are slightly different with respect to the first test: probably, this is due to the different environmental conditions (mainly temperature) as well as to the structural deterioration affecting the building.

Results of modal identification have been used to validate the FE model of the structure. Correlation with experimental results has been evaluated for the following classes of models:

- Absence vs. presence of tuff masonry walls;
- Absence vs. presence of the basement parallelepiped structure;
- Floor modelling: shell elements vs. rigid diaphragm,

in order to overcome some uncertainties related to modelling hypotheses. Comparisons allowed the selection of the best representative model, which is characterized by presence of tuff masonry walls, presence of basement and floors modelled by shell elements. Later on, a manual tuning of the model led to the identification of the elastic properties of materials (tuff and concrete).

In Table 5.3 a comparison between numerical and experimental frequencies for the updated model is reported, pointing out the good agreement obtained between model and actual structure response.

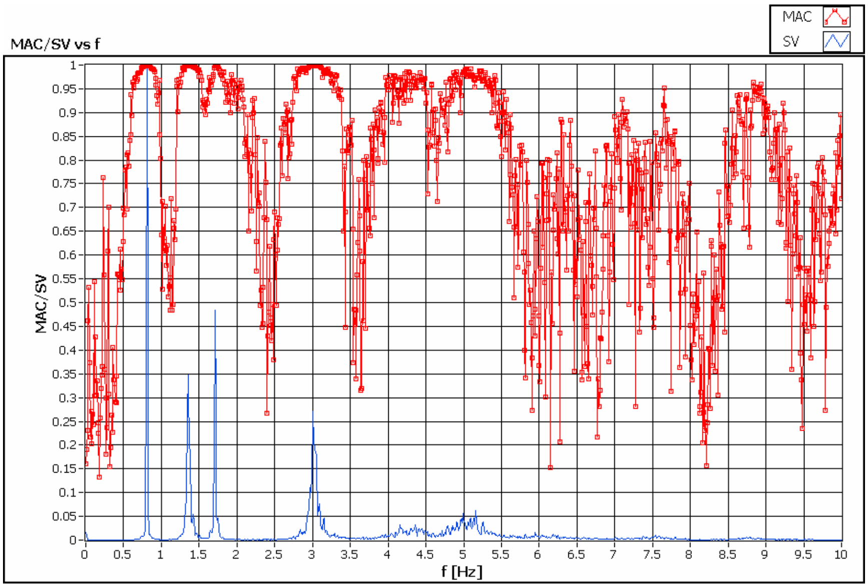


Figure 6 MAC vs. frequency plot and SV plot

Table 5.2 Automated identification results

Mode	**EFDD** [Hz]	**Automated FDD** [Hz]	**scatter** [%]
1	0.81	0.81	0
2	1.38	1.35	-2.17
3	1.73	1.71	-1.16

Table 5.3 Comparison between experimental and numerical natural frequencies for the updated model

Mode	**Updated model - f** [Hz]	**OMA - f** [Hz]	**Scatter** [%]
1	0.76	0.79	-3.76
2	1.38	1.31	5.03
3	1.65	1.65	-0.02
4	3.11	2.96	5.05
5	4.04	4.21	-4.04
6	4.92	4.92	0.03

Values of MAC index obtained by comparing numerical and experimental mode shapes are reported in Table 5.4:

Table 5.4 MAC matrix

$$\begin{bmatrix} \mathbf{0.958871} & 0.0003709 & 0.000763 \\ 3.33E\text{-}6 & \mathbf{0.996876} & 0.034436 \\ 0.000556 & 0.007613 & \mathbf{0.913202} \end{bmatrix}$$

6. CONCLUSIONS

The unique structural techniques which affects a large part of relevant structures from an architectural or historical point of view and the uncertainties about geometry and materials make accurate structural analyses and assessment of the effective behaviour of the structure in its operational conditions difficult. Therefore, the knowledge of the modal properties of historical structures is very important, in particular for the evaluation of the structural performances in presence of extreme load conditions such as during an earthquake. In the present paper a well-established Operational Modal Analysis technique and a new automated algorithm for output-only modal parameter extraction have been used in order to identify the modal parameters of a valuable historical RC building like the Tower of the Nations. Efficiency of the numerical procedures adopted to extract modal parameters, namely periods and shapes, is much more relevant in the case of historical constructions. In fact, dynamic measures based on environmental vibrations allow to really minimise the impact of structural assessment on the construction, especially whenever monuments are located in very urbanised areas.

Experimental results have been used for a model updating application. A number of models have been prepared according to different assumptions. The level of correlation between experimental and analytical results has been used for model selection. The result of this process was a well-refined model, where all simplified assumptions were mitigated in order to obtain a more detailed model. Particular attention is paid to floor simulation and influence of curtain walls on the dynamic response under operational conditions. The optimization procedure has given as a result a very high correlation with the experimental results and a value of the elastic modulus of concrete very close to the average value obtained from tests.

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REFERENCES

Allemang, R.J. and Brown, D.L. (1982). A correlation coefficient for modal vector analysis, *Proceedings of the 1st SEM International Modal Analysis Conference*, Orlando, FL, USA.

Bendat, J. S. and Piersol, A.G. (1986). Random Data: Analysis and Measurement Procedures, John Wiley & Sons, New York.

Brincker, R., Zhang, L. and Andersen, P. (2000). Modal identification from ambient responses using frequency domain decomposition, *Proceedings of IMAC 18*, San Antonio (TX), USA.

Brincker, R., Andersen, P. and Jacobsen, N.J. (2007). Automated Frequency Domain Decomposition for Operational Modal Analysis, *Proceedings of the 25th SEM International Modal Analysis Conference*, Orlando, FL, USA.

Cosenza, E., Fabbrocino, G., Manfredi, G., Parretti, R., Prota, A. and Verderame, G.M. (2006). Seismic Assessment and Retrofitting of the Tower of the Nations. Paper 0997. The 2nd International *fib* Congress, Naples.

Direttiva del Presidente del Consiglio dei Ministri del 12/10/2007, pubblicata in G.U. n. 24 del 29 gennaio 2008, per la valutazione e la riduzione del rischio sismico del patrimonio culturale con riferimento alle norme tecniche per le costruzioni (in Italian).

European Standard Eurocode 8 (2004). Design of structures for earthquake resistance EN 1998, European Committee for Standardization.

Gentile, C. (2005). Operational Modal Analysis and Assessment of Historical Structures, *Proceedings of the 1st IOMAC Conference*, Copenhagen, Denmark.

Rainieri, C., Fabbrocino, G. and Cosenza, E. (2007). Automated Operational Modal Analysis as structural health monitoring tool: theoretical and applicative aspects, *Key Engineering Materials* **Vol. 347**, 479-484.

Rainieri, C., Fabbrocino, G. and Cosenza, E. (2008a). An approach to automated modal parameter identification for structural health monitorino applications, *Proceedings of CST 2008*, Athens, Greece.

Rainieri, C., Fabbrocino, G., Verderame, G.M., Cosenza, E. and Manfredi, G. (2008b). Structural and dynamic assessment and model updating of heritage buildings, *Proceedings of ISMA 2008*, Leuven, Belgium.