Proceedings of the 9th International Conference on Structural Dynamics, EURODYN 2014
Porto, Portugal, 30 June - 2 July 2014
A. Cunha, E. Caetano, P. Ribeiro, G. Müller (eds.)
ISSN: 2311-9020; ISBN: 978-972-752-165-4

Structural Monitoring and Damage Identification on a Masonry Chimney by a Spectral-based Identification Technique

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ABSTRACT: The present work deals with the damage identification of a historical masonry chimney located in Guimarães (Portugal), including a detailed survey, inspection and diagnosis. The chimney was object of a continuous monitoring campaign carried out to catch the evolution of the modal parameters and evaluate the success of the rehabilitation works planned after a lightning accident. Based on the dynamic features extracted from the OMA data, a damage identification analysis was performed making use of different damage identification techniques. Considering the explicit dependence of output-only power spectral densities on frequency contents, a spectral-based identification method was used to detect the damage. Finally, an appropriate localization index was defined combining evolutionary complex eigenvectors obtained from the decomposition of the power spectral density matrix. The results allow to conclude that the spectral-based dynamic identification method is a non-destructive tool able to capture the global behavior of a structure and may reveal itself of great help for exploring damage at an early stage in historical constructions.
KEY WORDS: Masonry chimneys; Spectral-based method; Dynamic identification; Damage detection; Damage Localization; Structural health monitoring.

1 INTRODUCTION

Any structure, whether existing or not and independently on the structural system and the constituting materials, may be subject to damage. Damage is a structural condition characterizing a system no longer operating in its ideal and sound configuration, but still functioning satisfactorily. Nevertheless the impairment of value, usefulness and normal function resulting in a construction affected by damage can be avoided if tools able to assess structural conditions are adopted. This is the case of dynamic-based damage identification methods, which basic assumption is the possibility of detecting damage starting from changes in modal parameters, notably eigen frequencies, mode shapes and damping ratios, that can be considered as 'damage indicators' since they are a function of the physical properties of the structure, thus any changes in physical properties (such as stiffness or flexibility) will cause changes in dynamic characteristics. It also needs to remark that vibration-based methods are 'global' techniques that give not only a qualitative indication of the presence of damage in a structure, but also provide information about its possible location, contributing to move forward into the subsequent task related to the estimation of the extent of damage. Within this framework, the spectral-based identification method here addressed plays a major role since it is a non-destructive tool suitable to Operational Modal Analysis (OMA) that may reveal itself considerably helpful in case of masonry structures, especially as far as historical constructions are concerned.

After a brief description of the case study in terms of geometrical features and materials characterization, the paper focuses on: a) the dynamic identification tests carried out on the chimney hit by a lightning before and after the rehabilitation works, b) the structural health monitoring performed during the structural intervention, c) the numerical analysis and the related FE Model Updating for dynamic calibration and, finally, d) the damage identification of the chimney by means of the spectral-based approach. Comparisons with other damage identification methods available in literature are also presented and the results obtained are widely discussed.

2 CASE-STUDY: MASONRY CHIMNEY

The masonry chimney object of this paper belonged to a former industrial complex (**Errore. L'origine riferimento non è stata trovata.**Figure 1) located in the city center of Guimarães, historical town in the North of Portugal. The structure was already monitored by the University of Minho between November 2010 and June 2011 and then subjected to a series of topographic measurements and visual inspections that pointed out its poor structural condition. Further information about this experimental campaign are provided in Ramos et al. **Errore. L'origine riferimento non è stata trovata.**.

Figure 1. The masonry chimney.

Figure 2. Openings caused by the lightening.

A new phase of inspection and diagnosis was again necessary after the accident occurred in July 2012, when the chimney was hit by a lightning and the situation made worse with the addition of two large openings to the existing cracks (Figure 2**Errore. L'origine riferimento non è stata trovata.**). In order to reinstate the sound condition of the chimney, in-depth repair works were carried out between December 2012 and February 2013. The intervention was preceded by a first phase of data collection of the structure, including geometrical and damage surveys, material characterization by NDTs and global dynamic identification by ambient vibration tests. A second phase of dynamic monitoring was put into practice to follow the evolution of the modal properties during the works and a last phase marked again by OMA tests was performed. Hereafter a more detailed description of all the phases is presented.

2.1 *Geometrical Survey*

The Chimney was built in brick masonry with mortar joints arranged along regular horizontal rows and is characterized by a cone frustum shape with a pipe cross-section that tapers upwards decreasing in diameter - from 2.93 m to 0.94 m - and thickness - from 0.70 m to 0.20 m. Circa 27 m in height, the Chimney rests on a quadrangular foundation block and presents a rectangular opening (about 0.90 m × 1.20 m) at the lower level that allowed to trigger the 'chimney effect' for the smoke dispersion of the former industrial complex.

2.2 *Damage Survey*

The last inspections highlighted the presence of two significant holes caused by the electrical discharge and the increase of the existing cracks, besides spotted spalling, widespread biological growth and rising humidity in the bottom part of the chimney (Figure 3). The two 'new openings' worsened the structural condition of the chimney already affected by a slight rigid rotation of the upper part of the chimney, a disconnection of the top of the structure with respect to the rest of the body, a permanent plastic deformation affecting the upper two thirds and a series of minor cracks. Urgent repair works were planned and executed to re-establish the chimney safety, including consolidation through reconstruction of damaged parts, cracks closing and mortar injections, chimney washing and waterproof protection. Details about the damage and the structural intervention are given in [1][1] e [3] [1].

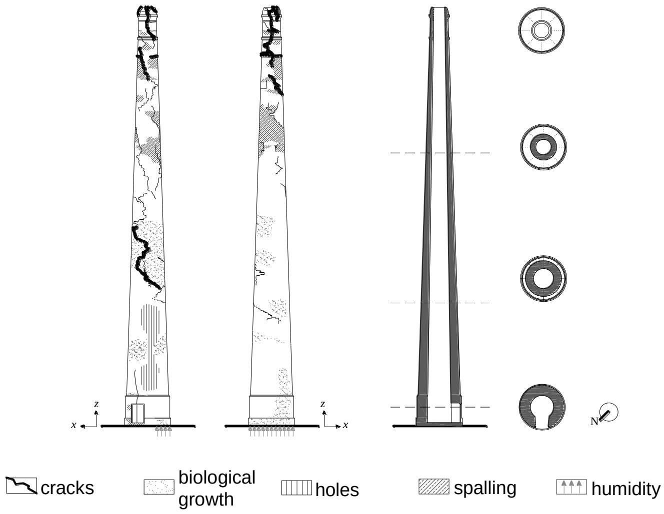

Figure 3. Geometrical and damage survey: west front, east front, sections.

3 OMA AND SHM

Being the chimney already damaged, no further investigation was necessary to detect its presence. Nevertheless, output-only identification techniques were used with the purpose of studying the dynamic response of the structure, referring to both the structural conditions (before and after rehabilitation works) in order to evaluate the efficiency of the intervention and catch the changes in the modal parameters due to the presence of damage.

3.1 *Dynamic identification before and after the rehabilitation works*

Before proceeding to OMA tests, a preliminary FE eigenvalue analysis was addressed to the choice of the measurements points (12), the sampling frequency (200 Hz) and the total sampling time (10 minutes) to set for the data acquisition.

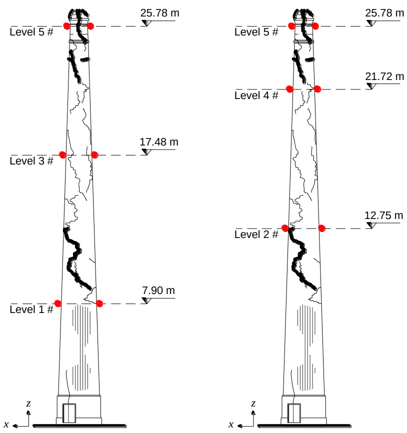

Figure 4. Test setups and measuring points.

Keeping the transducers on the top of the chimney as reference, 2 test setups, 3 levels for each setup and 4 accelerometers for each level were used (Figure 4) since it was necessary to measure an additional *y* direction, in diametrically opposed points, besides the three directions *x*, *y* and *z* in order to catch possible torsional components. Ambient excitations from wind and traffic were used as operational conditions.

Table 1 and Table 2 summarizes the results obtained in terms of frequencies and damping ratios by the SSI method [4]. As shown, the rehabilitation works led to an overall increase in the frequency values of the structure (on average around 8%), especially as far as the higher modes are concerned. A significant increase of damping ratios was detected as well (around 123% on average).

Table 1. Eigen frequencies values before and after works.

Mode	Before		After		
	ω [Hz]	CV_ω [%]	ω [Hz]	CV_ω [%]	Δ_ω [%]
1	1.015	0.26	1.018	0.18	+0.30
2	1.15	0.08	1.10	0.05	–4.09
3	3.20	0.75	3.39	0.26	+5.90
4	3.65	0.18	3.73	0.33	+2.11
5	6.39	0.50	–	–	–
6	7.32	0.24	7.79	0.21	+6.51
7	8.81	0.05	10.29	0.03	+16.85
8	11.40	0.07	12.51	0.32	+9.74
9	12.31	0.22	13.37	0.38	+8.61
10	13.93	0.19	13.53	0.28	–2.87
Average	–	0.40	–	0.23	+7.95*

Table 2. Damping ratios before and after repair works.

Mode	Before		After		
	ξ [%]	CV_ξ [%]	ξ [%]	CV_ξ [%]	Δ_ξ [%]
1	0.48	63.53	2.53	2.43	+429.6
2	0.95	20.91	3.30	6.25	+248.3
3	0.91	29.18	1.36	8.60	+49.43
4	0.90	15.07	1.96	6.58	+117.6
5	0.75	45.42	–	–	–
6	0.84	39.77	1.09	10.77	+30.26
7	0.58	9.79	0.91	24.17	+56.44
8	1.24	31.92	1.84	1.94	+47.91
9	1.46	16.22	1.58	24.21	+7.87
10	2.56	33.33	2.29	39.97	- 10.62
Average	1.21	27.31	1.87	13.88	+123.43*

Regarding the mode shapes comparison between the two structural conditions, despite similarities in the mode configurations, it is possible to observe a weak correlation in terms of MAC values concerning all the modes except the lower ones (Figure 5). The existence of damage, especially referring to the two holes caused by the lightening besides all the cracks, is reflected in a series of local effects clearly deviating the response of the damaged structure from the monolithic (sound) behavior that characterizes the chimney after the works.

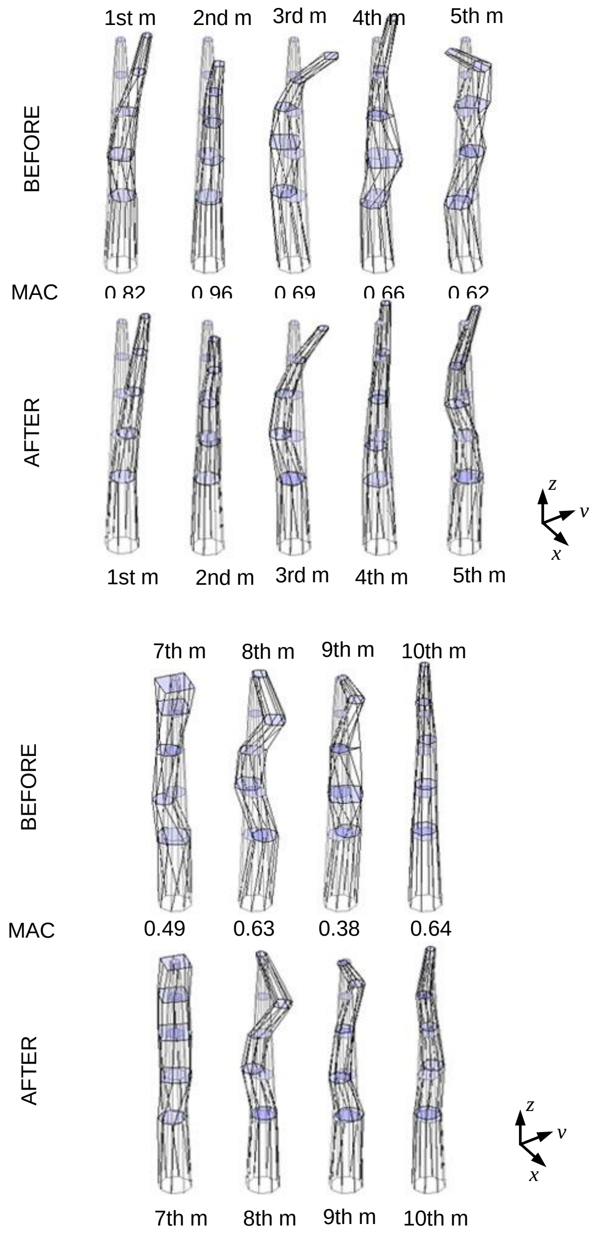

Figure 5. Experimental mode shapes and MAC values before and after rehabilitation works.

3.2 *Dynamic monitoring system*

Aiming at following the evolution of the natural frequencies during the consolidation works, the dynamic monitoring task was performed using a limited number of sensors, namely the four acceleration transducers placed on the top. This task was carried out from December 2012 to February 2013 in three campaigns (Table 3) and particularly attention was paid during the reconstruction of the masonry panels in the areas where the lightening caused the holes. The first six eigen frequencies were taken into account. As shown in Figure 6, significant changes mostly involved the higher natural frequencies, whereas the lower ones did not suffer any considerable changes.

Table 3. Series of data from the monitoring system.

Data series	From	To	Number of events
I	5-Dec-12	14-Dec-12	160
II	18-Dec-12	22-Dec-12	73
III	4-Jan-13	22-Jan-13	313

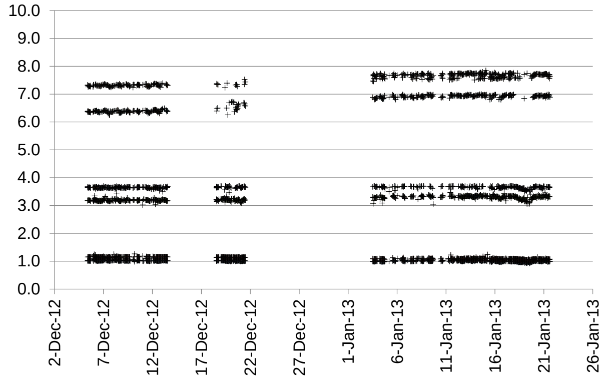

Figure 6. Structural health monitoring.

Putting together all the results, it is possible to conclude that the presence of damage changed the dynamic behavior of the structure with respect to the original configuration in terms of damping ratios and natural frequencies, as the OMA tests pointed out. Particularly, the higher the modes, the higher the frequency shift. Considering also the data from the dynamic monitoring, the efficiency of the structural intervention can be stated: this is quite evident if one looks at the third campaign of data collection, when the reconstruction of masonry panels led to an increase of stiffness that turned into an increase of frequency as well. Altogether, it is possible to stress that the rehabilitation works were able to reinstate the chimney safety.

4 DAMAGE IDENTIFICATION OF THE CHIMNEY

The field of damage identification is very broad and encompasses several different methods categorized according to various criteria, such as the effect of damage on a structure or the level of damage provided. With respect to the effect of damage, vibration-based damage identification methods can be classified as linear or non linear, depending on the behavior assumed after the damage occurrence. Linear methods can be further classified as model-based and non-model-based methods, depending on the use of a numerical model for the damage identification or not. Regarding the level of damage, after the first classification presented by Rytter [4] in which four hierarchical levels of damage were established, a new classification with the introduction of another level (level 3) has been addressed more recently in [6] and [7]:

- Detection (level 1) – the method gives a qualitative indication that damage might be present in the structure;
- Localization (level 2) – the method gives information about the probable location of the damage;
- Classification (level 3) – the method gives information about the type of damage;
- Assessment (level 4) – the method gives an estimate of the size of the damage;
- Prediction (level 5) – the method offers information about the safety of the structure, estimating the residual operating life.

Despite the amount of papers dealing with the task of the damage identification have been increasing more and more during the last years, no method able to provide accurate results through all the levels mentioned above has been addressed [8]. In case of masonry structures, the complexity of both geometry and materials makes the applicability of VBDIMs (Vibration-based Dynamic Identification Methods) more complicated and even moving from level of damage 1 to level 2 may be hard. Nevertheless, a new global technique based on output-only power spectral densities is presented here with the purpose of catching the existence of damage in the masonry chimney and its possible location. Comparisons with other damage identification indexes available in literature are also addressed and discussed.

4.1 Proposed approach and selected methods

The proposed damage identification technique, so-called spectral-based method, embraces the first two levels of damage identification, namely detection and localization. Starting from the consideration that output-only power spectral densities strictly depend on frequency contents, this technique is based on an eigenvalue problem consisting of the following main steps: 1) construction of the Power Spectrum Matrix over the frequency domain; 2) decomposition of the matrix in eigenvalues and eigenvectors; and 3) damage detection and localization by means of a proper index obtained from the combination of the extracted parameters. Basically, each eigenvalue denotes the energy of the vibration mode at a certain frequency, whereas each eigenvector is a mode shape estimation corresponding to that eigenvalue [9]. As frequency shifts and mode shapes changes are considered damage indicators, the same applies to eigenvalue shifts and eigenvectors changes. Therefore, only eigenvalues cannot provide spatial information about structural damage, since they refer to global properties of the structure while the damage is a local phenomenon, thus their combination with the related eigenvectors become a must in order to identify more than damage (level 1). According to the levels of the damage identification process previously listed, a group of methods was selected with the purpose of comparing the proposed approach and validate its reliability:

- The Unified Significance Indicator (USI);
- The COMAC values;
- The Parameter Method (PM);
- The Mode Shape Curvature Method (MSCM);
- The Sum of all Curvature Errors method (SCE);
- The Changes in Flexibility Matrix method (CFM).

The expressions of each method are briefly reported in the table below. Detailed description and comparison are presented elsewhere [10].

Modal curvatures were numerically calculated from the mode shapes by the central difference theorem, or the second order approximation, as:

$$\varphi'' \approx \frac{\varphi_{i+1} - 2\varphi_i + \varphi_{i-1}}{\left(\Delta L^2\right)} \qquad (1)$$

where ΔL is the distance between the points i and $i+1$.

Table 4. List of selected damage identification methods.

Method	Damage	Index
USI	Level 1	$\sum_{j=1}^{m} \frac{\omega_j^u - \omega_j^d}{\sqrt{(\sigma_\omega^u)_j^2 + (\sigma_\omega^d)_j^2}}$
COMAC	Level 2	$\frac{\left\| \sum_{j=1}^{m} \varphi_{i,j}^u \varphi_{i,j}^d \right\|^2}{\sum_{j=1}^{m} (\varphi_{i,j}^u)^2 \sum_{j=1}^{m} (\varphi_{i,j}^d)^2}$
PM	Level 2	$\sum_{j=1}^{m} \left[\varphi_j^d \left(\frac{\omega_j^u}{\omega_j^d} \right) - \varphi_j^u \right]$
MSCM	Level 2	$\sum_{j=1}^{m} \left\| \varphi_{d,j}'' - \varphi_{u,j}'' \right\|$
SCE	Level 2	$\sum_{j=1}^{m} \left\| \frac{\varphi_{d,j}'' - \varphi_{u,j}''}{\varphi_{u,j}''} \right\|$
DIM	Level 2	$\beta_{i,j} = \frac{\left[\int_a^b (\varphi_j^{d''})^2 dx + \int_0^L (\varphi_j^{d''})^2 dx \right]}{\left[\int_a^b (\varphi_j^{u''})^2 dx + \int_0^L (\varphi_j^{u''})^2 dx \right]} \cdot \frac{\int_0^L (\varphi_j^{u''}) dx}{\int_0^L (\varphi_j^{d''}) dx}$
CFM	Level 2 and 3	$\beta = diag\{\mathbf{F}^d - \mathbf{F}^u\};\ \mathbf{F} = \sum_{j=1}^{m} \frac{1}{\omega_j^2} \phi_j \phi_j^T$

In order to compute the CFM index, mass-scaled mode shapes were necessary. As the system identification was performed by output-only techniques and the input was unknown, the following scaling factor suggested in [11] was applied to scale the modes:

$$\alpha = \frac{1}{\sqrt{\varphi^T \cdot \mathbf{M} \cdot \varphi}} \qquad (2)$$

It should be stressed that the construction of the mass matrix used to compute the scaling factors was obtained based on the assumption of lumped masses in order to simplify and speed up the damage analysis process. So the scaled and un-scaled mode shapes are related by the equation:

$$\phi = \alpha \cdot \varphi \qquad (3)$$

4.2 Spectral-based damage identification technique

Using direct and cross spectra of output signals as primary data, a N order square matrix $\mathbf{S}_X$ (where N denotes the number of measured DOFs) was built and decomposed [12] by solving the following eigenvalue problem:

$$\mathbf{S}_X(\omega) = \mathbf{\Psi}_X(\omega) \mathbf{\Lambda}_X(\omega) \mathbf{\Psi}_X^T(\omega) \qquad (4)$$

in which $\mathbf{\Lambda}_X(\omega)$ is a diagonal matrix containing real positive singular values in descending order and $\mathbf{\Psi}_X(\omega)$ is a complex matrix including singular vectors as columns. The diagonalisation of the spectral density matrix, namely the eigenvalues plotting, yields the eigenfrequencies as local maxima and allows to detect even closely spaced modes, since more than one singular value can reach a local maximum around the close eigenfrequencies. Regarding the case-study object of this paper, a [15×15] square matrix was computed in MATLAB [13] taking into account both x and z directions outputs for the North-side (5 measurement points) and the only y direction for the South-side (5 measurement points), so that all the three directions could be considered. Figure 7 and Figure 8 show the eigenvalues plotting obtained from the spectrum-driven method and their comparison with the values from the SSI-PC, respectively.

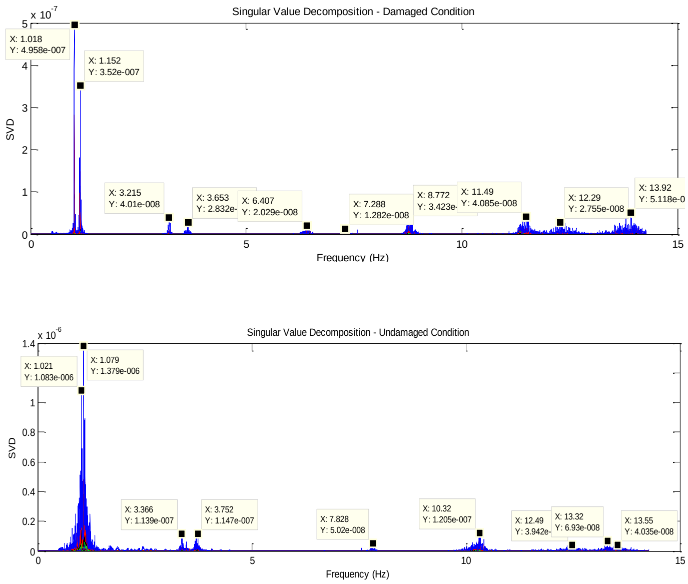

Figure 7. Eigenvalues plotting for damaged (before) and undamaged (after) conditions.

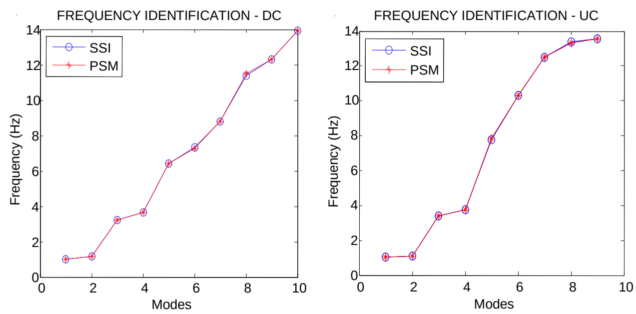

Figure 8. Comparison between PSM and SSI-PC methods.

As highlighted in Table 5, the maximum percentage error between the resonant frequencies values is lower than 0.8% (except for mode 2 in the undamaged condition), so it is stressed that the results are highly accurate. The frequency shift concerning the higher modes and already pointed out in the previous section is perfectly caught as well and it proves to be a qualitatively indicator in the damage identification analysis.

Table 5. Dynamic identification before and after rehabilitation works: eigenvalues vs. eigenfrequencies.

Mode	Before			After		
	$\omega_{d,psm}$ [Hz]	$\omega_{d,ssi}$ [Hz]	Δ_ω [%]	$\omega_{u,psm}$ [Hz]	$\omega_{u,ssi}$ [Hz]	Δ_ω [%]
1	1.018	1.015	0.29	1.021	1.018	0.29
2	1.15	1.15	0.17	1.08	1.10	–1.82
3	3.21	3.20	0.31	3.37	3.39	–0.58
4	3.65	3.65	0.08	3.75	3.73	0.54
5	6.41	6.39	0.31	–	–	–
6	7.29	7.32	–0.41	7.83	7.79	0.51
7	8.77	8.81	0.45	10.32	10.29	0.29
8	11.49	11.40	0.79	12.49	12.51	–0.16
9	12.29	12.31	–0.16	13.32	13.37	–0.37
10	13.92	13.93	–0.07	13.55	13.53	+0.15

In order to move to a Level 2 identification and since the limited feasibility of using exclusively frequency changes for damage localization, every singular vector corresponding to a non-zero singular value was also taken into consideration leading to the definition of the following damage index, then applied to the case-study:

$$\Delta\psi = \sum_{j=1}^{n} \left\| \left| \sum_{i=1}^{m} \left[\psi_i^d(\omega_i) \cdot \sqrt{\lambda_i^d(\omega_i)} \right] \right| - \left| \sum_{i=1}^{m} \left[\psi_i^u(\omega_i) \cdot \sqrt{\lambda_i^u(\omega_i)} \right] \right| \right\| \quad (5)$$

where ψ denotes the eigenvector amplified by its related eigenvalue λ over the whole frequency domain, m the frequency range, n the mode number and upper scripts d, u denote damaged and undamaged conditions, respectively. Basically, the index consists of the difference between spectral modes directly obtained from nodal time-histories responses. Unlike the eigenvalues, the eigenvectors are much more sensitive to structural local-damage as they are function of location coordinates. For this reason, two different spectral matrices were built so that both the responses along the planes *x-z* and *y-z* could be investigated: a [5×5] square matrix with outputs spectra in *x* direction and a [5×5] square matrix with outputs spectra in *y* direction. Figure 9 shows the DOFs investigated in each direction and the results obtained in terms of localization.

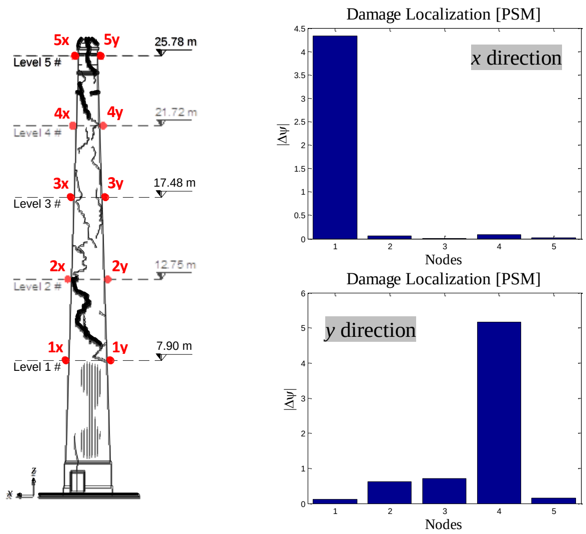

Figure 9. Damage localization in the chimney by PSM.

The bar graphs clearly indicate the presence of damage in nodes 1 and 4 that are exactly the nodes closest to the parts of the chimney most affected by the damage. Node 1 is located near the severe openings caused by the lightening and node 4 is located where both the disconnection and rigid rotation affecting the upper part of the chimney begin. In the former case, the damage altered the structural behavior in the *x-z* plane, whereas in the latter case the dynamic response varied in the *y-z* plane.

4.3 Comparison with other damage identification methods

With the purpose of evaluate accuracy and reliability of the spectral-based method, comparisons with the damage identification methods presented in the previous section are addressed.

The first method applied was the USI, a statistical analysis method providing a sensitive indicator of structural damage based on frequencies shifts and estimated standard deviations [14]. A similar significance indicator defined for estimated damping ratios was also computed. Because of the presence of only one damage scenario, the sum of all the frequency and damping significance indicators over the measured modes to get a unified indicator was not possible. Therefore SI values were calculated for each single mode and the presence of damage was clearly identified from the frequency shifts (Figure 9). Being a Level 1 damage identification method, no additional information regarding the possible location of the damage was provided.

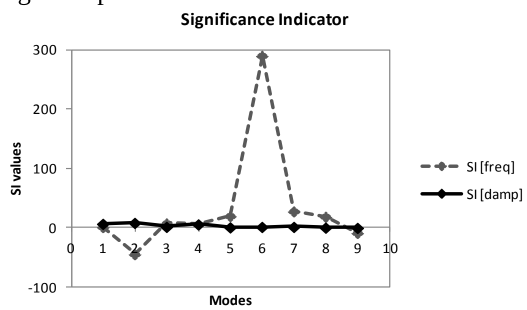

Figure 10. Damage detection by Significance Indicators.

Concerning the other non-model based methods (Levels 2 and 3), all the indexes were computed taking into account the responses in *x* and *y* directions separately. Figure 11 shows the results obtained in terms of damage location making use of *x* direction outputs. From the comparison with the undamaged configuration, it is possible to draw the following conclusions:

- the COMAC values for modal displacements pinpoints the presence of damage at position 1, whereas the COMAC for modal curvatures at positions 1 and 5;
- the SCE indicates the first node as possible damage location;
- the DIM shows no accurate results, but positions 1 and 2 seem the most affected;
- the PM for both modal displacements and curvatures identifies possible damage locations in the upper part of the chimney (nodes 4 and 5) and so do the MSCM;
- the CFM for modal curvatures highlights the presence of damage in node 5, while the CFM for modal displacements in nodes 3 and 4.

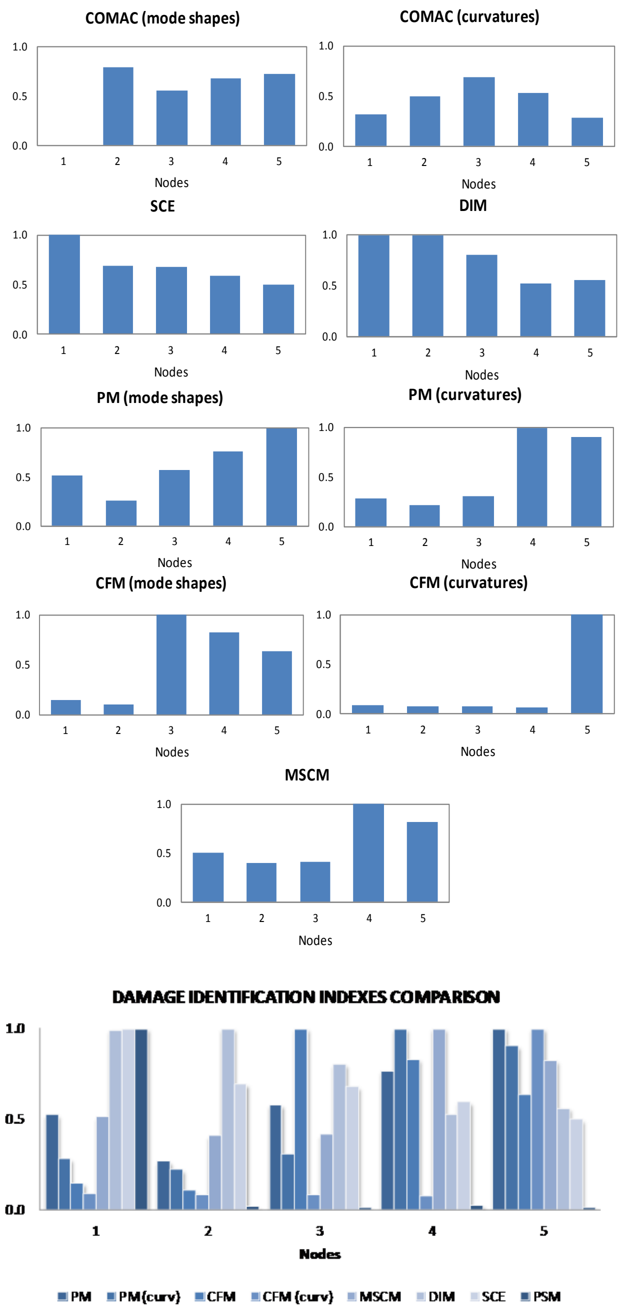

Figure 11. Damage localization by non-model based methods (x direction).

Figure 12 shows the results obtained computing the indexes from y direction outputs. From the damage analysis, the following considerations can be stressed:

- the SCE, the MSCM and the CFM for modal displacements clearly indicate the presence of damage at position 4, whereas the CFM for modal curvatures shows node 5 as possible damage location;
- the PM for modal curvatures and the MSCM values locate damage in the upper part of the chimney at both positions 4 and 5;
- the COMAC values for modal curvatures and the PM for modal displacements indicate the damage in three points, namely 3, 4 and 5;
- the COMAC values for modal displacements identify the damage at position 3, followed by nodes 4 and 1;
- the DIM gives inconclusive results.

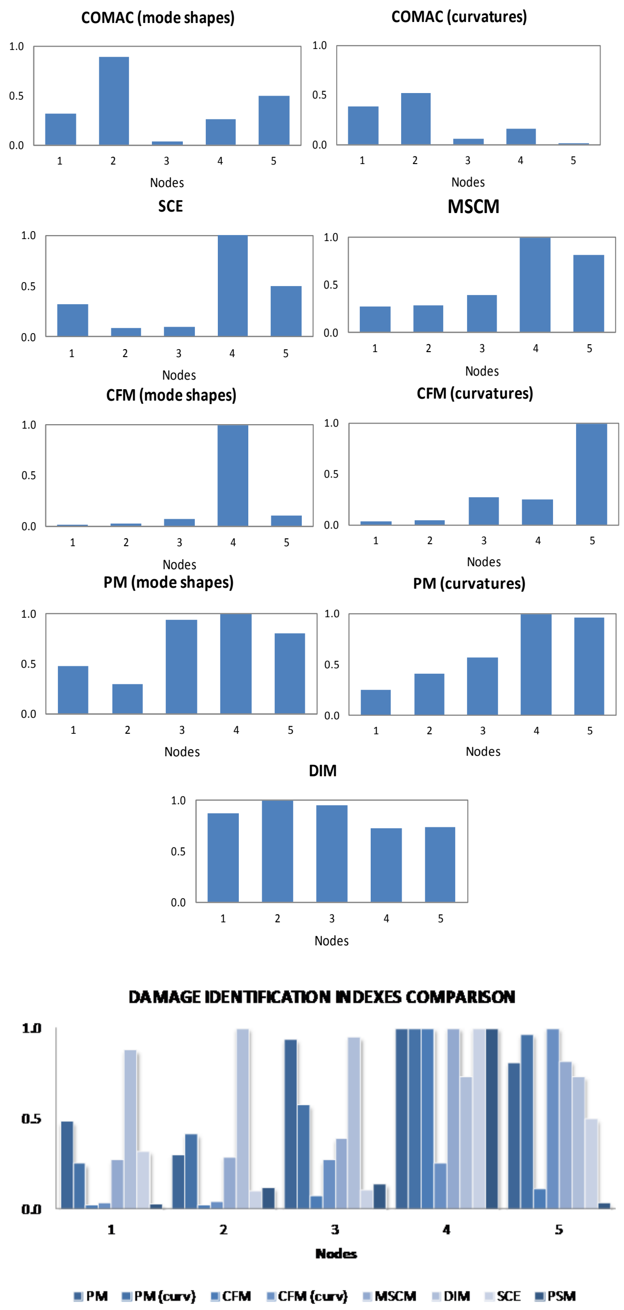

Figure 12. Damage localization by non-model based methods (y direction).

5 SUMMARY AND CONCLUSIONS

The dynamic identification of a masonry chimney was addressed in this paper. The structural response before and after rehabilitation works was analyzed in order to assess their efficiency and a dynamic monitoring was carried out with the same purpose. Taking advantage of the knowledge of both reference scenario (after repair works) and damage scenario (before repair works), a group of damage identification methods available in literature was selected and applied to the case-study in order to compare them with the spectral-based method proposed and evaluate the accuracy and reliability of all of them. The damage analysis was not an easy task for such a structure since the damage was quite widespread. In spite of this drawback, the spectral-based technique was successful in detecting and locating the parts of the structure heavily hit by damage. Furthermore, contrary to what expected at first sight, the damage affecting the upper part of the chimney proved to be heavier than the one caused by the lightening in the bottom part. Taking into account that the slenderness of the chimney increases upwards making harder to maintain its stable configuration if damage occurs in the upper part, the result seems to be reasonable. Indeed, the loss of mass due to the holes is around 4%, thus the robustness of the bottom part does not suffer from it.

As far as the other non-model based methods are concerned, the observations listed below can be made.

- As Level 1 damage identification method, the USI detected nothing else but the presence of damage.
- The COMAC provided quite good results mostly for modal displacements since each value is based on the correlation between the measured DOFs of two structural conditions and the dependence on local coordinates helps when seeking local information.
- The PM failed as likely as not because of the presence of the frequency ratio in the damage index formulation: in fact, the slight frequency shifts between damaged and undamaged conditions made the weight of the frequency ratio almost negligible and did not help in providing spatial information about the damage.
- The CFM was able to catch the damage, but just with regard to the upper part of the chimney. Being the inverse of the stiffness matrix, the measured flexibility matrix can be estimated from the mass-normalized mode shapes and frequencies, but because of the inverse proportion to the square of the modal frequencies, it is most sensitive to changes in the lower-frequency modes of the structure [15]. Since most of the changes in the dynamic behavior of the chimney involved the higher modes and these modes are the ones controlling the response of the upper part of the structure, the results obtained in terms of damage location were more than expected. Furthermore, the mass matrix change between the two structural conditions is so minor (≈4%) that the difference in the scaling factor values between both the scenarios is very small, so the use of an index based on mass-normalized mode shapes does not allow to get better results.
- The MSCM did not provide any information about the damage in the part of the chimney affected by the two holes, but just at positions 4 and 5. The reason leading to that is likely due to the formulation of the index itself. Basically, the MSCM is based on the difference between the modal curvatures of two structural conditions, but being these shifts really minor in the modes dominating the dynamic response of the bottom part of the chimney, namely the lower ones, catching the presence of damage at position 1 is practically impossible.
- The SCE provided reliable results in terms of damage localization identifying both the most affected areas.
- The DIM did not catch any accurate results; the cause is essentially due to the minor changes of the modal curvatures between the two structural conditions, as mentioned previously.

Merging all the results it is possible to conclude that moving from a damage Level 1 to a damage Level 2 is not an easy issue, especially if the damage is not limited to a small area and the changes in the modal parameters are not so evident, like in the case object of this study. Therefore, it can be noticed that the spectral-based method was more successful with respect to the other methods for the present work and this is doubtless due to the capacity of catching closely spaced modes and to the use of an index weighing the eigenvectors over the whole frequency domain, not only with respect to the resonant frequencies.

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