SHM of a Masonry Chimney after a Lightning Accident

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ABSTRACT

The paper focuses on the SHM works carried out on a historical masonry chimney located in a former industrial complex in Guimarães city centre, Portugal. The chimney was hit by a lightning in the morning of July 26th, 2012. The electrical discharge blew the chimney wall creating two significant openings. After the accident, an intervention was planned and executed to reestablish its sound structural condition.

Before and during the structural works, a SHM plan was put into practice. Several ND tests were performed aiming at evaluating the loss of stiffness and mass, as well to control the execution of the rehabilitation works. A permanent dynamic identification system was installed in the chimney and the evolution of modal properties was followed during the site works. A FE model was built and calibrated with inverse problems to the two structural conditions. Finally, all the information was merged to evaluate the effectiveness of the rehabilitations works. The paper presents detailed information about the damage, the two structural conditions before and after the intervention works and the SHM results.

INTRODUCTION

Located in the city center of Guimarães, historical town in the North of Portugal, the Chimney belongs to a former industrial complex (see Figure 1). The structure was already object of a monitoring performed by the University of Minho from November 2nd 2010 to June 26th 2011 in order to control its structural condition during the building works of the Advanced Education Center, rather close to the chimney.

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Figure 1. The Chimney and the severe openings caused by the lighting.

A campaign of topographical measurements and visual inspections was carried out detecting respectively a slight rigid rotation of the upper part of the chimney in the North-East direction and a series of slight structural cracks. Besides, it was pointed out a permanent plastic deformation affecting the upper two thirds of the structure as well as a disconnection of the top of the chimney with respect to the rest of the body, mainly due to horizontal and vertical serious cracks. Detailed information on the mentioned structural monitoring are provided in Ramos et al. [1].

The accident occurred in July 26th 2012, made the structural condition of the chimney even worse causing two further severe openings (see Figure 1) and the increasing of crack openings, so that, firstly, urgent temporary remedial works were carried out to maintain the chimney in safe condition and, secondly, an in-depth intervention was planned and executed to re-establish its healthy structural condition [2]. During this lapse of time, a detailed survey of the chimney was carried out to inspect all the anomalies, as well the dynamic response of the structure was monitored to catch changes in the modal parameters. The permanent dynamic identification system for the monitoring was also used as reference system for the Ambient Vibration Tests performed to investigate the two structural conditions.

The intervention was carried out between December 2012 and February 2013. The works included: (a) chimney consolidation through reconstruction of damaged parts, cracks closing and mortar injections, (b) chimney washing and waterproof protection.

This paper tackles the dynamic identification carried out on the chimney both before and after the rehabilitation works, the subsequent FE model updating analysis aimed at investigating the mechanical features of the constitutive materials and the SHM plan performed during the structural intervention. The obtained results are widely discussed and might reveal themselves of great help in the understanding such a structural typology quite spread over the Portugal land.

CHIMNEY SURVEY

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

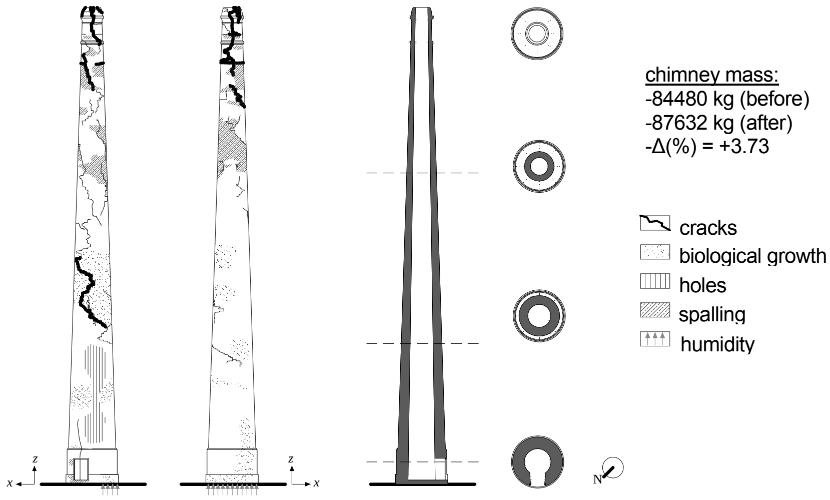

Figure 2. Geometrical survey and damage pattern in the chimney: West front, East front, sections.

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.

Damage Pattern

The previous monitoring had already highlighted the structural condition of the Chimney: slight rigid rotation of the upper part in the North-East direction, several structural cracks, permanent plastic deformation affecting the upper two thirds of the structure and severe disconnection of the top of the chimney with respect to the rest of the body due to horizontal and vertical cracks.

In addition to this, the chimney was hit by a lightning in the morning of July 26th 2012 since the lightning rod located on the South-East side of the structure was in poor condition or cut at 6 m high from the ground floor. The electrical discharge blew the chimney wall in the side right opposite to the lightning rod creating two significant holes: one at 3 m height from the ground floor (close to the chimney opening) and the other one at 6 m height (see Figures 1-2). The masonry bricks were totally exploded and fell down on surrounding roofs circa 15 m far from the chimney. The accident did not worsen the permanent deformation of the chimney, but it caused an increasing of the existent vertical cracks width of 3 mm. Furthermore, due to the lack of maintenance, the damage survey that took place in November 2012 also recorded spotted spalling, widespread biological growth and presence of humidity in the bottom part of the chimney (see Figure 2).

DYNAMIC IDENTIFICATION OF THE CHIMNEY

It is widely known that parameters such as eigenfrequencies, mode shapes and damping ratio are the 'fingerprints' of a structure and their change implies a change in the global dynamic behavior of the structure itself [3]. Indeed, for the purpose of studying the dynamic response of the Chimney and catching the evolution of its modal parameters, output-only identification techniques were carried out using ambient excitations from wind and traffic as operational conditions. The main goals were comparing the response of the chimney with the two different structural configurations and evaluating the efficiency of the rehabilitation works.

Test Setups

Before proceeding to the operational modal analysis, a preliminary FE dynamic analysis was addressed to the optimization of the sensors layout and the choice of the sampling frequency (200 Hz) and the total sampling time (10 minutes) to set for the data acquisition. The first system identification analysis was performed in November 2012 and the second one in February 2013. The scaffolding for the rehabilitation works was used to access the measuring points.

The dynamic acquisition system was composed by 12 uniaxial piezoelectric accelerometers and the 4 channels DAQ system was connected to a laptop by an USB cable. To record the accelerations in 12 measurements points, 2 test setups, 3 levels for each setup and 4 accelerometers for each level were used, keeping the ones on the top of the chimney as reference (see Figure 3).

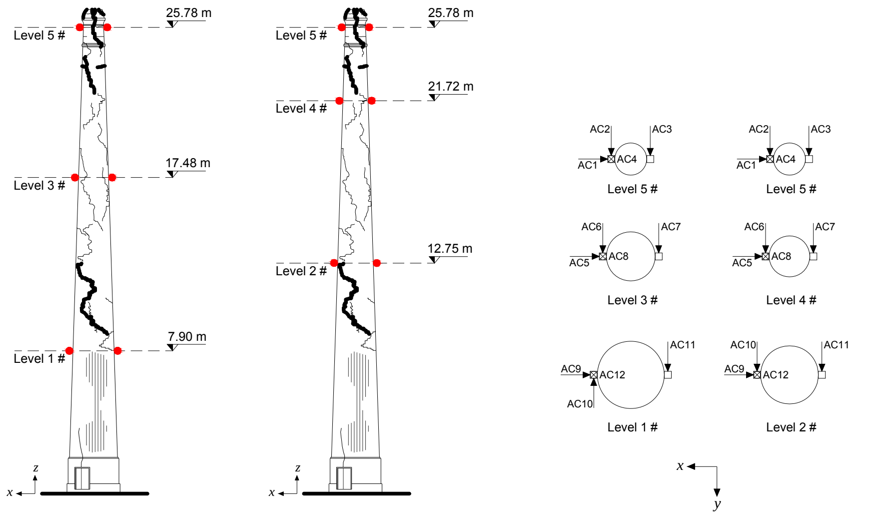

Figure 3. Test setups and measuring points: front view and top view schemes.

Dynamic Identification Before and After Rehabilitation Works

In order to estimate the modal parameters related to the structural conditions before and after rehabilitation works, two different identification techniques were performed: the Enhanced Frequency Domain Decomposition (EFDD) [4] and the Stochastic Subspace Identification (SSI) [5], implemented in ARTeMIS [6]. Both methods were able to identify 10 mode shapes for the initial configuration (before) and 9 mode shapes for the final configuration (after). Table I summarizes the results obtained in terms of frequencies and damping ratios by the SSI method (Principal Component).

TABLE I. DYNAMIC IDENTIFICATION RESULTS (BEFORE AND AFTER)

Mode	Before ω [Hz]	Before CV_ω [%]	After ω [Hz]	After CV_ω [%]	Δ_ω [%]	Before ξ [%]	Before CV_ξ [%]	After ξ [%]	After CV_ξ [%]	Δ_ξ [%]
1	1.015	0.26	1.018	0.18	+0.30	0.48	63.53	2.53	2.43	+429.6
2	1.15	0.08	1.10	0.05	–4.09	0.95	20.91	3.30	6.25	+248.3
3	3.20	0.75	3.39	0.26	+5.90	0.91	29.18	1.36	8.60	+49.43
4	3.65	0.18	3.73	0.33	+2.11	0.90	15.07	1.96	6.58	+117.6
5	6.39	0.50	–	–	–	0.75	45.42	–	–	–
6	7.32	0.24	7.79	0.21	+6.51	0.84	39.77	1.09	10.77	+30.26
7	8.81	0.05	10.29	0.03	+16.85	0.58	9.79	0.91	24.17	+56.44
8	11.40	0.07	12.51	0.32	+9.74	1.24	31.92	1.84	1.94	+47.91
9	12.31	0.22	13.37	0.38	+8.61	1.46	16.22	1.58	24.21	+7.87
10	13.93	0.19	13.53	0.28	–2.87	2.56	33.33	2.29	39.97	- 10.62
Average	–	0.40	–	0.23	+7.95*	1.21	27.31	1.87	13.88	+123.43*

*Average value calculated only with positive differences and for comparable modes

Taking into account the comparable modes, it is evident that the higher stiffness gained thanks to the rehabilitation works led to an overall increase in the frequency values of the structure, quite slight for the lower modes whereas more significant for the higher modes (except the 2nd and the last mode that suffered a frequency decrease). Furthermore, granted that for the second campaign there was a better estimation, as the Coefficients of Variation (CV) shows, it needs to be stressed an important increase in the damping ratio of the final structural configuration with respect to the previous one.

Regarding the mode shapes comparison between the two structural conditions, it is possible to remark a good fit in terms of mode configuration as well as a quite fine correlation in terms of MAC values (see Figure 4).

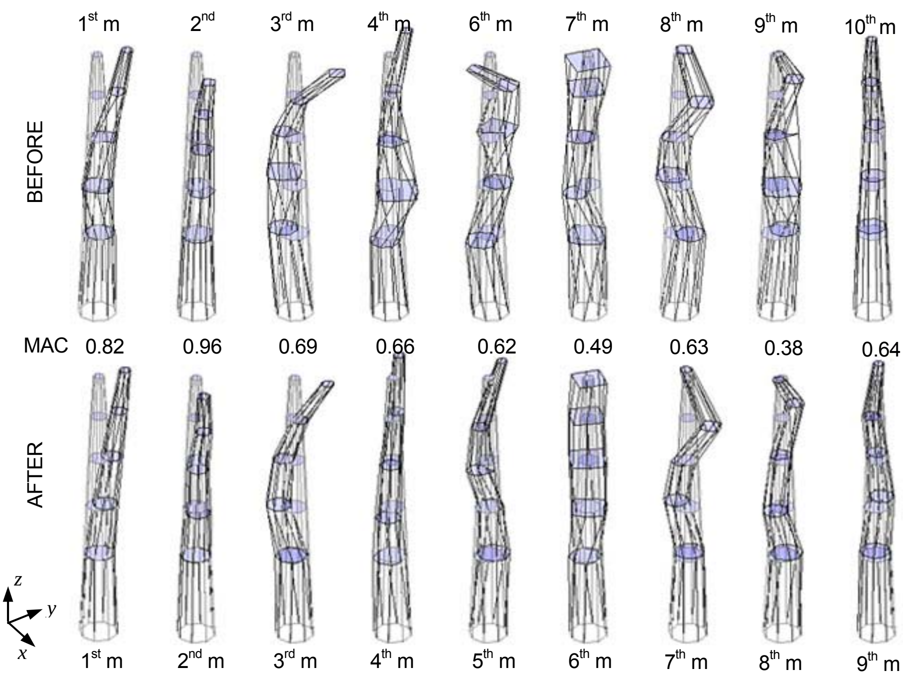

Figure 4. Experimental mode shapes and MAC values before and after rehabilitation works.

Analyzing the modal displacements in detail, local effects essentially due to the existence of both holes and severe cracks affecting the upper part of the chimney can be observed before the rehabilitation works, while a monolithic behavior characterizes the structure after the intervention. In fact, the higher changes in terms of frequency content are recorded for modes 7, 8 and 9, exactly reflecting the local effects attenuation that is also evident for the first modes even though, in this case, the frequency content does not change significantly.

Merging all the results, one can conclude that: (a) the presence of damage changed the dynamic behavior of the structure with respect to the original one, particularly as far as the higher modes are concerned; (b) the chimney suffered an in-depth strengthening intervention that led to a change in the mass and stiffness matrices causing an increase in damping as a consequence; and (c) finally, the rehabilitation works can be considered efficient.

MODEL UPDATING AND STRUCTURAL ASSESSMENT

Based on the dynamic features extracted from the experimental data, a FE Model Updating was carried out in order to investigate the structural behavior under the two specific conditions and weigh the real efficiency of the intervention. The task was accomplished by the FEMTools software [7] that uses an iterative model updating method based on a sensitivity formulation leading to identify sensitive and insensitive areas of a structure for a given responses and parameters combination. Taking advantage of this tool, a suitable selection for model updating concerning both responses and parameters was possible.

The FE model built to simulate both the structural conditions was a tapered 3D shell element model characterized by structured triangular meshes. Initial values equal to 1.0 GPa, 0.2 and 1600 kg/m^3 were respectively fixed for the Young's modulus, the Poisson coefficient and the mass density, while an average decreasing thickness was assigned to each of the 5 levels in which the chimney was split (0.60 m, 0.49 m, 0.42 m, 0.33 m, and 0.23 m).

As initial step to tune analytical and experimental data, a correlation analysis marked by spatial correlation (node-point pairing) and mode shapes correlation (mode shapes pairing) was performed allowing to compute a matrix of Modal Assurance Criteria (MAC) [8] coefficients. Additionally, in order to overcome the lack of measured DOFs with respect to the ones of the FE model, a Pseudo Orthogonality Check (POC) was carried out reducing the FE mass matrix down to the set of test DOFs. Afterwards, the sensitivity analysis supported the selection of parameters (E) and responses (measured resonance frequencies) for the modal-based model updating. The new values were obtained following the Bayesian estimation and setting both the correlation coefficients (EPS1 and EPS2) to 0.001% [9].

Aiming at avoiding unrealistic results, boundary constraints were applied to the updating parameter. Table II shows the starting and updated values before and after the rehabilitation works. Analyzing the final results, it is possible to observe significant changes of the E Modulus in the 1st , 3rd and 4th level of the chimney, particularly with an increase in the 1st and 4th level and an unexpected decrease in the 3rd level.

TABLE II. UPDATED ANALYSIS BEFORE AND AFTER REHABILITATION

Updating Parameters	Before Initial Value	Before Final Value	After Initial Value	After Final Value	Difference	Δ(%)
E_1 [GPa]	1.00	1.06	1.00	1.25	+0.19	+17.7
E_2 [GPa]	1.00	1.08	1.00	1.01	–0.07	–6.65
E_3 [GPa]	1.00	2.52	1.00	0.97	–1.56	–61.8
E_4 [GPa]	1.00	0.39	1.00	1.18	+0.79	+205
E_5 [GPa]	1.00	0.84	1.00	0.85	+0.01	+1.58

*Each of the 5 updating parameters corresponds to one of the 5 levels bounded by the measurement points.

Table III shows the updated frequencies and MAC values used in pairing and comparing mode shapes for both the structural conditions. Unlike the frequency pairing, the matching of mode shapes was a difficult task. The weak correlation that marks the MAC values might be linked with difficulties to model the cracks and the holes in the chimney for the damage condition and need of modeling the permanent deformed shape of the chimney in the consolidated condition. Further updating analysis is needed to complete this task.

TABLE III. UPDATED FREQUENCIES AND MAC VALUES (BEFORE AND AFTER)

Mode Shape	Before ω_{exp} (Hz)	Before ω_{an} (Hz)	Before Δ_ω (%)	Before MAC	After ω_{exp} (Hz)	After ω_{an} (Hz)	After Δ_ω (%)	After MAC
1	1.015	1.01	–0.49	0.63	1.018	1.02	+0.20	0.61
2	1.15	1.15	–	0.72	1.10	1.10	–0.18	0.72
3	3.20	3.21	+0.31	0.72	3.39	3.39	–	0.86
4	3.65	3.64	–0.27	0.66	3.73	3.72	–0.27	0.84
5	7.32	7.29	–0.41	0.41	7.79	7.79	–	0.55

STRUCTURAL HEALTH MONITORING

During the structural consolidation works the chimney was monitored by four acceleration transducers placed at the top, namely at Level 5# (see Figure 3). The aim was to follow the evolution of the natural frequencies while the reconstructions works were carried out. Especially attention was paid during reconstruction of masonry panels in the areas where the lightning explosion occurred to seek if the reconstruction would change significantly the dynamic response.

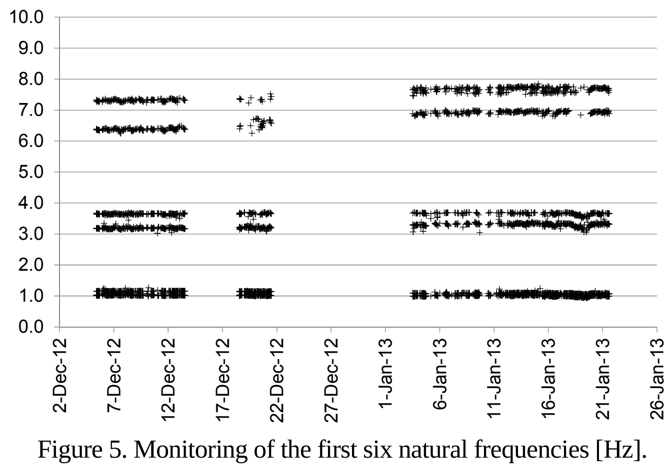

Figure 5. Monitoring of the first six natural frequencies [Hz].

The results of the first six natural frequencies are presented in Figure 5. As can be seen, only the upper natural frequencies suffer significant changes due to the structural consolidation works, while the first two frequencies close to 1 Hz didn't change is values.

CONCLUSIONS

The paper presents the SHM works carried out on a historical masonry chimney located in a former industrial complex in Guimarães, Portugal, after a lightning discharge blew the chimney wall creating two significant openings.

With the works carried out so far it is possible to conclude that (a) the presence of damage changed the dynamic behavior of the structure with respect to the original one, particularly as far as the higher modes are concerned; (b) the chimney suffered an in-depth strengthening intervention that led to a change in the mass and stiffness matrices; and (c) finally, the rehabilitation works can be considered efficient.

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