Original Article

Ambient vibration testing and seismic analysis of a masonry chimney

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ABSTRACT At the end of the nineteenth and the beginning of the twentieth century there was a considerable development in Portugal, characterized by the flourishing of many industrial plants. Brick masonry chimneys represent some of the most interesting elements of the industrial architectural heritage of that time. This article shows the study and analysis of a chimney from a former ceramic factory that is now part of a cultural and leisure Public Park located near Porto, Portugal. The focus in this work is given on the detailed *in situ* survey of the chimney involving geometrical characterization, visual inspection, with damage

registration, and structural and material assessment based on *in situ* dynamic tests. This survey allowed assessing the *in situ* mechanical characteristics of the chimney and to construct a realistic numerical model to evaluate the seismic vulnerability of the chimney. Two different approaches regarding the chimney damage state were followed for the calibration of the numerical model. The models from both approaches were afterwards subjected to accelerograms matching the chimney site conditions and the responses were analysed and compared. The importance of a good mechanical characterization of the materials involved is underlined in this analysis.

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INTRODUCTION

Most of the Portuguese old building heritage, from important structures like bridges, palaces, churches and monasteries, to ordinary urban or rural buildings and industrial plants, is made of different types of masonry. They all stand as valuable examples of the architecture and construction techniques of the past that should be preserved. The current practice that privileges the construction of new buildings instead of the rehabilitation of old buildings is largely responsible not only for the loss of important building heritage, but also for the continuous ‘cooling of relations’ between people and old constructions. Industrial architecture is in this point a good example. In Portugal there are a large number of old industrial plants as the result of the considerable industrial development of the end of the nineteenth and the beginning of the twentieth century. Many of these plants, which imported architectural concepts, essentially from England where the industrial revolution had a great impact, are today unused and exposed to strong degradation, being in ruins or exhibiting significant damage. Brick masonry chimneys probably represent the most valuable architectural symbols of this industrial period.

Nowadays engineers have the adequate computational and technical resources to perform sustainable rehabilitation interventions on these types of structures. Furthermore, structural assessment of masonry structures, namely the evaluation of the seismic vulnerability based on numerical modelling, is frequently used and seen as a powerful tool for *decision making* (Almeida, 2000). However, sometimes the material/structural characterization is considered to play a secondary role in the process; this phase is skipped, as the lack of proper codes and/or material knowledge make difficult the characterization of the masonry properties, therefore standard material properties are adopted instead of *measuring* them *in situ*.

This article will focus on the importance of constructing realistic numerical models through a good characterization of the mechanical properties of the materials using *in situ* assessment or testing. The object of study is a brick masonry chimney with circular cross section (see Figure 1), located near Porto, Portugal. Originally built to be part of a ceramic factory, it was converted into a ‘sculpture’ 10 years ago and serves to remind us of the industrial heritage. This work describes the detailed *in situ* survey of the chimney, which involved geometrical characterization through three-dimensional laser scanning, visual inspection with damage registration, and structural and material assessment through *in situ* dynamic identification. This survey allowed assessing the *in situ* mechanical characteristics of the chimney and to construct a realistic numerical model to evaluate the seismic vulnerability of the chimney. Two different approaches regarding the

Figure 1: General view of the chimney.

chimney damage state were followed for the calibration of the numerical model. The models from both approaches were afterwards subjected to accelerograms matching the chimney site conditions and the responses are analysed and compared at the end.

GEOMETRICAL ASSESSMENT

When performing a numerical analysis, the first data to be considered are the structural geometry. In the case of old structures, this information is frequently missing, having been lost, or not available or even no geometrical assessment exists. Although topographic measurements were made in the past to control the deformations of the chimney, no information existed concerning its geometry. Following this purpose, the chimney's global geometry was assessed using laser scanning technology operated by a private company working in this field. This technology may also allow monitoring the structure in the future. The result of laser scanning is a very dense point cloud, with each point containing the information on the three coordinates of a particular point on the structure (see Figure 2). However, such large amounts of data are unsuited for the construction of a finite element mesh. Therefore, the scanning results were also provided in the form of vertical and horizontal cuts, allowing an easier data manipulation and, at the same time, a considerable reduction on the number of points to build the finite element mesh.

The laser scanning allowed the measurement of the whole volume of the chimney, in particular: the height, the decrease of the external and internal diameters along the height (see Figure 3, where t indicates the thickness of the chimney's wall) and the flexural deformation, which was quite perceptible from a direct view. The finite element mesh was built based on the exterior geometry given by the first laser scanning, and on the average thickness measured by the superposition of the inside and outside point clouds

Figure 2: Point cloud of the exterior scan.

Figure 3: Vertical cut on the chimney structure – different thickness values (t).

from the laser scanning on the chimney. The flexural deformation measured by the laser scanning, a displacement of 24 cm at the chimney top in the west direction (see Figure 4), was considered in the mesh. The chimney height measured by the laser scanning (39.90 m) was increased in the numerical model by 1.50 m. That part corresponds to the chimney below the soil that was partially exposed and surrounded by a thin reinforced concrete wall 10 years ago (see Figure 5).

With a total height of 41.40 m and an external base diameter of 3.70 m, the chimney has a slenderness ratio (height over base diameter) of approximately 11; normal slenderness ratios on these kinds of structures are between 8 and 11 (Pinho and Duarte, 2000). With the geometry well defined in a .dxf file, the finite element mesh, composed by eight nodes tridimensional elements, was developed with the pre and post-processing software *GiD* (GiD, 2006). Finally, the mesh was completely built and introduced in the structural analysis software *Visual Cast3m* (CEA, 2003) (see Figure 6).

Figure 4: Horizontal cut on the chimney's base (red) and top (blue), with indication of the maximum top displacement.

Figure 5: Execution of a small concrete wall (10 years ago).

VISUAL INSPECTION

Introduction

As a vital step in the process of the evaluation of the chimney's state, either for the numerical simulation or for the future rehabilitation process, a visual inspection of the structure took place. This procedure allows the characterization of the structural elements and materials and identifying the critical and/or damaged zones of the structure. During the inspection some brick and mortar samples were taken to proceed to chemical/material identification. The chimney presented 14 steel confining rings distributed along the height.

Figure 6: General view of the finite element mesh.

Damage identification

With the help of a crane, the chimney was surveyed along its height. Different damage states were observed and properly documented through photography and supported by drawings provided by the laser scanning. The visual inspection also identified the flexural deformation (Figure 7) detected by the laser scanning and already referred to in the section ‘Geometrical Assessment’.

Two types of brick masonry were identified: (Masonry type 1 (M1) – Figure 8 and Masonry type 2 (M2) – Figure 9), indicating two different periods of construction. This information, missing in the municipal archives, was confirmed by local people. The line dividing the two construction periods is located 26 m (Figure 10) above the ground.

According to the visual inspection, different zones were also identified inside each category M1 and M2 based on the brick and/or mortar degradation state, allowing the identification of a total of six material types (Figure 11). Figure 12 shows photographs of the different material types. Major cracks were localized and are represented in white in Figure 11. As for the steel rings, they presented important levels of corrosion (Figure 13). Moreover, some of these rings were not properly closed and there were opened cracks on

Figure 7: Chimney deformed shape.

Figure 8: Masonry (type I – Chimney's basis).

the masonry crossing them (Figure 14). Therefore, they were not considered in the numerical model.

***IN SITU* DYNAMIC TESTS**

Introduction

Material and structural characterization of masonry structures is a key issue when analysing its behaviour through numerical modelling. Local testing, as coring or flat-jack

Figure 9: Masonry (type 2 – Chimney's top).

Figure 10: Two material zones.

testing (Binda *et al*, 2002) can provide very interesting data, namely to the characterization of the masonry nonlinear behaviour. However, they provide mostly local information (Miranda *et al*, 2009), and several tests in different zones should be made in order to characterize the structure properly. In the case of the chimney, these tests could only be made close to the basement, as no scaffolding existed to assess higher areas of the chimney. Thus, these procedures would not allow characterizing the masonry of the different identified material types. The modal identification using ambient vibration was

Figure 11: Material and damage identification – north, west, south and east view.

Figure 12: Different types of material identified, in accordance with Figure 11 – (a) Material A; (b) Material B; (c) Material C; (d) Material D; (e) Material E; (f) Material F.

used instead. Provided the mass of the structure is accurately estimated, this *in situ* testing technique gives good results concerning the identification of the dynamic properties of the structure, namely natural frequencies, mode shapes and damping coefficients. These results are obtained by modal identification of an output-only system, that is, without knowing the excitation of the structure. The stiffness estimated for the different structural material corresponds only to the elastic branch, for the *in situ* conditions, and it is determined by running a modal analysis and comparing the numerical to the experimental response. Following a trial and error approach, convergence can be reached in few steps and different stiffness values can be found for the different material types.

Test setup

The test data were acquired with *LabVIEW* (Arêde *et al*, 2004) and using four uniaxial piezoelectric accelerometers (Figure 15) with sensitivity of 1000mV/g, frequency range between 0.5 Hz and 2000 Hz and measurement range between -5 g and 5 g, connected to

Figure 13: Inactive corroded steel ring.

Figure 14: Opened crack crossing a steel ring.

a four channel USB dynamic signal acquisition module (Figure 16) with 24 bit resolution. To avoid the introduction of noise in the wire connections, plastic sleeves were introduced (Figure 17).

A preliminary numerical modal analysis (Lopes, 2007) showed that the main vibration directions were determined by the opening that exists at the bottom of the chimney to access the inside of the structure (Figure 18), located at the northeast direction, and not by the existing flexural deformation. This was confirmed afterwards by the *in situ* dynamic measurements. Therefore, the test setup was decided based on this previous analysis, and the accelerometers were placed along the two main directions (Figure 18 and Figure 19). Figure 19 shows the position of the accelerometers on five levels, dividing the chimney into five equal parts, approximately 8 m long each. Each of the nine setups used two fixed accelerometers at the top as fixed, marked in black in Figure 19, and two others in each one of the grey positions marked in Figure 19.

Figure 15: Accelerometers fixation.

Figure 16: Data acquisition system.

In order to obtain torsional and circumferential modes, the setups included accelerometers in the xx and yy directions on both sides of the chimney (Figure 18). The accelerometers were bolted on L shaped steel pates and then fixed on the chimney wall (Figure 15).

According to the literature (Neves, 2004), the minimum acquisition time in order to well characterize the lower natural frequency should be given by the following equation:

$$T \geq \frac{1000}{f_{\min}} \quad (1)$$

The preliminary modal analysis estimated the value of 0.65 Hz for the first natural frequency. As a result, the recommended acquisition time was about 27 min. Owing to the

Figure 17: Protected connections.

Figure 18: Principal horizontal modal directions: xx and yy .

limitations in the use of the crane, and to the limitation of the total testing time, each setup acquired data for only 15 min. This was possible because the procedure to transform the time domain data in frequency domain data in *ARTEMIS* software (SVS, 1999–2006) used Hanning windows with a 66.7 per cent of overlapping time, which makes almost the 27 min required.

Test results

The acquired data were properly decimated and filtered using *Matlab* (MathWorks, Inc., 2007). The procedure for the filtering followed the following steps:

- baseline correction;
- signal decimation to a frequency of 200 Hz;
- application of low-pass filter at the frequency of 80 Hz, corresponding to 80 per cent of the Nyquist frequency;
- transformation to the frequency domain with a high-pass integration filter at 0.3 Hz and application of Hanning windows with 66.7 per cent overlapping.

Figure 19: Test setups.

Figure 20: Enhanced frequency domain decomposition peak picking.

Figure 21: Example of a normalized auto correlation function.

Then the *in situ* frequencies were identified using *ARTEMIS* software (SVS, 1999–2006) and the *Enhanced Frequency Domain Decomposition Peak Picking (EFDD)* procedure, as shown in Figure 20.

The *EFDD* is a frequency domain method for modal identification, included in the software *ARTEMIS*, which makes the *Singular Value Decomposition (SVD)* of the spectral matrix, giving a set of auto spectral density functions, each of them equivalent to a Single Degree of Freedom (SDOF) system in correspondence with the structure’s vibration modes (Brincker *et al*, 2001b). Using an inverse Fast Fourier Transform (FFT), the auto

Table 1: Modal identification results

Mode	Frequency [Hz]	$\sigma_{\text{Frequency}}$ [Hz]	Damping Ratio [%]	$\sigma_{\text{Damping Ratio}}$ [%]	Comment
EFDD Mode 1	0.608	0.00347	2.391	0.2678	BENDING XX
EFDD Mode 2	1.878	0.00540	1.256	0.3716	BENDING YY
EFDD Mode 3	1.956	0.01048	1.428	0.2560	BENDING XX
EFDD Mode 4	4.318	0.01062	0.858	0.4107	BENDING YY
EFDD Mode 5	4.532	0.01629	0.939	0.3819	BENDING XX
EFDD Mode 6	7.674	0.01582	0.721	0.1182	BENDING YY
EFDD Mode 7	7.950	0.01605	0.628	0.0968	BENDING XX
EFDD Mode 8	11.350	0.03212	0.691	0.1609	BENDING YY + TORSION
EFDD Mode 9	11.960	0.02568	0.848	0.0724	BENDING XX + TORSION
EFDD Mode 10	15.670	0.03326	0.641	0.1634	BENDING YY + TORSION
EFDD Mode 11	16.050	0.03431	0.526	0.2176	BENDING XX + TORSION
EFDD Mode 12	17.140	0.03981	0.604	0.0902	TORSION
EFDD Mode 13	19.720	0.04122	0.360	0.1550	BENDING YY + TORSION
EFDD Mode 14	20.440	0.03702	0.586	0.2109	BENDING XX + TORSION
EFDD Mode 15	23.390	0.05149	0.685	0.0494	TORSION
EFDD Mode 16	24.680	0.01291	0.057	0.0048	BENDING XY

spectral density functions are transformed back to the time domain, and free decay functions corresponding to the auto correlation functions of the SDOF system are obtained (Brincker *et al*, 2001b) (see Figure 21). From these functions, natural frequencies and damping coefficients are assessed.

The mode shapes corresponding to the natural frequencies of the structure are obtained from the singular vectors given by the *SVD* (Brincker *et al*, 2001a). The main results of the modal identification are shown in Table 1.

NUMERICAL MODELLING

Introduction

After collecting all the *in situ* relevant data and constructing the geometrical model of the chimney, a fitting process was used to identify the mechanical characteristics of the materials. In particular, two different sets of mechanical characteristics were considered and calibrated to fit the experimental results of the dynamic *in situ* measurements: *Model 1*, considering just one type of material for the whole chimney; *Model 2*, considering different materials for the cracks and for the different material types (A–F – Figure 22) identified during the visual inspection and properly documented in Figure 11.

This calibration was done by fitting the numerical frequencies and mode shapes to the *in situ* ones through the tuning of the Young modulus (Silva *et al*, 2006). The quality of the fitting was measured not only by the frequency error, but also through the MAC coefficient (Caetano, 1992), given by the following equation:

$$MAC = \frac{(\tilde{\varphi}_j^T \cdot \varphi_k)^2}{(\tilde{\varphi}_j^T \cdot \tilde{\varphi}_j) \cdot (\varphi_k^T \cdot \varphi_k)} \quad (2)$$

where σ_k and σ_j are a numerical and an experimental vibration mode, respectively. The MAC coefficient gives values from 0 to 1; values above 0.8 denote a good fit between the two modes.

Figure 22: Identification of the different materials considered in Model 2: (a) +x view; (b) -y view.

Table 2: Dynamic parameters for Model 1 and Model 2

Experimental modes		Numerical modes							
		Model 1				Model 2			
Modes	Frequency (Hz)	Modes	Frequency (Hz)	Error (%)	MAC	Modes	Frequency (Hz)	Error (%)	MAC
1	0.608	1	0.571	6.086	0.941	1	0.606	0.329	0.955
2	1.878	4	1.921	2.290	0.936	4	1.922	2.343	0.942
3	1.956	3	1.913	2.198	0.923	3	1.893	3.221	0.920
4	4.318	-	-	-	-	6	4.248	1.621	0.808
5	4.532	5	4.344	4.148	0.928	5	4.199	7.348	0.905
6	7.674	7	7.848	2.267	0.974	9	7.830	2.033	0.900
7	7.950	8	7.871	0.994	0.963	8	7.740	2.642	0.914
8	11.350	10	11.885	4.714	0.616	12	11.528	1.568	0.913
9	11.960	11	11.913	0.393	0.683	13	11.693	2.232	0.962
10	15.670	14	16.627	6.043	0.540	14	16.113	2.827	0.448
11	16.050	13	16.609	3.483	0.406	15	16.330	1.745	0.718
12	17.140	16	19.263	12.386	0.886	17	17.182	0.245	0.918
13	19.720	18	21.839	10.745	0.830	18	20.974	6.359	0.869
14	20.440	17	21.779	6.551	0.728	19	21.389	4.643	0.802
15	23.390	19	26.660	13.980	0.894	20	24.384	4.250	0.929

Calibration of models based on modal analysis

The calibration of the two numerical models, Model 1 and Model 2, was made with the objective of maximizing the MAC values for as much modes as possible and, at the same time, of minimizing the differences of the corresponding frequencies. The results of the calibration of both models are presented in Table 2. In general, it was possible to achieve higher MAC values for a higher number of modes in the case of Model 2. In most of the cases the differences on the frequencies were also smaller for Model 2.

The Young modulus obtained for Model 1 and Model 2 are shown in Table 3. In both models, the Poisson ratio was 0.20 and the density 1650 kg/m^3 (Pinho and Duarte, 2000).

In Figure 23, the ninth mode shape is compared for Models 1 and 2, showing in blue the zero reference line, in dashed red the experimental mode shape and in green the

Table 3: Young modulus obtained for Model 1 and Model 2

Model 1		Model 2	
Material	E (GPa)	Material	E (GPa)
A	1.43	A	1.80
B		B	1.60
C		C	1.80
D		D	1.00
E		E	1.40
F		F	0.60
Cracks		Cracks	0.30

Figure 23: Ninth experimental mode (dashed red) versus numerical mode (green): (a) Model 1; (b) Model 2.

numerical mode shape. The results show how Model 2 is much more effective reproducing torsional-bending effects, in comparison to Model 1. The consideration of cracks in Model 2 is most likely responsible for this effect.

Seismic analysis

After calibration, both models were subjected to artificially ground accelerograms (Vanmarcke *et al*, 1969) for seismic actions type 1 (see Figures 24 and 25) and type 2 (see Figures 26 and 27), in accordance to EC8 (EN 1998-1, 2004) and the site conditions (Cansado Carvalho, 2007). The horizontal components were taken equal to 100 per cent in the xx direction and to 30 per cent in the yy direction. The vertical component was also considered in accordance to EC8 (EN 1998-1, 2004), that is, with 90 per cent of the xx acceleration.

The power spectra of each of the generated accelerograms (Figure 25 and Figure 27) do not have considerable peaks around the first frequency of the chimney (≈ 0.6 Hz); for the type 1 accelerogram the main peaks are very close to 2.0 Hz, and for the type 2 accelerogram the main peaks are slightly above 4.5 Hz, although some peaks are found close to 2.5 Hz.

Figure 24: Artificially generated accelerogram for seismic action type I.

Figure 25: Power spectrum of the type I accelerogram.

Figure 26: Artificially generated accelerogram for seismic action type 2.

Figure 27: Power spectrum of the type 2 accelerogram.

Figure 28: Comparison of the results of the seismic analyses for seismic action type I.

The analyses were made using the Newmark time integration algorithm within the software *Visual Cast3m* (CEA, 2003), considering $\gamma = 1/2$ and $\beta = 1/4$ (Hilbert *et al*, 1977). The integration step Δt was chosen based on the value of the higher frequency likely to be excited (f_m), in this case, f_m is approximately 10 Hz; Δt was taken equal to 0.01 s, as the recommended value is $\Delta t \leq 1/(f_m \times 10)$ (Guedes, 1997). A Rayleigh damping matrix was adopted and tuned for the damping values obtained in the *in situ* tests for the third and sixth modes (see Table 1). The maximum results of the seismic analysis are presented in Table 4, being σ_{11} and σ_{33} the maximum and the minimum principal stresses.

The deformed shapes for the maximum top displacement and the patterns for the maximum principal stresses are shown in Figure 28 and 29 for the two types of seismic actions. The results of the seismic analyses using the two models clearly show that the most critical area, that is the area where the maximum tensile stresses happen (red colour on the σ_{11} patterns in Figure 28 and 29), is not close to the basement, but to the top, denoting, most probably, a higher participation of the second and (or) third horizontal

Table 4: Seismic analyses results

d_{max} (cm)	Seismic action type 1			Seismic action type 2			
	$\sigma_{11,max}$ (MPa)	$\sigma_{33,min}$ (MPa)	$\sigma_{33,base}$ (MPa)	d_{max} (cm)	$\sigma_{11,max}$ (MPa)	$\sigma_{33,min}$ (MPa)	$\sigma_{33,base}$ (MPa)
Model 1 11.15	0.40	-1.19	-0.87	7.01	0.40	-0.97	-0.77
Model 2 9.56	0.51	-1.24	-0.94	6.92	0.52	-1.11	-0.91

Figure 29: Comparison of the results of the seismic analyses for seismic action type 2.

mode shape in the xx direction on the seismic response. Moreover, in the case of this chimney, the consideration of zones with different levels of damage in the numerical model (Model 2), namely cracks, is responsible for an increase of approximately 20 per cent on the maximum principal stresses. Furthermore, stress patterns obtained for both models are different, with more stress concentration zones for Model 2, namely around the cracks. As for the displacements, the differences between Model 1 and Model 2 are smaller, with around 10 per cent higher maximum top displacements for Model 1. However, Model 2 shows higher displacements on the second third of the chimney, reflecting the different distribution of stiffness along the chimney height.

CONCLUSIONS

The numerical analysis of an existing structure is a complex task that requires *in situ* investigation to properly assess the actual geometrical and mechanical characteristics of the materials. These data are essential for any sustained realistic numerical study. This article shows the methodology applied to the seismic analysis of a brick masonry chimney, namely the procedures followed to characterize the geometry and the damage state of the structure, through visual inspection and *in situ* dynamic identification. Because these data are critical to describe properly the shape and the mechanical properties of the structure, these steps preceded the construction of the numerical model.

The modal identification using ambient vibration proved to be a powerful tool for the characterization of the dynamic properties of this structure, allowing the experimental identification of 15 vibration modes. The *EFDD* method used showed a very good efficiency identifying natural frequencies, mode shapes and damping coefficients, while at the same time attested to its user friendliness.

The data collected through the inspection and the *in situ* dynamic testing gave origin to two different numerical models; a first one considering the chimney made of a single material (Model 1), and a second model considering different materials according to the different levels of observed damage (Model 2). The calibration results were very satisfying, as the results provided low values for frequency errors and high MAC values, for both models. Although Model 1 showed a good capacity for the reproduction of the dynamic behaviour of the chimney, Model 2 proved how important is the consideration of material damage in these problems is, as the results obtained with this model were, generally, much better than the ones given by Model 1. This conclusion is underlined when considering the torsional-bending modes, as shown in Table 2 and Figure 23.

The results of the seismic analyses using both models clearly show that, in the case of this chimney, the consideration of the model defined by different materials (Model 2), namely cracks, is responsible for an increase of approximately 20 per cent on the maximum principal stresses and a decrease of around 10 per cent on the maximum displacements. Furthermore, stress patterns obtained for both models are quite different, with more stress concentration zones for Model 2, namely around the cracks.

As a final conclusion, these results show that it is important to accurately evaluate the mechanical characteristics of the materials to properly assess the response of a structure using numerical models. The poor detailing of this assessment may result on an underestimation of the level of stresses on the structure. Regarding this, the dynamic *in situ* identification tool is a powerful non-destructive instrument for the assessment of the mechanical characteristics of a structure. However, this practice must follow closely the visual inspection, as this is the essential tool for evaluating and calibrating the final results of the identification procedures.

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