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Procedia Engineering 199 (2017) 3410–3415

Procedia Engineering

www.elsevier.com/locate/procedia

X International Conference on Structural Dynamics, EURODYN 2017

Dynamic identification and condition assessment of an old masonry chimney by using modal testing

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Abstract

The renovation of old industrial sites for modern use requires the knowledge of the health status of old structures in order to ensure their use in safety conditions. The main goal of this paper is to assess the dynamic behavior of a masonry industrial chimney built in Spain in the early XX century. The paper also focuses on determining health status of the structural system and understanding where the errors and uncertainties of the numerical modelling are originated. The chimney is 38.30 m high and is founded on a concrete truncated pyramid. The paper shows the different test carried out in laboratory to obtain the mechanical parameters of the materials by means of analyzing the bricks and mortar before doing the dynamic study. After that, the chimney has been monitored for the study of the dynamic behavior and the results provided from the ambient-vibration and modal testing are presented in the paper. To this aim, Operational Modal Analysis (OMA) is used to determine the dynamic characteristics of the chimney including natural frequencies and modes shapes. The outcomes of the experimental analysis have been compared with the numerical results updating the Finite Element (FE) model used for the theoretical simulation of the chimney. The results show that the health status of the chimney is satisfactory and the combination of gravitational and wind loads do not supposes a risk for the physical integrity of the structure.

Peer-review under responsibility of the organizing committee of EURODYN 2017.

Keywords: masonry, dynamic monitoring, finite element model, modal analysis.

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Peer-review under responsibility of the organizing committee of EURODYN 2017.
10.1016/j.proeng.2017.09.485

1. Introduction

Nowadays, old industrial masonry chimneys are remained landmarks which represent the history and industrial past in some areas in our cities. These old structures cannot be recovered for modern use as it happens with other industrial buildings. Thus, they are mere ornamental elements and can be considered as part of our cultural heritage. Therefore, when new uses are required in the areas where these structures are located the conservation or destruction of these buildings must be questioned. In some cases they are protected by law but in other cases it is necessary to make a decision about the preservation of the structure. The answer to this question is not easy because many factors affect the conservation of the building. In this decision the cost of the rehabilitation and conservation is a fundamental aspect. Indeed, one of the main factors is the current health status of the building which obviously has an important impact on the rehabilitation cost.

The strong industrial past of the community of Cantabria has left many of these structures scattered along this Spanish region. Some of them have passed from private property to public property and have been preserved in good conditions. However, others have been abandoned for many years without any conservation program or repairs. In these cases it is necessary to obtain the current health status of the structure in order to assess the cost of the repair and maintenance. This is the case of the chimney studied in this paper where the deterioration for many years of abandonment is remarkable. This chimney is located in the Corrales de Buelna which is a small town with a strong industrial activity from the beginning of the XX century. The purpose of the work presented here is to evaluate the health status of the chimney under static and dynamic loads.

During the last decade structural health monitoring of historical buildings have gained great importance [1,2,3]. Structural health monitoring can be defined as the process to evaluate the health status of the structure, and determining its damage and predicting their remaining life [4]. In this context, the dynamic behavior of the structure plays an important role because one of the main loads that this kind of structures supports is caused by the wind. Wind can excite dynamically the structure and the mode shapes and natural frequencies should be determined. Experimental modal analysis is the process to determine the dynamic characteristics of the structure [5,6]. The measured dynamic characteristics of the structure can be compared with the theoretical analysis and determine the health status of the building. This is known as dynamic-based damage identification which assumes the possibility of detecting damage from changes in modal parameters, especially natural frequencies, modes shapes and damping ratios. These modal parameters can be considered as indicators of the health status of the structure since they are function of the actual physical properties of the building [7,8]. Thus, any change of the physical properties (i.e. mass, stiffness and damping) will cause changes in the dynamic behavior. Standard modal analysis requires knowing both excitation of the structure and response. However, in buildings like chimneys full knowledge is not available because is not possible to apply a controlled excitation and for this reasons only the response is known. Thus, ambient-induced vibration is used as input in modal analysis. This means that the excitation is produced by the real load, i.e. the wind. This kind of modal analysis is known as Operational Modal Analysis (OMA) [7,9,10] and has been demonstrated to be a useful tool in this kind of structures. OMA is based on spectral identification and has great importance as a non-destructive tool [11,12,13].

Although existing literature related to the dynamic analysis of chimneys is rather scarce, several works about the determination of modal characteristics of masonry structures can be found in the literature [14,15]. A review of the state of the art has been presented by Pallares et al. [16] where the construction methods and the theoretical modelization of chimneys is described to assess their vulnerability. Many of these works are focused on seismic-induced vibrations [17,18] where some methodologies are applied to assess the state of preservation of tall historic buildings after earthquake. In [19] the modal pushover analysis is used to evaluate the health status of the chimney damaged by an earthquake. Several works present the results obtained from modeling chimneys using linear finite element analysis under both seismic and wind conditions [20]. Nonlinear finite element analysis is presented by [21] where the modelization of the failure by cracking in the chimney base is also included. An experimental methodology for updating the theoretical model was developed by [22] where the mode shapes are identified obtaining the stiffness variation along the chimney due to the possible damage. Similar procedure is presented by [23] using an experimental calibrated numerical model.

2. Case study: Description of the masonry chimney

The chimney under study is located in the north of Spain and was built at the beginning of the XX century. It belongs to a former industrial complex which has been remodeled to be used as public space. The exact date of construction is unknown and there are no blueprints or information about the details and the materials used to build it. Thus, all necessary information to carry out this study has been obtained in-situ including the description of the materials and the mechanical properties. Fig. 1a shows the current situation of the building and Fig. 1b shows the general scheme with the details of the interior and exterior parts of the chimney and its foundation.

The chimney can be divided in three different parts: the exterior, interior and foundation which includes the access for the smoke. As is shown in this Fig. 1 it has truncated conical shape and the height of the chimney is 38.30m with a diameter at the base of 4.02m and 2.02m at the top. The inner pipe is also characterized by cone frustum shape with a diameter at the base of 2.31m and 1.52m at the top. Masonry bricks and mortar joints were the main materials used in its construction. The chimney rests on a concrete foundation block with pyramid frustum shape. It has an internal pipe with rectangular section that allowed trigger the chimney effect for the circulation of the smoke. The scheme of the foundation is also shown in Fig. 1b. The foundation geometry has 6.57m at the base and the height is 1.02m.

The dimension of the brick used in the construction was 21.0cm x 11.5cm x 6.0cm. The thickness of the chimney wall, mechanical characteristics of the cross section and the foundation were obtained by extracting specimens and testing. The thickness of chimney wall is formed by four bricks at the base, three at the middle and two at the top. The geometrical dimensions were obtained in situ and in some cases by means of using photogrammetry.

3. Condition of the chimney and tests for the determination of mechanical properties

Visual inspection did not detect structural damage. However, superficial decay of materials, mainly bricks and mortar, was found especially at the top of the chimney. This damage was caused by the natural ageing and the lack of maintenance. Obviously, the upper part of the chimney has suffered greater deterioration because it is the most exposed to wind. Different cracks are present along the structure as is shown in Fig. 1c and 1d.

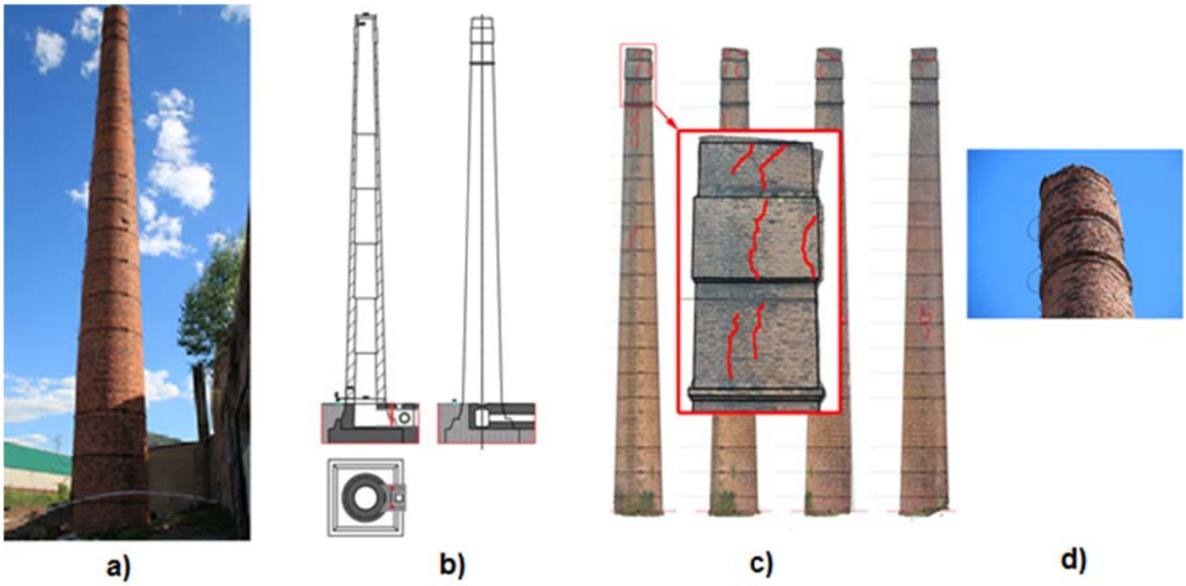

Fig. 1. (a) The masonry chimney; (b) scheme including the foundation, (c) Condition of the structure; (d) detail of a deteriorated part of the chimney..

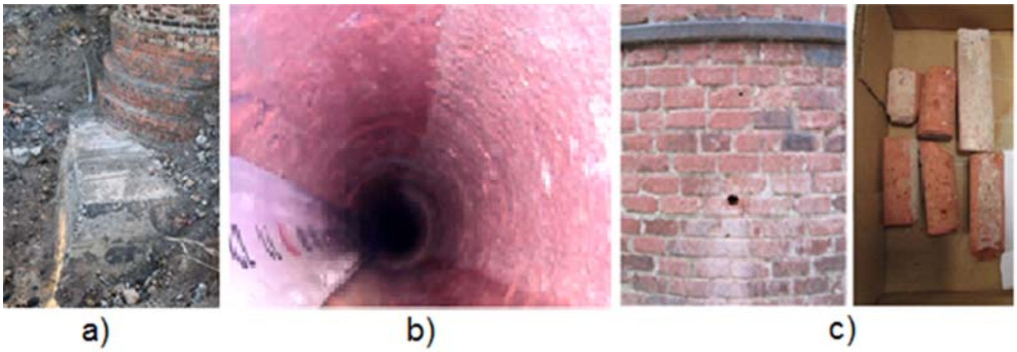

Fig. 2. Study in-situ of the structure: (a) foundation; (b) endoscopy on the chimney's wall and (c) extraction of samples.

Two test pits were carried out in order to determine the depth of the foundation and to characterize the cross section at its base above the ground (see Fig. 2a). Inspection by laparoscopy was done to check the homogeneity of the brick wall (see Fig. 2b). A rebar locator (Profoscope®) was used to determine the presence and orientation of steel rebars under the surface of the foundation. Samples of bricks and mortar were extracted from the structure to obtain the mechanical characteristics in laboratory (see Fig. 2c).

In order to obtain the ultimate compression strength of the materials, Young's Modulus and Poison ratio experimental tests were carried out in the laboratory. Fig. 3a shows the compression test used to obtain the mechanical parameters of the mortar and the ultimate compression strength. Fig. 3b shows a brick tested in laboratory. The deformation properties were obtained in-situ by using a double flatjack test. To this aim two parallel flatjack were used imposing a compressive load in the masonry wall as is shown in Fig. 3c. The deformation of the masonry between the two flatjack was measured to obtain the stress-strain curve as can be seen in the same figure. This curve was used to estimate the Young's Modulus.

The outcomes of the test showed that the behavior can be approximated as linear and homogenous. The Young's Modulus was estimated to be 6519MPa and the Poisson ratio 0.10. The ultimate compression strength of the material was estimated as 31.21MPa. The unit weight of the material was estimated to be 18 kN/m^3.

4. Theoretical and experimental dynamic analysis

Using all the information obtained from the inspection, tests and analysis of the structure a numerical model was considered in order to evaluate the dynamic behavior. The structure was modeled and analyzed using Finite Element Analysis (FEA) in Abaqus®. The discretization used 480 hexagonal elements with three degrees of freedom at each node. The chimney base was modelized fixed to the ground because of the stiffness provided by the foundation and obtained from the in-situ measurements. This model is depicted in Fig. 4 where the first five mode shapes are shown. The natural frequencies were identified as 0.95Hz, 8.48Hz, 26.92Hz, 38.33Hz and 44.78Hz.

This model required a calibration process in order to make both theoretical model and experimental results coincident. By permitting independent variations of parameters (i.e. Young's Modulus, Poison ration, etc.) in FEA it was possible to have a sense about how these parameters affects to the stiffness and mass of the chimney. Although these parameters have been obtained using experimental testing a degree of uncertainty in the material properties is always present. The sensitivity analysis provides a relationship between the modal parameter and material properties. The sensitivity is obtained by using the following formula:

$$S_i = \left[\frac{\partial g_i}{\partial p_j}\right]\left[P_j\right] \quad (1)$$

where S_i is the sensitivity, g_i and p_j stand for the modal parameter and material property, respectively. The matrix P_j is diagonal with the actual values of the material properties.

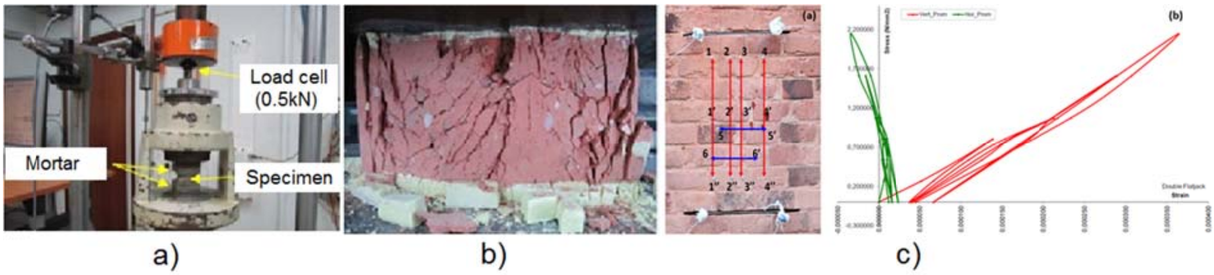

Fig. 3. Material testing: (a) mortar; (b) bricks and (c) double flatjack test.

Ambient vibration testing was carried out for modal identification (OMA) using unidirectional capacitive accelerometers which were distributed along the chimney structure. The vibration mode shapes of interest were translational modes in the North-South directions because it is the predominant direction of the wind. Frequency Domain Decomposition (FDD) and Peak Picking were the methods uses for the identification of the mode shapes and natural frequencies, respectively. FDD methodology allowed identifying four modes which correspond with the modes 1, 2, 3, and 5 provided by FEA. Peak Picking methodology allowed the identification of the frequencies using the average of singular values of the spectral density matrices for all the test carried out in the structure. These frequencies are shown in the second column of Table 1. In this table is possible to compare the natural frequencies obtained with the first FEA and the updated model. Modal Assurance Criterion (MAC) is used to compare the results provided with OMA.

Table 1. Calibration of the model.

Mode	OMA (Hz)	FEM - Initial		FEM - Updated	
		(Hz)	MAC (%)	(Hz)	MAC (%)
1	0.76	1.12	56	0.95	82
2	8.41	8.81	78	8.48	91
3	23.05	27.31	59	26.92	57
4	---		---	38.33	---
5	39.14	45.99	51	44.78	66

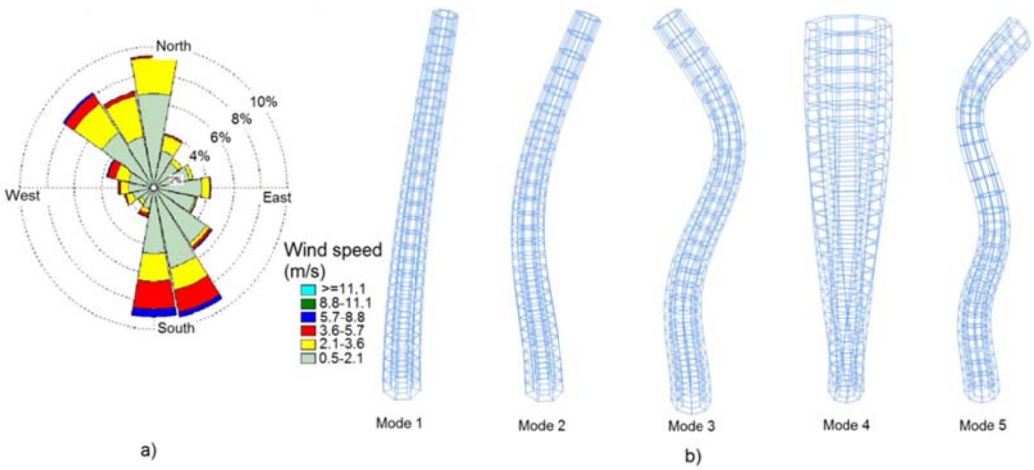

Fig. 4. Dynamic model: (a) measured predominant wind and (b) mode shapes.

5. Conclusions

In this paper a dynamic structural study of an old industrial chimney has been carried out. There is no original information about the structure so this study includes the determination of all parameters taking part in the analysis. The modal properties of the chimney have been obtained finding out that there is a good correlation between OMA and theoretical results. The in-situ inspection of the chimney shows that some cracks are present along the structure but they seemed to be only superficial. The results of the modal analysis corroborated this hypothesis because the chimney was theoretically modeled as a continuum structural system, and this model confirmed the measured results. The experimental outcomes did not reveal the existence of a torsional mode. This is because of the use of unidirectional transducers and their location on the structure. Although torsional modes were not considered essential in this study an exhaustive dynamic analysis will require the use of additional location for the measurements to obtain the information about these modes.

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