Modal and Structural Identification of a Masonry Chimney

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SUMMARY. The modal identification of an old masonry chimney and the model updating of a coherent *f.e.* model based on the measured modal characteristics, are presented in this paper. The old industrial site has been deeply modified to permit its reuse for commercial purposes. The right path necessary to permit a control on the design assumptions will be described as well as the subsequent necessary steps able to perform a reliable retrofitting action.

1 INTRODUCTION

The modern reuse of old industrial sites involves the renovation of urban environment as well as, in many cases, the restoration of critical structural elements. This is the case of the transformation of the old *Crisanti-Diodoro* kiln, established in Abruzzo at the beginning of the last century (1906), into a modern commercial site. The idea to maintain the old kiln-chimney as a link with the past, motivates the need of a study necessary to permit the necessary transformation.

In the paper, the results of modal testing on the masonry chimney (see Fig.1) before and after such transformation works, are reported together with the numerical results of a validated finite element (*f.e.)* model used as a base of the retrofitting actions.

Figure 1: The masonry chimney.

The masonry chimney is about 36.0 m high, with a base diameter of 3.40 m and a top diameter of about 1.50 m.

The *f.e.* model used for design purposes, was based on original technical drawings of a similar kiln established at the end of the XIX century in the North of Italy (see Fig. 2) and on an accurate *in situ* survey that permitted a detailed *3D* modelling. The model is based on *2D*-shell elements generally having 4 nodes for element; in case of local structural complexity, 3-nodes shell-elements have been adopted. The model has been used, *i)* to describe the stress level under gravity loads, *ii)* to perform a modal analysis to be compared with the experimental results in order to obtain a validated model, *iii)* to forecast the effects of the needed structural modifications.

Both fixed boundary conditions and a Winkler elastic soil have been considered in the relevant analysis. The main design objective was to forecasting the structural behaviour after the needed modifications, consisting in the lowering of the foundation plane of about four meters.

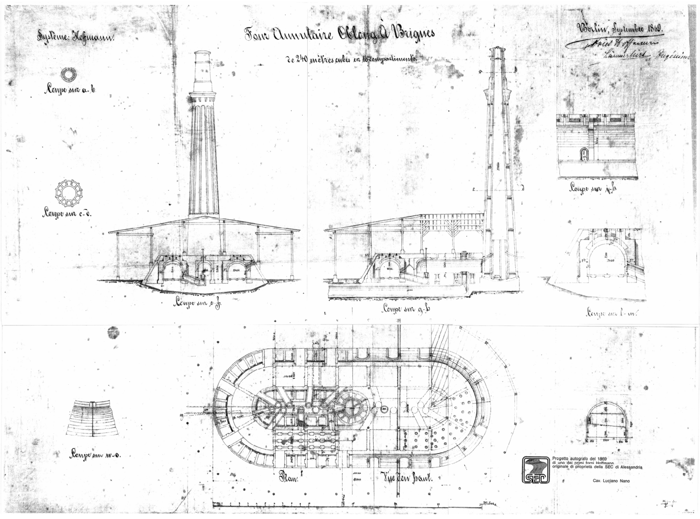


Figure 2: The original drawings

Among the different works necessary for the renovation of the industrial site, the chimney foundations have been structurally modified to permit, as mentioned before, the lowering of the nominal ground level of about four meters by using a grid of *r.c.* poles and horizontal beams surrounding the original direct foundation (Fig. 3, right).

In order to judge the feasibility of the action, the *f.e.* model, was used to represent the site and the boundary conditions before and after the restoration works.

In order to validate the *f.e.* model to forecast the real structural behavior, a model updating procedure was used, basing the optimization process on the results of dynamical tests performed before and after the modification works.

The dynamical tests carried out after the base modification were also used to analyze the influence of structural modifications on the global dynamic behavior and to observe if the desired design performances were achieved. On this regard, it was important to assess that the chimney preserved nearly constant original structural stiffness after the structural modifications. In fact, a lowering of natural frequencies would have emphasize a weakening of the structure while their undesired increasing would have translate the spectral properties towards values more dangerous from a seismic point of view (the seismic analysis of the chimney is conducted in a parallel work).

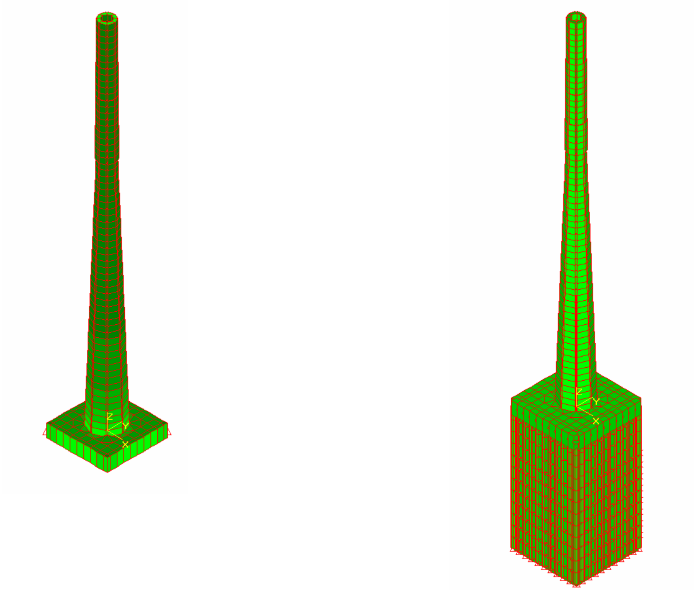


Figure 3: The *f.e.* models representing the chimney before (left) and after (right) the restoration works.

Two techniques were used to identify the frequencies and modal shapes; both of them are based on *output-only* measures. The first method is frequency-domain based and makes use of the singular value decomposition of the power spectral density matrix of accelerations measures [1]. The second method is a time-domain based method and uses a stochastic subspace identification technique to fit a parametric model directly from the raw acceleration time series returned by the transducers [2, 3].

The study involves a survey of the stages which were followed and an overview on the used modal and structural identification methods.

2 THE MODAL IDENTIFICATION AND THE *F.E.* MODEL UPDATING

The dynamic tests had the main objectives to provide the reference basis of the modal properties used to validate a *f.e.* model of the chimney. Different tests were carried out on April 2006 to measure the response of the structure before the restoration works, using different environmental excitations of (pure ambient, extra-traffic induced vibrations).

The adopted setup, reported in Fig. 4, was based on the use of 9 horizontal accelerometers attached to the external surface of the chimney, at three different levels.

Time series, organized in different datasets and generally corresponding to 3000 first natural period (about 3000 *s*) of the structure were acquired at a sampling rate of 400 Hz.

The acquisition system used during the tests has 16 differential channels and it is interfaced to a remote PC and its storage unit by using a parallel port. Nine Sprengnether servo-accelerometers, operating in the frequency range of 0–60 Hz, were used during the test.

The adopted transducers are able to acquire even components of the motion at very low frequencies as the frequencies associated to the first and second chimney flexural mode.

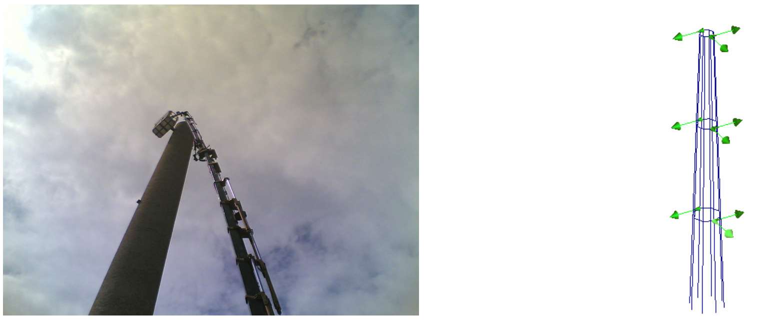


Figure 4: The accelerometers mounting and the relevant setup for modal identification.

The signal returned by each transducer is locally conditioned by using pre-amplifiers having a variable gain controlled by the remote computer. The signal is transmitted in differential modality to the acquisition system where is again converted in single-ended modality to be filtered and passed to the *A/D* converter before being stored, in different formats, on the storage unit.

As mentioned before, the modal identification from *output-only* vibration data, was carried out by using two different techniques available within the commercial software *ARTeMIS* (Ref. [4]).

The *SSI* method (time domain method), computationally more time consuming than the *FDD* (frequency domain method), has been applied with the twofold objective of validating the results obtained by using the *FDD* technique and to have a more accurate identification even in the cases of closely-spaced modes, always found in axial-symmetric structures.

Before performing the modal identification, the measured time series of all datasets were decimated 20 times; afterwards: *(a)* the spectral matrix (*FDD* technique) was estimated using the modified periodogram approach using sub-windows constituted by 66.7% overlapping blocks for spectral averaging (Ref. [7]); *(b)* stochastic state space models (*SSI* technique) are identified for different state-space order *N*, ranging from 2 to 120.

The results of the operational modal analysis in terms of natural frequencies can be summarized through Fig. 5; the figures show the *1st* singular value and the stabilization diagrams obtained by applying the *FDD* and the *SSI* technique to the acquired data. The inspection of Fig. 5 yields to the identification of 6 modes, common to all acquired datasets, in the frequency range 0–10 Hz.
Fig. 5 clearly highlights that: *i)* the *FDD* technique provides a clear indication of the modes through well-defined local maxima in the 1st singular value; *ii)* in the case of the first two bending modes having a frequency separation very small, the frequency domain method (*FDD*), with the adopted identification parameters and in the specific particular situation, seems unable to catch the two flexural (*N-S* and *E-W*) modes having nearly coincident frequencies and returns “modes” actually being a linear combination of them; *iii)* the time domain method (*SSI* algorithm is,), on the contrary, able to perfectly identify the first two flexural modes having nearly coincident frequencies; *iv)* in the analyzed frequency range, the alignments of the stable poles in the stabilization diagrams of the *SSI* method are placed exactly at the same frequencies identified by using the *FDD*, indicating a very accurate estimation.

In Fig. 6, the identified modal shapes are reported together the corresponding natural frequencies. The corresponding modes obtained by using the two mentioned techniques (*FDD*, *SSI*) have been compared through the frequency discrepancy $DF = |(\nu_{SSI}-\nu_{FDD})/\nu_{SSI}|$ and the *MAC* (Modal Assurance Criterion Ref. [5]). In the analyzed case, the identified frequencies have a discrepancy always less than 2% and a similar very good correspondence is found for the modal shapes, with a MAC index always greater than 0.98.

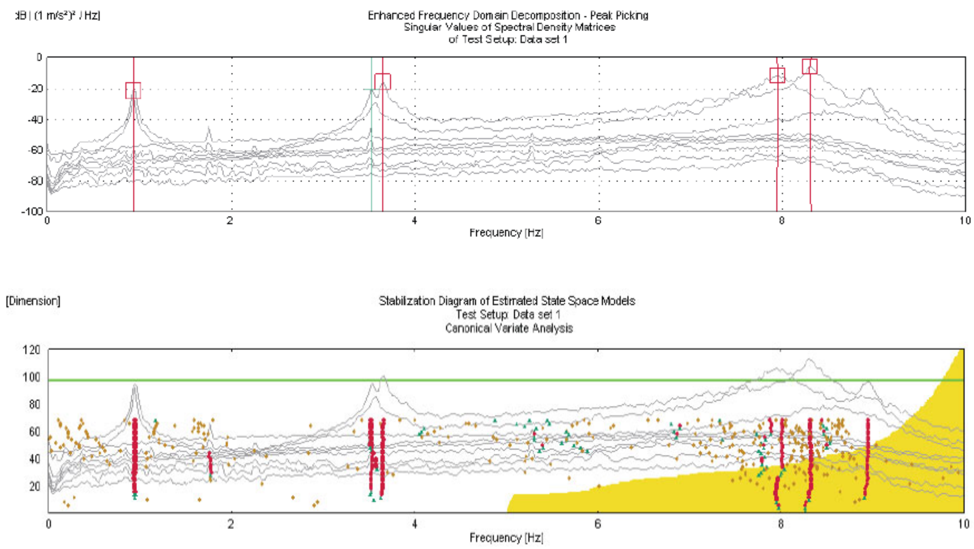
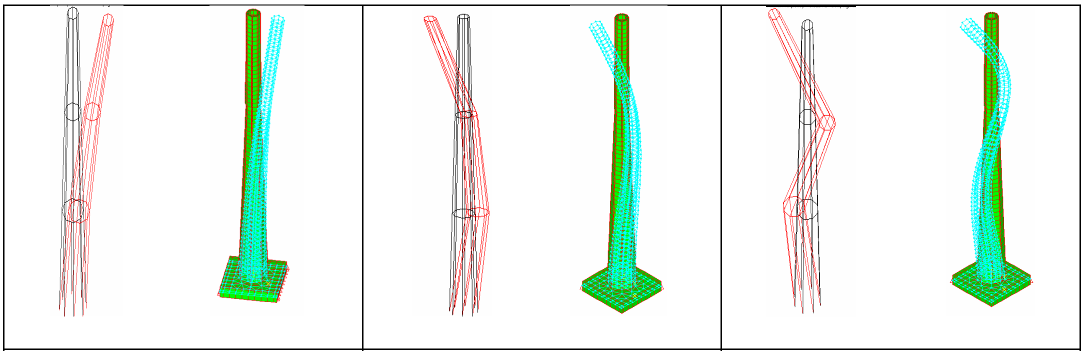


Figure 5: Modal identification (*EFDD* up and *SSI* low)

In Fig. 6, together with the experimental results of the modal identification, the result of the dynamic analysis performed by using the adopted *f.e.* model, are presented. The initial model, named in the following the *base model*, is based on numerical values of structural parameters deduced by *in situ* tests and an accurate survey of materials having similar characteristics.

The base model has been updated by using the *Douglas and Reid* model updating technique [6]. The elastic modulus of different parts of the chimney and the Winkler coefficient of the soil-foundation system, have been adopted as identification parameters. A preliminary sensitivity analysis enlighten the influence of assumed parameters on the first six natural frequencies adopted, in this case, as observed quantities. The corresponding error function, measuring the difference between the experimental and corresponding numerical frequencies through the frequency discrepancy *DF*, has been minimized by using a standard minimization algorithm. The updated *f.e.* model, as it is possible to verify from the results reported in Fig. 6, is in very good agreement with the experimental results with a maximum error on the observed quantities less than 5%. Similar very good agreement has been verified on the corresponding modal shapes compared, in this case, by using again the *MAC* index after a projection of the numerical modal shapes on the instrumented points.

After the *f.e.* model calibration, the *validated* model can be used, with a large confidence, to forecast as the needed structural modifications could have influence on the global structural behavior.



1st–2nd mode: 0.93-0.95 exp-0.93 num	3rd–4th mode: 3.53-3.65 exp-3.49 num	5th–6th mode: 8.32-8.48 exp-8.54 num

Figure 6: Experimental and numerical modal shapes (frequencies in Hz)

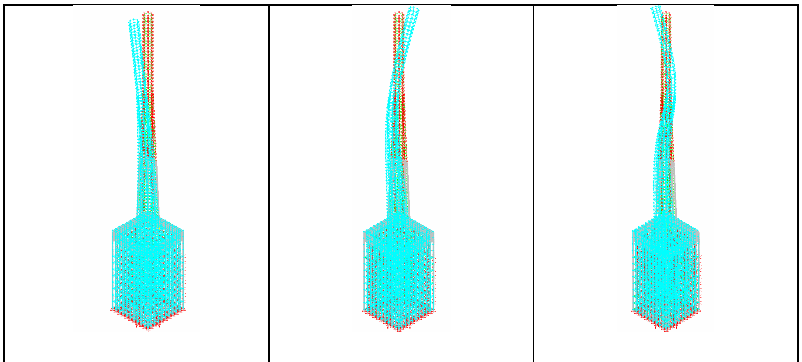
3 THE CHIMNEY BEHAVIOR AFTER THE WORKS

A modified chimney structural conditions considering the original foundation surrounded by the poles-beams grid necessary to lower the foundation plane of about 4 meters, has been simulated with the validated model (Fig. 3 right).

As mentioned before the design objective was a not reduced global stiffness of the system without moving the natural frequencies towards more dangerous range of the response spectrum, adopted in the site of construction, for the seismic analysis.

The forecasted frequency spectrum in the modified situation is reported together with the corresponding modal shapes in Fig.7. The numerical values of the frequencies after the structural modifications indicates that the needed work could be safely executed: in fact, after the modifications, the chimney frequency spectrum remains nearly stable (on the respect of the corresponding values before the works) indicating that the global stiffness of the soil-structure system is maintained nearly constant.

After the modification of the foundation, an experimental modal analysis has been conducted to verify the design performances.



1st–2nd mode: 0.93 Hz	3rd–4th mode: 3.63 Hz	5th–6th mode: 8.65 Hz

Figure 7: Modified conditions: numerical frequencies and mode shapes

The second experimental modal testing campaign for control purposes, was conducted on the October 2006. During the work necessary to lo the lowering of the foundation plane, the structural designer decided to reinforce the masonry chimney by using steel rings surrounding, at different levels the chimney external walls; the different rings were also connected by vertical steel webs positioned every 20° on the chimney perimeter.

The obtained performances are reported in the following Table 1:

	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
Frequencies before the works [Hz]	0.93	0.95	3.53	3.65	8.32	8.48
Frequencies after the works [Hz]	0.99	1.00	3.59	3.70	8.55	8.76

The corresponding modal shapes don't show any meaningful modification on the respect of the experimental modal shapes already reported in Fig.6 (*1st*, *3rd* and *5th* columns).

4 CONCLUSIONS

We have experimentally and numerically (*f.e.*) investigated the spectral properties of an old masonry chimney constructed in Teramo, Abruzzi region, on 1906. Because of necessary works able to reuse the old industrial site for commercial purposes, the chimney foundation had to be strongly modified. To assess the feasibility of the needed works, a synergic action of experimental tests and numerical modeling was conducted with the aim of validating and controlling the design performances. First the experimental modal analysis of the chimney before the structural modifications was conducted. After that, an accurate *f.e.* model based on *2D* shell elements was constructed. Then the *f.e.* model parameters have been calibrated by adopting the *Douglas-Reid* procedure, assuming, as observed quantities, the first six natural frequencies. The calibrated model gives results, concerning the observed quantities, nearly coincident with the measured ones. The validated model was eventually used for design purposes to forecast the chimney behavior after the needed works. After verifying that the spectral properties of the chimney would have not strongly modified by the needed actions, the needed restoration works were executed. After the works, a validation of the design assumptions was conducted by executing again an experimental modal analysis in the modified conditions. The verification of the design performances ended the process of simultaneous and synergic use of modal testing and numerical modeling in a correct design path.

References

[1] Brincker, R., Zhang, L., Andersen, P., "Output-Only Modal Analysis by Frequency Domain Decomposition", in *Proceedings of ISMA25*, 2, (2000).
[2] Overschee, Van P., and De Moor, B., "Subspace Identification for Linear Systems", *Kluver Academic Publishers*, (1996).
[3] Peeters, B., and De Roeck, G.: "Reference-based stochastic subspace identification for output-only modal analysis", *Mechanical Systems and Signal Processing*, **6**(3), 855-878 (1999).
[4] ARTeMIS Program Overview, http://www.svibs.com, 2006.
[5] Allemang, R.J., and Brown, D.L.: "Correlation coefficient for modal vector analysis", *Proc. 1st Int. Modal Analysis Conf.*, 1983.
[6] Douglas, B.M. and Reid, W.H., "Dynamic tests and system identification of bridge", *J. Structural Div. ASCE,* 108(10), 2295-2310, (1982).
[7] Welch, P.D.: "The use of Fast Fourier Transform for the estimation of Power Spectra: a method based on time averaging over short modified periodograms", *IEEE Transactions*, (1967).