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Structural behaviour of ancient chimneys

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Abstract

As part of several schemes to restore and qualify a number of Italian industrial complexes dating back to the second half of the 19th century, this study analyses the type and structure of chimneys built between the 1870s and the first decades of this century, mainly in the Piedmont and Veneto regions. The analyses were carried out on three typical examples for which sufficient information was available, i.e.: a 55 m high double-stack chimney (in a water scooping plant in Codigoro, Ferrara); a 47.5 m high double-stack chimney (at the Luigi Botto & Figli woollen mills of Valle Mosso, Biella); a 35 m high double-stack chimney (Stucky Mills in Venice). The numerical analysis was performed with a FEM linear program. Among the forces taken into account, we should mention in particular the action of the building's self-weight. The effects of wind, earthquake and temperature differences were also studied, on the basis of current Italian regulations. Accurate investigations were carried out to explain the onset of some of the most severe damages detected in the chimneys, i.e., the opening of cracks and the loss of verticality which were both frequently observed.

1 Introduction

Within the framework of the restoration programs undertaken to requalify several Italian industrial complexes built between the 1870s and the early decades of this century, the authors conducted a study concerning the construction, technology and structure of a vast selection of brickwork chimneys located in northern Italy [1] [2]. Among other things, this made it possible to identify recurring defects and the criteria underlying maintenance and repair interventions.

A structural analysis procedure was developed to determine the conformity of typical brickwork chimneys, in normal loading conditions, to modern safety and stability requirements. In particular, mathematical models were developed for chimneys exhibiting the same cross-sectional morphology (double stack) but having different height and slenderness characteristics.
The 55 m high twin double-stack chimneys of the Codigoro (Ferrara) water scooping plant ware erected in 1907 on a design project by Ing. Pasini, during the restructuring works of the old plant (originally built in 1871) (fig. 1). They disposed of the fumes and steam produced by 12 steam boilers which originally powered the water scooping machines employed in the land reclamation program. The drawings show a double-stack setup with an internal compartment extending over 4/5 of the total height, a tapering ratio of ca 2.84 cm/m and stack wall thickness varying from 1.05 m to 0.24 m at the top. The chimneys feature an elegant base, about 5.00 m high, standing on a reinforced concrete foundation bed on piles.
Today these chimneys are in excellent conditions of repair, mostly thanks to the intelligent on-going maintenance and preservation program implemented by the local Environmental and Architectural Preservation Authority, and also thanks to their periodical activation.
The second chimney examined is located in Valle Mosso (Biella) and is typical of the industrial landscape of the area, although it is much higher (47.50 m) than the average brickwork chimneys of the region (generally from 25 to 30 m high), (fig. 2). It is an interesting example of the great skills and building expertise of an artisan company (Rinaldo Sola) which built as many as 150 brickwork chimneys between 1920 and 1935, many of them still standing and in excellent conditions of repair.

Figure 1: The twin double-stack chimneys at Codigoro (Ferrara).

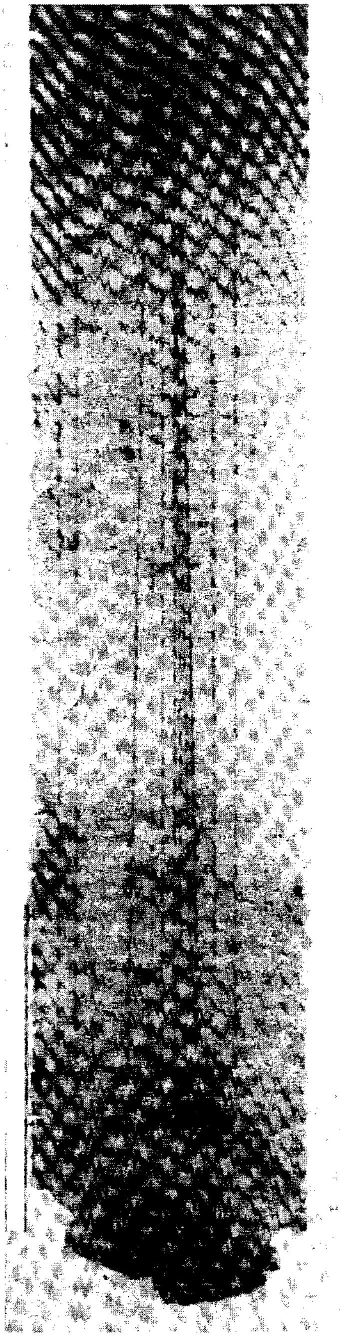

Figure 2: The Luigi Botto & Figli woollen mills chimney in Valle Mosso. Biella.

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The third chimney is parts of the Stucky Mills complex in the historical city centre of Venice. Built in 1879 to dispose of the fumes originating from a "pasta" factory, it was modified in 1903 in connection with the installation of new steam boilers and machinery. According to the original design project, the chimney stack was to be 33 m high and featured a double stack structure with truncated-conical cross-section and a tapering ratio of ca 2.52 cm/m. The internal conduit tapered upward (from 1.20 at the base to 0.90 m at the top). The present day chimney is somewhat different from the original conception, as the diameter and thickness of the stack at the bottom have been slightly reduced and a portion of the top has been torn down for safety reasons. All around the base and on the northern side, all the way to the top of the chimney (which has not been activated since 1954), the masonry shows evident signs of the aggression of humidity.

2. Geometric-mechanical characteristics

The three chimneys have different characteristics and can be viewed as significant samples of a diversified panorama from the standpoint of structural response.
The Codigoro chimney is the tallest and features a sturdy structure: it is a double-stack chimney with a slender interior stack converging into the outer stack at a height of 23.5 m. The interior stack has no significant connections with the outer one, other than at the top: hence on account of the preponderance of the outer stack, from the static standpoint the chimney is closer to the single-stack configuration. The outer diameter at the base is 5.50 m, and the wall thickness of the outer layer is 1.35 m. The last ring, under the top crown, has an outer diameter of 2.18 and a thickness of 0.24 m. The cross-sectional area and thickness values vary between these two extremes as the structure tapers in systematic decrements of ca 10 cm. The resulting structure is considerably stiff with respect to bending moments and shear and is stable to toppling under horizontal actions. From the dynamic standpoint, it is characterised by a period T = 1.59 sec. relative to the first vibration mode.
The 47.5 m high double stack Valle Mosso chimney has a slender structure, reduced to the essentials from the static standpoint. It is organised around two concentric rings, the outer one having a constant thickness of 0.25 m and the inner one tapering gradually from the bottom up. The inner stack consists of a constant diameter cylinder. The two stacks are mutually connected by vertical ribs and horizontal crowns of masonry. The outer diameter is 3 m and the diameter at the top is 1.50, resulting in a light-weight, extremely flexible structure, with reduced margins of safety in terms of stability against toppling. From the dynamic standpoint it is characterised by a period T = 2.49 sec. relative to the first vibration mode.
In its original configuration, the third chimney (Venice) was 35 m high and it also had a double stack. It is heavier and sturdier than the Valle Mosso chimney: the conical outer stack has variable cross-section with a thickness of 0.71 at the bottom and 0.225 m at the top. The inner stack tapers progressively

towards the top until it converges into the outer stack at a height of 27.50 m (the current height, after the demolition of the end portion). This leaves a constant diameter cylinder up to the top of 1.20 m. The two stacks are connected by six vertical ribs and horizontal rings evenly spaced at 4 m intervals. The outer diameter is 2.62 m at the base and 1.20 m at the top. Of the three chimneys being considered this is the sturdiest and its behaviour, in many respects, and especially in terms of flexural stiffness, can be likened to the Codigoro chimney, as discussed later on. From the dynamic standpoint, it is characterised by a period T = 1.26 sec. relating to the first vibration mode.
The main geometric and numerical characteristics are summarised in table 1.

Table 1

Characteristics	Codigoro	Valle Mosso	Stucky Mill
Height (m)	55	47.5	35
Outer diam. at base (m)	5.50	3.00	2.62
Outer diam. at top (m)	2.18	1.50	1.20
Total weight (t)	786.968	274.400	165.460
Design moment of inertia at base (m^4)	42.9723	2.2580*	3.5656
Design moment of inertia at top (m^4)	0.6987	0.1994	0.0817
Natural periods for the three vibration modes	1.59; 0.47; 0.21.	2.34; 0.606; 0.25.	1.29; 0.34; 0.14.

* value relating to the starting point of the two stacks

3 Modelling and calculation model

The analysis was conducted by simulating the three structures by means of finite elements models in the elastic field, with isotropic materials with excellent tensile and compressive strength. Though it departs from reality, this assumption is meant to capture fundamental aspects of the structural behaviour of the chimneys as a whole, rather than detailed and punctual data: in this perspective, the type of analysis performed is rough but highly effective. The calculation program employed is Cosmos/M by SRAC (USA), PC version.
All the elements used were 8-node solids, resulting in models characterised by:
- Codigoro: No. 3468 elements; 4382 nodes; 12603 degrees of freedom;
- Valle Mosso: No. 3856 elements; 5957 nodes; 17484 degrees of freedom;
- Stucky Mills: No. 5880 elements; 8624 nodes; 25680 degrees of freedom.

The following observations were made for the materials, on the basis of the test results obtained on similar masonry structures of the same age [3] [4] [5]:
- Young Modulus E = 3000 N/mm^2;
- Poisson coefficient = 0.20;
- Masonry density: 18 KN/m^3.

The three chimneys are perfectly restrained at the base, in relation both to the solid foundation bed on which they stand and to their record of absence of settlements.

4 Actions

The three structures were subjected to the following actions: dead weight, earthquake, wind (according to Italian standards), temperature gradients.
The action of the wind was taken to be a static horizontal load acting on the surface of the three structures. It was also deemed of interest to investigate the response of the structures to a similar dynamic action of the same intensity, although, strictly speaking, this does not correspond to experimentally demonstrated effects and actually it should be rated as more severe than the dynamic actions of the wind in real conditions.
The seismic action was imposed through an acceleration at the bottom according to the response spectrum specified by Italian standards. The dynamic analysis is mandatory according to Italian legislation for structures with fundamental period $T > 1.4$ sec. It should be noted that despite the fact that none of the chimneys being studied rises in a seismic zone, this analysis was deemed necessary because the Authors believe that the entire Italian territory should be viewed as exposed to a weak seismic hazard.
The action of the temperature was investigated by assuming that a fourth of the outer surface is at +20°C and the fourth on the opposite side is at -20°C: this simulates the conditions of a chimney which is no longer in use and can reach limit conditions, with one side exposed to the sunlight and the opposite in the shade. The aim of this assumption is to investigate the reasons for the fast rate of structural deterioration which has been systematically observed in abandoned chimneys.

5 Results

The results are summarised in table 2. Save for the dead weight, for all the other actions the significant values to be considered are not maximum stress peaks, but rather the set of stresses characterising significant portions of the structure: hence, the values given in the table refer to stress ranges whose limits are the maximum and minimum data obtained through the calculation.
To illustrate more clearly the results of the analysis, the deformation shapes of the Valle Mosso chimney when subjected to the combinations of: dead weight, dead weight and wind (static action), dead weight and earthquake (dynamic action), are also presented (fig. 3). Stress results cannot be shown in black and white figures, however, it was deemed worthwhile to show the deformation of the cross-section and the stress data relating to the action of the temperature for the Codigoro chimney (fig. 4).

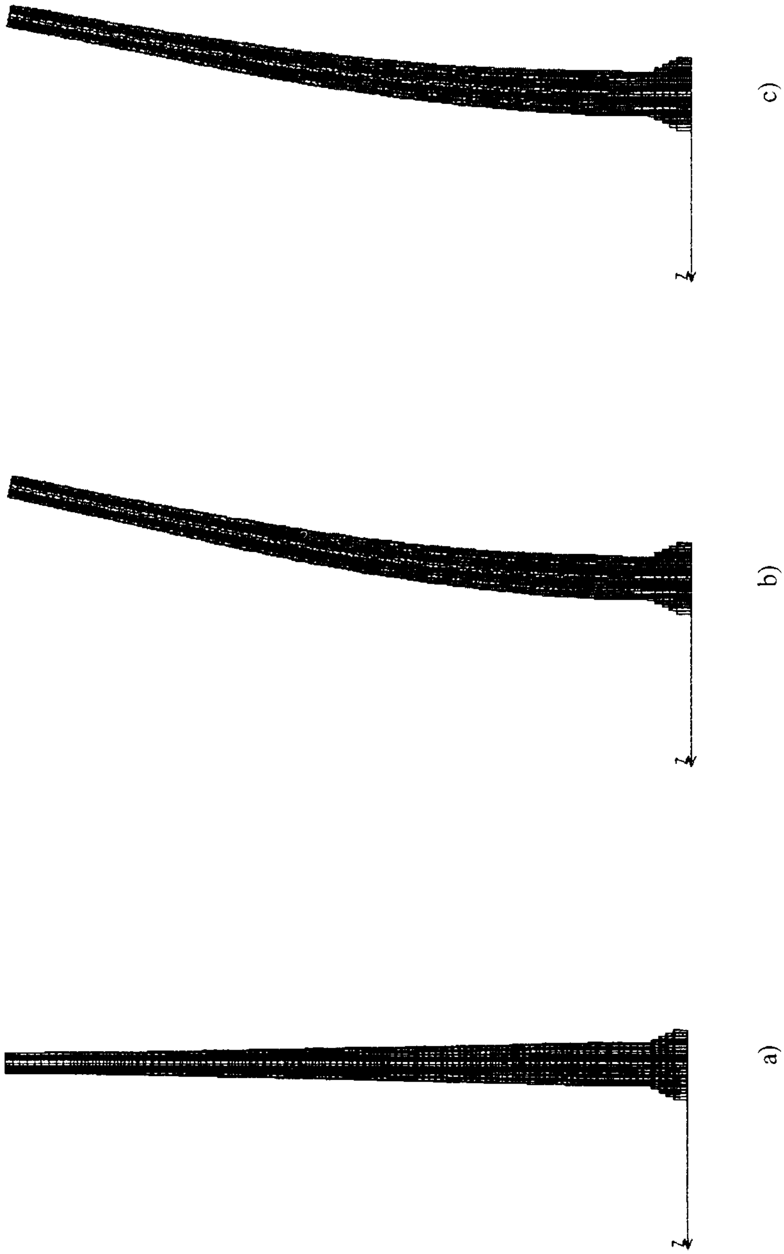

Figure 3: Deformation shapes of the Valle Mosso chimney for: a) dead weight; b) wind (static action); c) earthquake (dynamic action).

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Figure 4: Deformation of the cross-section (8 m above ground) due to the effects of temperature.

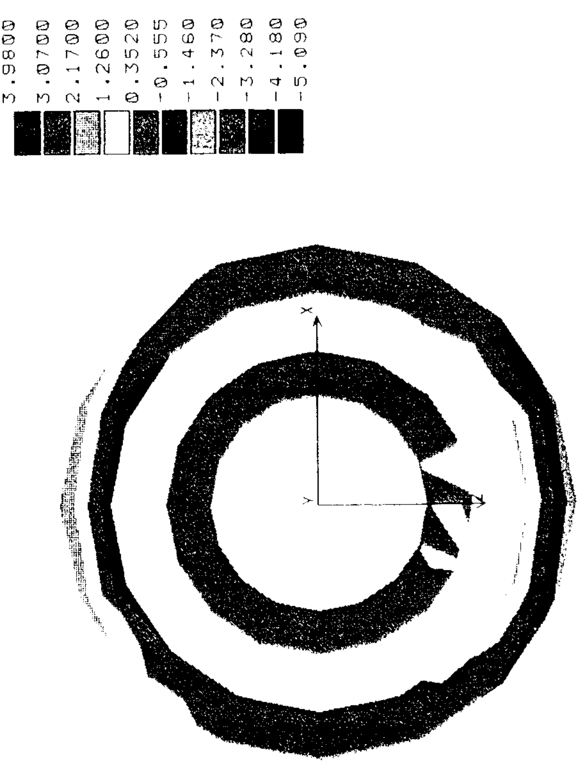

Figure 5: Stress distribution in the cross-section due to the effects of temperature.

Table 2

Characteristics		Codigoro	Valle Mosso	Stucky Mill
Dead weight	Max. vertical displacement [mm]	4.39	3.60	1.80
	Max. vertical stress [N/mm^2]	- 0.38	- 0.474	- 0.363
Dead weight + wind (static action)	Max. horizontal displacement (mm)	130	265.3	76.9
	Max. stresses [N/mm^2]	+(0.122-0.243)	+(0.691-0.962)	+(0.244-0.383)
	Min. stresses [N/mm^2]	-(0.847-0.968)	-(1.48-1.750)	-(0.868-1.010)
Dead weight + wind (dynamic action)	Max. horizontal displacement [mm]	217.8	453	148.3
	Max. stresses [N/mm^2]	+(0.565-0.796)	+(1.480-1.950)	+(0.741-1.000)
	Minimum stresses [N/mm^2]	-(1.280-1.510)	-(2.260-2.730)	-(1.360-1.630)
Dead weight + earthquake (static action)	Max. horizontal displacement [mm]	178.2	317.9	110.1
	Max. stresses [N/mm^2]	+(0.470-0.680)	+(1.000-1.350)	+(0.548-0762)
	Min. stresses [N/mm^2]	-(1.210-1.420)	-(1.780-2.130)	-(1.170-1.390)
Temperature + 20 °C – 20 °C	Max. stresses [N/mm^2]	+(1.84 - 2.73)	+(1.61 - 2.55)	+(1.26 - 3.07)
	Min. stresses [N/mm^2]	-(1.75 - 2.65)	-(1.21 - 2.15)	-(2.3 - 3.20)

6 Discussion of the results

The numerical analyses attest the validity of the design for the three chimneys, as the vertical stresses due to their dead weight are modest and can be easily withstood by the brickwork of excellent workmanship.

As for the horizontal actions, instead, the situation is worrisome: the action of wind alone, even when considered in static terms, already gives rise to diffused high tensile stresses in the three structures, and especially in the Valle Mosso chimney. Though the results should be evaluated with caution (in actual fact the presence of high tensile stresses may cause cracking phenomena resulting in load redistributions - an aspect that was disregarded in the modelling process), it should be emphasised that the formation of horizontal cracks represents an irreversible step in the deterioration of the structure. Seismic analysis and the dynamic analysis of the action of the wind can be viewed as extreme conditions: both of them lead to a marked increase in the problems already pointed out in connection with the static action of the wind, and show that the structure reaches and probably exceeds the boundaries of the stability domain. The foregoing considerations may explain why the chimneys, designed and built by highly skilled builders according to the "rules of the craft", work most effectively, with no apparent problem, as long as they are in use, essentially thanks to the material which remains "optimal" and able to withstand extremely

adverse conditions under strong winds or small quakes. When the chimneys are taken out of use, however, the materials become vulnerable to the aggression of the atmospheric agents (freezing and thawing, in particular), the structural response is impaired and the progressive deterioration process that sets in may eventually lead to structural collapse. The presence of horizontal cracks, as revealed by the tensile stresses originated in the models by the effects of extraordinary horizontal actions, clearly accounts for the typical broken evolution of the deformation curves observed by the authors in some cases and mentioned in the literature [6].
The values of the tensile stresses calculated for the structure in the presence of anti-symmetrical temperature variations are therefore seen to be very high, and the effects of the continuous temperature cycles are combined with the progressive weakening of the material exposed to aggressive weather conditions. This applies in particular to the northern side of the chimneys which is subjected to tensile stresses of over 0.2 N/mm^2, a stress level, that is, which can hardly be withstood by the masonry. Though it should be noted that the results of the numerical simulation are obviously biased by the ideal material being considered (which rules out stress redistributions in the plastic field, as may occur in actual practice) and by the relative infrequency of occurrence of such extremely adverse circumstances, the analysis suggests a possible explanation for the occurrence of the typical vertical lesions that appear in many chimneys, notably on the northern side.

7 Conclusions

The numerical analyses performed to supplement the investigations presented in [1] and [2] have shown that:

- the structures are perfectly adequate to withstand the permanent actions arising from their dead weight;
- prolonged inactivity weakens the material and may prove very harmful in connection with extraordinary events, such as the dynamic action of the wind or an earthquake; the tensile stresses that are reached in such extreme circumstances cannot be withstood by the structures being examined and are bound to give rise to the formation of horizontal cracks;
- the action of the temperature cycles combined with the deterioration of the material is, in all likelihood, the cause of the vertical cracks that are often seen to appear on the northern side of the chimneys.

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