OLD INDUSTRIAL MASONRY CHIMNEYS: REPAIRING AND MAINTENANCE

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Abstract.

The aim of this paper is present a review of the current state of research in industrial masonry chimneys and a deeper approach to them to facilitate their knowledge. For this, the first part of the paper is devoted to review the history of these chimneys, why and how they were constructed, the shape and dimensions and having pathologies or causes that may lead to the need for repair or strengthening. A detailed description of the main problems on these structures is presented: inclination, vertical cracks, alteration of the masonry mortar joints, and expansion of mortar due corrosion of steel elements, etc. This description includes a possible origin of these structural pathologies. The second part of the paper presents the preliminary results of a case of study: The chimney of the factory “La Paz” in Agost (Alicante-Spain). This construction is in phase to be declared local monument by the City Council of Agost. This structure presents examples of all the previously described pathologies and shows a severe crack pattern. A 3D numerical model with the actual deformation of this structure and with the main crack patterns is developed to obtain the actual stability of the structure under self weight and extreme wind loads. Finally a general description of possible repairing action for each pathology is presented with some real examples.
1 INTRODUCTION

The industrial chimneys dealt with here were mostly built during the 19th century during the Industrial Revolution, thanks to the invention of the steam boiler, widely used in industry for the mass production of manufactured goods. Fuel was burned in the boiler to produce steam to drive the machinery, for example in the textile, paper and oil industries, although in some factories the boiler itself was the only production unit, for example in the ceramics industry. After a time, in this latter case the Hoffman-type boiler became the most commonly used. This consisted of several furnaces connected to a common chimney, through which the smoke and gases were expelled. To keep construction costs to a minimum, it was common practice for different factories to share a single chimney, which often meant that the structures were of bigger size. During the period of industrial expansion, large numbers were built in many cities, forming typical skylines such as that shown in Figure 1.

![Figure 1: Industrial area in Oliva (Valencia-Spain)](image)

Chimney height varied widely, depending on many factors such as the prevailing wind, type of goods manufactured, nearness to towns, topography, etc. The vital criterion in deciding height was that nearby populations should not be affected by smoke, so that some were well over 100 metres, such as that at the Anaconda Smelter Company, in Montana (USA), which reached 178 m. Chimney geometry also varied and many went beyond merely practical considerations and were adorned in accordance with the financial resources of the owner. On many occasions there was rivalry to be the possessor of the biggest and best chimney in the locality.

The observation of factory chimneys shows that their structures can be divided into three clearly differentiated parts: crown, stack and base [1]. The crown is the topmost element of the chimney and its function is purely ornamental. Different builders used the crown as their distinguishing mark. The stack is the most important element and conducts the smoke upwards. It is usually conical in shape. The base forms the lower part of the chimney and is usually quadrangular or octagonal with variable height. Its function is to distribute the loads over the ground to avoid failures in the foundation. Shapes also varied widely, from, for example, round or octagonal bases with round, square, rectangular, octagonal or helicoidal stacks (Figure 2). If the chimney is relatively small, this part of the chimney may be almost unnoticeable. In this zone was situated the access to the chimney interior for maintenance.
Allowances were made for the weight of the structure itself and the prevailing wind in the structural calculations. Graphic calculations were often performed to obtain the funicular polygon of the loads and determine the stability of the structure [2, 3].

Actually, many of these chimneys have been declared protected buildings for their social and historic interest. This means that in regions prone to seismic events their resistance to such forces, which were not taken into consideration when they were built, should be investigated. Furthermore, many chimneys are located within built-up areas (Figure 3) and thus need an analysis of their structural behaviour and their resistance to earthquakes for the protection of the surrounding buildings and population. The actual interest in the study of these structures is remarked by examples of studies: Ghobarah and Baumber [4], Riva and Zorgno [5], Pistone et al. [6], Aoki et al [7], Pallarés et al [8, 9] or Lopes et al [10].
2 GENERAL STRUCTURAL PATHOLOGIES

After the observation of multiple chimneys it’s possible to distinguish two general types of lesions: cracks that are marked on the brickwork and changes in the constituent materials:

2.1 Cracks

On the tree chimneys common parts is possible to distinguish different cracks patterns:

- **Stacks cracks.** Almost always occur in the vertical direction. Sometimes, however, occur on the surface of winding stack or in a zig-zag marking the joint mortars of the masonry. They are usually more abundant in the upper part of the stacks, but in fact, there is no clear law regarding its location. In terms of width, used to be quite homogenous, that finding can be generalized to all cases. (Figure 4a)

- **Base cracks**: Similar to those of the stacks in their verticality, with the uniqueness that generally match weaker sections containing the mouth of the tunnel which connects to the boiler. (Figure 4b)

- **Coronation cracks**: Are not uncommon cases where in this part are evident damages caused due to electric shock from lightning. This problem clearly affects this area and even can be derived to vertical cracks in the upper third of the stack. (Figure 4c)

2.2 Masonry material alterations

According with the observation of many chimneys is possible to present the next classification:

- **Changes in volumetric materials**: Needless to relate porosity and possible chemical changes of the materials that make up the masonry. They are causing a visible inclination in stacks of numerous chimneys and they occur especially in the upper part of the stacks and in the borders of the coronation body. (Figures 4a)

- **Disintegration of the mortar joints of the masonry**: It causes reduction of the resistant section of the material. The affected areas may coincide with the salt wind exposed face or the face or wetter stack or the coronation body. (Figure 5a)

- **Superficial spalling of ceramic bricks**: This problem it’s similar to the disintegration of the mortar joints effects and also occur preferentially in the upper parts and in areas affected by the wind and humidity. (Figure 5b)
Discoloration of masonry materials: This pathology often occurs in areas most affected by changes originated by chemical affections. Some differences are presented depending on the exposure in relation to the prevailing wind or moist wind or even original differences in the characteristics of porosity of the bricks with which it was performed: in heavily polluted geographical areas, color changes are more frequent and visible. (Figure 5c)

2.3 Causes of cracks and changes of materials

The origin of structural pathologies in masonry chimneys can be established from the analysis of the loads to which they are subjected and the relationship of such activities with the specific circumstances arising from the function developed in their industrial process. It’s possible to remark the following circumstances:

- The smoke temperature when it passes through the chimney was always higher than 100 °C, and could sometimes exceed 200 °C. Obviously, given this information, thermal stresses which were subjected the masonry at these elevated temperatures can be important.
- Any combustion process generates \( \text{H}_2\text{O} \) and \( \text{CO}_2 \), other gases further appear, if the fuel contains sulfur, it is common the occurrence of \( \text{SO}_2 \). \( \text{CO}_2 \) and \( \text{SO}_2 \) combined with water may produce acidic liquids, carbonaceous or sulphurous oxides capable of reacting with lime (\( \text{CaO} \)), sodium (\( \text{NaO} \)) or magnesium (\( \text{MgO} \)), and the sulfoaluminate seen in the brick masonry that are built these chimneys. Specifically, the sulfate thus formed, in the presence of water, crystallizes and expands, causing the volume increases of the masonry area concerned. These same sulfates, in the presence of an additional amount of water from condensation or exterior penetration, can be put into the solution and cause efflorescence altering more or less permanently masonry color, depending on the holding power of combustion products expelled through the chimney and the impurity content of the atmosphere. These factors, together with that of efflorescence, also affect the observable dirt on the outside of the chimney. Spalling bricks and the disintegration of the mortar joints are other consequences of chemical alterations produced by the hydrolysis of salts generated in these processes.

After the observation of many chimneys, the main damages are a consequence of the two circumstances previously described. Thus, most pathologies today are visible on its surfaces.
have their origin in thermal stress caused by the high temperature of the fumes. The particular site where these cracks are presented in each case depends on the temperature regime of the fumes and the construction characteristics of each chimney (variable masonry section along the structure, the presence of weak sections at the bottom, etc.)

Another observable damage in a big number of chimneys is the inclination of its main body. It is related to the circumstances mentioned above, from the combustion of coal and, in general, of all fuels containing sulfur, since inclination of the main body is due in general to differential expansion of the masonry joints affected by mortar sulfation that held following the process detailed above. The direction in which they are inclined may vary depending on the dominant action in each case, which can be very diverse. It is possible to distinguish, for example, the following possibilities:

- Inclination of the upper section of the main body to the south, because the water coming to condense the steam circulates inside the main body dries faster, and has less possibility of formation, in the south of the main body in the north, which induces the mortar joints of the face north masonry to expand more than the south face.

- Inclination in the direction and sense of the dominant moist wind, if it is the wind that causes the penetration of moisture by the porosity of the masonry. In many of these chimneys the moist wind direction is distinguished by its correspondence with the status of 'clean face' of the main body that gives front, thus differentiating the area downwind, more dark and dirty.

- Inclination in the direction of the dominant dry or warm wind and in the opposite direction to that wind, if that is the action which becomes dominant in the moisture balance of the masonry.

Apart from these, there may be other causes, more or less decisively affecting the formation of the pathologies discussed, it’s possible to detect others, no less important:

- Corrosion of steel bars forming the interior stairs of the chimneys, which can promote the expansion of mortar and thus wedging effect on the plant. (Figure 6)

![Figure 6: (a) Steel interior stairs. (b) Corrosion of steel elements. (c) Corrosion of steel stairs. (d) Masonry cracks produced by corrosion, interior part of the chimney](Image)
- Particular mechanical actions in the construction phase or in the early years of the chimney, such as a strong wind even when the mortar joints are not sufficiently hardened.
- Others ... and unverifiable and apply only from knowledge of the effects of the processes of construction of each chimney: laying the bricks with mortar of different plasticity, defects crashes initial implementation, use of bricks with different porosities or containing different salts, long interruptions of work, the impact of lightning while his life, ... etc.

3 CASE OF STUDY: MASONRY CHIMNEY OF “LA PAZ” FACTORY

The masonry chimney of the former ceramic industry of “La Paz” was an image of the industrial development of the town of Agost (Alicante, Spain) and has become the image of the historical progress of the town during the XX century. Nowadays there are only two masonry chimneys still standing. The more slender one, which is the object of this study, is actually in a worse preservation condition. This structure is located beside the CV-820 local road, which communicates Agost with Alicante (Fig. 7). Moreover, the chimney is approximately 12 km away from the waterfront and there are not any significant barriers, which could protect the structure against the wind.

Recently the town council of Agost has decided to start the catalog of the structure as historical heritage (local interest heritage). Thus, the Department of Civil Engineering of the University of Alicante has made a structural analysis to study the chimney stability, under both static loading and seismic events. A previous pathology report has detected a group of longitudinal cracks along the shaft. Therefore, the aim of this work has been the analysis of the chimney in its current state before attempting a future structural reinforcement. Moreover, the conclusion of this paper will be the base for the structural instrumentation and monitoring, which will be used for the dynamic identification.

![Figure 7. Chimney location (left), distance between the structure and Mediterranean Sea (right).](image)

The importance of the current work is assessing the actual conditions of the structure (a heavily damaged masonry chimney), and how this state affects the numerical modelling. All the structural pathologies presented in this paper, are present on this chimney.

3.1 Geometrical characteristics and structural pathology

The chimney (Fig. 8) has a squared base section of 2.82x2.82 m with a 0.80 m thickness. In addition, there is an access in the lower part of the NE wall. However, there are not any connections to the other industrial buildings of the former factory. The other elements, i.e.
stack and crown, have a regular octagonal cross section, with variable dimension, for a total 24.63 m height. Moreover, the stack thickness is thinner for higher sections, varying from 0.6 m in the base connection to 0.12 m in the upper part and crown (Fig. 8d). Fig. 8(c) includes a photograph of the longitudinal crack that appears continuous on the shaft from an elevation of 13.7 m to 21.1 m. Furthermore, Fig. 8(e) and 8(f) show a permanent deflection in the NE direction, where the crack appeared. This damaged face is consistent with tension stresses due to bending moments caused by the prevailing winds.

![Figure 8. (a) East wall. (b) West wall. (c) Image of the vertical cracking pattern along the stack. (d) General dimensions: elevation plan and longitudinal cross section. Actual deformed shape: (e) northeast elevation, (f) southeast elevation.](image)

3.2 Structural analysis

In order to study the dynamic behavior of the structure in its current condition a numerical model has been made using SAP2000 V14.1 [11]. The 3D geometric model includes the main cracks identified during the previous pathology study (Fig. 9a and 9b). The external restraint conditions consider an initial hypothesis with the base fixed. In addition, the variable thickness has been considered as shown in Fig. 9(c).

The structural model is formed by “Shell Elements” with four nodes and three degrees of freedom per node. The mesh size has been limited to a maximum size of 1/10 of the section thickness and it includes the main cracks detected on the structure. All the displacement has been restrained at the bottom of the base.

A preliminary elastic linear model was selected for the masonry, which has been modelled as a composite material with an M type brick and a weak mortar, according to EN 1996-1 [12]. Table 1 includes the mechanical parameters for both brick and mortar, and the curve included in Fig. 9(d) has been obtained considering the suggestions made by Bilgin et al. [13].
Old industrial masonry chimneys: repairing and maintenance

Figure 9. (a) Numerical model 3D view. (b) Detail of the crack modelling. (c) Variable thickness sections considered. (d) Nonlinear behavior curve for masonry. (d) Non-linear curve obtained for masonry.

Table 1. Mechanical properties of the materials considered in the numerical model

<table>
<thead>
<tr>
<th></th>
<th>Brick</th>
<th>Mortar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>( f_b ) (MPa)</td>
<td>( E_b ) (MPa)</td>
</tr>
</tbody>
</table>
| M      | 17.7  | 5300   | Weak | 1:0:6  | 3.1    | 545

For this preliminary study of the stability of the chimney, 1800 kg/m\(^3\) has been considered for the density of the masonry material. Only the combination of self weight and wind loads are evaluated in this initial analysis. According to Eurocode 1 [14] a high wind has considered acting on the structure to simulate an extraordinary situation: a value of 35 m/s has been selected. The application of this standard produces a horizontal pressure of 0.9 kN/m\(^2\), that has been applied along all the structure (Figure 9d). More accurately analysis has been made for earthquake loads [15].

The maximum normal stresses obtained under this numerical analysis (Figures 10a and 10b) permits validate the stability of the chimney. The maximum stresses values are near the cracks and are lower than 0.15 N/mm\(^2\), the maximum tension stress estimated for this masonry. Figure 10d presents the maximum displacements, for this combination of self weight and extraordinary wind they are lower than 0.7 mm.

Other wind situations have been analyzed: the results derived from the FEM indicate that, for this heavy cracked chimney, under the action of strong wind (27 m/s), combined with the effect of the weight of the material, the masonry is not even under high tension stresses. When an extreme wind storm (35 m/s) is considered, tension stresses obtained are lower than the maximum capacity of masonry and they are situated only on the borders of the actual cracks. On the other hand, the compressive stresses generated for the maximum loads are lower than the maximum capacity of masonry. These results, which have been analyzed with this sample chimney, can be considered transferable to most of the chimneys of the similar characteristics and are also supported by the experience in his behavior. Actually, to date, they have not suffered significant damage.

Table 1. Mechanical properties of the materials considered in the numerical model
Figure 10. (a) Max normal stresses (N/mm²). (b) Detail max normal stresses near the main crack. (c) Initial structure, real inclination. (d) Wind loads. Deformed structure under these high wind loads. (mm)

4 THE OBSERVED STRUCTURAL PATHOLOGIES AND THEIR INFLUENCE ON THE STABILITY OF THE CHIMNEY

The real case analyzed presents the most common pathologies in chimneys. The results of this preliminary numerical evaluation allow obtain a relative calm on the stability conditions of this chimney. It’s important remark that this first deduction, when considering the effects of the combined action of several of the factors of the damage that can be seen in them, can generate some changes on the analyzed behavior and its initial conclusions:

- Thermally induced cracks tend to redistribute the vertical loads such that disappears its supposed initial homogeneous distribution in the lower sections of the stack and the base. This situation is considered in the numerical model, but it can produce stress concentration in these areas and a consequent progressive resulting runout. This behavior is modified when reinforcing elements are introduced on the stacks in fissured zones, and the initial conditions of continuity are restored.

- A similar process is derived from the inclination of the chimneys, which can add their effects to the crack effect already described. In this case, it is worth considering the incidence of the inclination on the modifications of the loads and equilibrium conditions set by the chimney. In our model the inclination of the structure is already considered.

- Sulfation of mortar joints is another factor to consider: The reduction of the initial conditions of adhesion between mortars and brick and consequently the reduction of the resistance of masonry. It is also possible that the effect of sulfation process reduces the mechanical properties of mortar itself.

It is possible to establish the diagnosis on the state of each particular chimney based on the evaluation of each of these factors and their possible confluence.

5 POSSIBLE REPAIRING ACTUATIONS

In order to dispose of a possible intervention catalogue to be carried out in each case of frequently presented damages in chimneys, Table 2 summarizes different group of causes that lead the damage and possible remedial measures to be taken. Some of these recommendations are presented by Diaz et al. [2]
### Table 2. Mechanical properties of the materials considered in the numerical model

<table>
<thead>
<tr>
<th>Possible solution</th>
<th>Application of sealants. Solution depending on the environment</th>
<th>Wall tying systems</th>
<th>Inner core self resisting, Steel/FRP elements.</th>
<th>Reduction of slenderness. Shoring permanent.</th>
<th>Underpinning of existing foundations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural Pathologies</td>
<td>Vertical cracks. Thermal effects.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Application in chimneys out of use. Depending on the masonry damage degree can be necessary adopt a supplementary reinforcement</td>
<td>Recommend solution.</td>
<td>Appropriate solution when the damage degree is advanced</td>
<td>Appropriate solution when the damage degree is advanced</td>
<td>-</td>
</tr>
<tr>
<td>Crack due compression or bending-compression</td>
<td>They can be applied. It should have assessed the masonry strength characteristics.</td>
<td>Appropriate solution when only compression cracks and effects of flexion and compression are absorbed by the masonry</td>
<td>Appropriate solution when the damage degree is advanced</td>
<td>Appropriate solution when the damage degree is advanced</td>
<td>-</td>
</tr>
<tr>
<td>Inclined-deformed structure.</td>
<td>-</td>
<td>Initially, option not recommendable.</td>
<td>It requires a chemical analysis to determine the degree of chemical masonry alteration. Can be necessary modify the top of the chimney most affected</td>
<td>Solution is not always appropriate. Previously required to perform chemical analysis of the material to check the affected area</td>
<td>-</td>
</tr>
<tr>
<td>Foundation differential settling</td>
<td>They can be applied to seal cracks after eliminating the cause of the settlement</td>
<td>No appropriate solution</td>
<td>Possible solution when the settlement is progressive</td>
<td>Possible solution when the settlement is progressive</td>
<td>The only appropriate solution when the settlement is progressive.</td>
</tr>
</tbody>
</table>

Some of these options can be displayed in Figure 11, where solutions ringed or banded with steel or FRP elements are frequently applied to chimneys affected by cracks due to thermal expansion. For some more damaged situation is necessary to rebuild the top of the masonry chimney, always more susceptible to the effects of sulfation of the mortar joints and the destructive effects of possible lightning. (Figure 12)

![Figure 11](image_url)

Figure 11. Structural systems to reinforce masonry chimneys: (a) Steel bars. (b) Steel bands. (c) Stainless steel bands. (d) Helicoidal FRP bands proposed by Pallarès et al. [16]. (e) Helicoidally FRP bands on a chimney in Bari.
Figure 12. Scaffolding, ad hoc brick manufacture and rebuilding the top part of a chimney in Oliva, Spain

When the structural analysis of these chimneys is developed for retrofitting it to the actual loads proposed by the standards and for earthquake loads, other disposition of the reinforcing elements are more adequate. Some recommendations are made by Pallarès et al [16] and they are presented in Figure 11 (c) and (d).

6 CONCLUSIONS

This paper presents a general description of the main structural pathologies observed in masonry chimneys and his possible interventions to assure their structural integrity. As sample of it a general study of La Paz factory chimney has been made. This structure presents a severe crack pattern and his structural integrity can be questioned. All the mentioned structural pathologies are presented on his structure. A preliminary static analysis shows that under a combination of strong winds and the self weight loads the structural stability is guaranteed, but not only these loads are acting on the structure: the deterioration of the mortars and the corrosion of the steel elements continues with the degradation process and its necessary design an intervention to maintain their future structural stability.

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