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Additional Information

Causes of damage to industrial brick masonry chimneys

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Abstract

From the early 19th to the middle of the 20th century, brick chimneys formed part of the industrial landscape. As technology advanced, factories were abandoned and became absorbed by the cities growing around them but masonry brick chimneys found a new role as part of the historical heritage. A large number of these structures are now protected buildings, which means they have to be maintained in a good state of conservation. Architects and engineers who have to assess the condition or retrofit these structures therefore need to be familiar with the different types of damage that can affect brickwork chimneys, and having access to a classification of the different types of damage they are prone to would be very useful to them. This paper classifies and describes the most common defects found in these structures, compiled after a close inspection of 538 Spanish industrial chimneys. The types of damage were classified according to: a) changes in the materials used in their construction, b) damage caused by repeated actions, c) damage due to extraordinary events, and d) damage caused by living organisms.

Keywords: *Industrial chimney; Masonry; Damage; Failure; Brick; Classification*

1. Introduction

The origin of industrial brick masonry chimneys is closely related to the appearance of the steam engine and the Industrial Revolution, when they were added to factories that needed to burn coal to produce steam to drive the machinery. These chimneys had to be high enough to obtain sufficient draught-power to achieve efficient combustion and carry away the smoke produced.

The first references to the construction and design of industrial brick chimneys go back to the first half of the 19th century. Some of the leading publications from this epoch include those of Buchanan [1], Gouilly [2], Wilson [3] and Bancroft & Bancroft [4] and references to manuals for the construction of brick chimneys are available from the early 20th century, such as those found in Gilbreth [5], Esselborn [6] and Lafon [7].

There has recently been a considerable growth of interest in the study of industrial brick chimneys. When their owners had no further use for them, they became part of the history of many cities and entered the architectural heritage. Many of them are now protected buildings, which means they cannot be demolished and must be maintained in a good state of conservation [8].

Diverse studies have been carried out on brick chimneys from the structural engineering point of view, especially as regards how they can be affected by earthquakes. Since they are tall, thin structures, earth tremors can cause them significant damage, and if sufficiently severe can cause their collapse. There are a large number of references in existence that document actual cases of chimneys damaged by earthquakes [9-13] and the scientific community has analysed the effects of earth movements on these structures, as for example in Riva et al [14], Pistone et al [15], Riva and Zorgno [16], Pallarés et al [17,18], Aoki et al [19], Lopes et al [20], Breccolotti & Materazzi [21] and Minghini et al [22]. Other research groups have focused on retrofitting techniques to counteract seismic events [9, 16, 23-26]. The interest in conserving and repairing these structures can also be seen in a number of studies related to other types of damage from sources other than earthquakes [16, 27-29].

In order to maintain and conserve a structure it is advisable to be aware of the damage to which it may be subjected. In this regard, there are references that classify possible damage to a wide variety of buildings [30-34], which are useful to the experts involved in their assessment and subsequent repair. In the field of brickwork chimneys, some attempts have been made to classify the possible types of damage they can suffer, such as in Pallarés et al [25] and Diaz & Gumà [27], who summarised the types of damage that could be found in these structures, but without going into any great detail.

This paper describes a study carried out in Spain that involved a detailed inspection of 538 industrial brick chimneys (see Fig.1). The aim was to classify the most common types of damage they were prone to, after which it was intended to create a tool for the use of architects, engineers and others involved in their maintenance and conservation. In this way, they would have access to information on the most common types of damage and their causes. The main novelty of this paper is therefore that it is the first to classify and describe in detail the different types of damage that can be found in industrial brick chimneys.

The paper is divided into seven sections, starting with the Introduction in Section 1. Section 2 describes the chimneys in detail and Section 3 the different types of damage they are subjected to, due to changes in the materials used in their construction (bricks, stone, mortar, tiles and metal elements). Section 4 deals with damage caused by frequent actions (e.g. prevailing winds, temperature variations, smoke and damp), while Section 5 goes into the damage that can be caused by extraordinary events, such as: high winds, lightning strikes, war damage and earthquakes. Section 6 describes the damage caused by living organisms (animals, insects, fungi, lichens, plants and human beings). Finally, Section 7 ends the paper with the main conclusions reached in the study.

2. The structure of industrial masonry chimneys

A chimney is a hollow vertical tube whose two main functions are to convey smoke to a certain height and provide enough draught power for efficient combustion. At the present time,

these chimneys are made of steel or concrete, but in the 19th and early 20th centuries they were built of bricks and mortar. The reason for using bricks for their construction instead of another material was due to the fact that bricks were small, could be held in one hand and were easy to carry around and pile into heaps, which meant that no advanced machinery was required to handle them and, as they lent themselves to being built in an infinite number of shapes, a wide range of aesthetic effects could be obtained.

A brick chimney is composed of three main elements (see Fig.2a):

- Base: This is the lowest part, whose fundamental purpose is to transmit the loads on the stack to the foundations, and allows higher chimneys without having to resort to large degrees of taper. The base is usually square, although it may also be circular or octagonal.
- Stack: This is the most important part of the chimney as it carries out the functions of carrying away the smoke and increasing the draught needed to burn the coal efficiently. According to Esselborn [6] and Álvarez [35], the stack's outer taper usually varies between 2 and 2.5% and its cross section may be round or in the form of a polygon.
- Crown: This is the top of the chimney and its function is mainly ornamental, although it also protects the structure against rainwater seepage.

Chimney height varies and depends on its location. The phenomena that must be kept in mind include: prevailing winds, topography, nearness to built-up areas, etc. Pallarés et al [25] point out that these heights can range from 20 to 50 m, although López-Patiño [8] found that most of those in Spain varied between 20 and 30 m. However, there have been chimneys higher than 100 m and even as high as 178 m [36].

Although these chimneys were first conceived in the United Kingdom, they quickly spread to the rest of Europe, as witnessed by the existing references [2, 8, 12-18, 20-29] and to America [9], Asia [10, 11, 19] and Oceania (see Fig.2b). Chimneys similar to those described here can thus be found in almost any part of the world.

3. Types of damage due to changes in materials

Many of the defects found in the masonry of industrial chimneys are due to the quality of the materials used, workmanship and construction procedures and to the surrounding environment [37]. This section deals with the types of damage most often found in brick masonry chimneys due to changes in the materials used, which can be classified by the elements of which a chimney is composed:

- Bricks
- Stone
- Mortar
- Ornamental ceramics
- Metal elements

3.1. Bricks

The bricks used to build chimneys are made of baked clay and suffer the typical damage these elements are subjected to, as has already been widely pointed out in the scientific literature [37, 38]. For the particular case of brickwork chimneys, Pallarés et al [25], Díaz & Gumà [27] and Ramos et al [29] have described some of the types of damage that can appear in these bricks, including efflorescence, spalling and hygrothermal problems.

In the inspections carried out, damage was found due to spalling or flaking of the bricks (see Fig.3a), in which they appear to break up into layers or flakes. This type of damage can in time evolve into the complete disintegration of the bricks.

Efflorescence was the most common type of damage observed during the inspections (see Fig.3b). This is in the form of whitish stains that are due to the crystallisation of the soluble salts on the surface that mainly appear on the chimney base, into which moisture seeps from the ground by means of capillary action.

3.2. Stone

In some cases, stone was used to construct the chimney base and this was often from the countryside close to where the chimney was built. The type of stone and its physical and mechanical characteristics determine its durability. After inspecting the 538 chimneys in the study, the most common problem found in the stone used for the bases was erosion due to environmental agents. Fig. 4 shows the case of a chimney with a base badly affected by erosion.

3.3. Mortar

Lopes et al. [20] studied a chimney badly affected by mortar degradation and Pallarés et al. [25] described the damage that can be found in the mortar used in industrial chimneys, dividing it into three types: chemical reaction with smoke, atmospheric agents and environmental contamination. Artoli et al. [12] and Minghini et al. [13] studied the effects of the Emilia-Romagna earthquake on a chimney which had been severely damaged in Ferrara (Italy). After an inspection, it was found that the mortar between the bricks had lost most of its properties due to the effect of atmospheric agents and this had weakened the chimney's resistance to the seismic action.

A large number of studies have dealt with how mortar in masonry structures can be damaged, and Lourenço et al. [37] provide an excellent classification, which can also be applied to chimneys. In the inspections of 538 chimneys, mortar was often found to have disappeared between the bricks, usually due to the degradation of the mortar itself or to defective workmanship. The worst cases were found to occur in mortar containing coarse aggregate, due to the reduced aggregate-binder specific contact surface, while in other cases the degradation was due to the lack of a binder. Cases of chimneys in which the mortar has disappeared from between the bricks can be seen in Fig. 5. It should be emphasised that such cases require immediate action since the resistance of the brickwork has been seriously reduced.

3.4. Ornamental ceramics

Ceramic elements, which are mostly tiles, were often used to decorate chimneys, usually in the form of a ring around the stack or in a broken vertical line. The main problem with tiles is their tendency to come away from the surface, particularly if they are attached directly to the masonry and not in specially prepared cavities. Cracks often appear in tiles due to their expansion and contraction under changes of temperature. Fig. 6 shows a chimney with a large number of missing and broken tiles.

3.5. Metal elements

Metal elements on chimneys mostly consist of:

- U-shaped bars inserted into the masonry to be used as a ladder
- Insulation carrying the lightning conductor cable to the ground.
- Metal hoops around the stack to act as reinforcement.

These elements are mostly affected by corrosion, which can damage the masonry itself, as has been pointed out by Lopes et al. [20]. When these elements undergo oxidation they increase in volume and create forces at the points in the masonry to which they are fixed. Fig. 7 shows a case of insulation elements that have corroded on a chimney and caused cracks in the bricks. Metal components can also create aesthetic problems due to the corrosion stains left by the rain running down the surface.

4. Damage caused by repeated actions

In this section, the damage caused to chimneys by frequent actions is classified, as distinct from accidental or extraordinary causes (which are dealt with in Section 5), whose effects on the chimneys are usually quite different.

Frequent actions are those considered to occur more or less continually throughout the life of the chimney, and the most common of these include:

- Prevailing winds
- Temperature variations
- Smoke produced by combustion
- Moisture in the base

4.1. Prevailing winds

Pallarés et al. [25] have shown that prevailing winds can induce permanent displacement of the top sections of chimneys and that this effect could be due to differences in mortar drying on different sides of the chimney. They cite the example of the city of Oliva (Spain), where most of the chimneys lean in the same direction. Ivorra et al. [28] maintain that the prevailing winds can cause permanent deformation due to creep in the masonry and give as an example the case of a chimney in Agost (Spain), the upper third of which has been deformed by the force of the wind. According to Pallarés et al. [25] and Ivorra et al. [28], the force applied by the prevailing winds affects the upper section of the stack, where the wind is strongest and chimney stiffness is weakest, and permanent deformation may be the result. In cases in which the crown is significantly displaced, serious cracks may appear in the windward side of the stack. Fig. 8a shows a chimney with a considerably deformed crown, and in Fig. 8b another chimney can be seen in which severe deformation caused cracking and a large cavity in both stack and crown.

4.2. Temperature variations

Ambient temperature variations can not in general cause significant damage to chimneys. The damage is mostly the result of the temperature variations and gradients caused by its function as a chimney [25] for the combustion and exhaustion of hot smoke and gases. These processes raise the chimney masonry to high temperatures, especially in the lower section of the stack, and as they are not continuous, the temperature quickly falls when combustion stops. This variation can cause tensile forces strong enough to produce cracks of diverse magnitude.

Cracks attributable to temperature variations usually appear near the base, which is close to the furnace, and are concentrated in the weakest part of the stack. Fig. 9a shows an example of a chimney with its base cracked by temperature variations and Fig. 9b shows another situation in which cracks are found in the zones of the lightning conductor insulation. Both the cracks in the base and the holes made in the masonry to fix the insulation generate a series of singular zones in which the stresses derived from the temperature variations are concentrated.

4.3. Smoke

The use of a chimney to exhaust smoke often causes dark stains to appear near the crown on the downwind side. Even though this type of damage does not represent a risk to its structural stability, it can be considered to be an aesthetic problem. Fig. 10 shows a newly constructed chimney in an urban area, where the aesthetic problem represented by the stains is not acceptable. It is therefore advisable to clean any smoke-stained zones, especially when the chimney has a symbolic or aesthetic value.

4.4. Moisture

Both bricks and natural stone can absorb moisture from the atmosphere or the ground by capillary action [38]. For example, Ramos et al. [29] studied an industrial brick chimney in Guimaraes (Portugal) which suffered from a damp problem due to absorbing water from the ground.

In the inspections carried out in the course of the present study, many cases were found of chimneys with evident symptoms of damp (see Fig. 11), one of which is the discoloration of the masonry in the affected zone. Moisture in a chimney can basically cause the degradation of the bricks, stone, mortar or metal elements, all of which contribute to reducing the chimney's resistance to the forces to which it may be subjected.

To avoid this problem, when chimneys are being restored it is therefore necessary to use appropriate techniques to ensure moisture cannot reach the structure from the ground.

5. Damage due to extraordinary events

Extraordinary events include those that only appear infrequently, as compared to those described in Section 4. In this section the extraordinary events are described which, due to their magnitude, can pose the highest risk to the structure's integrity, including:

- Strong winds
- Lightning strikes
- War damage
- Earthquakes

5.1. Strong winds

Section 4.1 described the effects of prevailing winds, considered as frequent actions, on chimneys. This section deals with the effects of strong winds, including tornadoes, hurricanes and high-speed wind gusts.

As chimneys are slim structures and are usually quite high, strong winds can cause considerable deformation, vibrations, local damage or in the worst cases complete collapse.

Aoki [19] found that chimneys in Tokoname (Japan) had suffered severe damage from typhoons. In Villar del Arzobispo (Spain) a chimney collapsed in 2007 due to wind gusts of over 130 kph (see Fig.12). As can be seen in the Fig. 12, most of the stack and crown collapsed and the remaining section shows signs of having been twisted by the high wind forces.

5.2. Lightning strikes

Pallarés et al. [25] studied the effect of lightning strikes on chimneys and Ramos et al. [29] and Masciotta et al. [39] analysed the case of a chimney in Guimaraes (Portugal) damaged by lightning that left two large holes in the masonry.

The authors also found lightning-damaged chimneys during the inspections carried out for this study. Even though lightning is capable of gouging holes in the masonry, as has been pointed

out by Ramos et al. [29] and Masciotta et al. [39], the effects of a lightning strike are usually limited to the loss of bricks in irregular patterns (see Fig.13).

The presence of a lightning conductor is usually enough to protect the chimney itself and any buildings nearby. This system consists of a metal cable that connects the lightning rod on top of the chimney with a metal earth in the ground that receives the electrical discharge. Lightning conductors need regular maintenance, since, if the cable is damaged the discharge will not reach the ground and the chimney will receive its full effects, which can be very severe.

5.3. War damage

In the course of the inspections, chimneys were found that had been damaged by artillery shells. Between 1936 and 1939 there was a civil war in Spain in which many chimneys were destroyed by artillery fire. These chimneys were sometimes used as strategic lookout points or shelters and were therefore frequently the targets of attack.

Fig. 14 shows the effects of shell fire on a chimney in Teruel (Spain). There is a large hole in the upper section and the masonry has been badly damaged by shrapnel. In situations such as that shown in Fig. 14 the chimney is seriously weakened and there is an imminent risk of collapse.

5.4. Earthquakes

Ghobarah & Baumber [9] were the first to study the effects of earthquakes on brick chimneys and found that the damage usually occurred near the base or in the upper third of the chimney and many other research groups later carried out studies on this phenomenon. Many authors have described the destructive force of earthquakes; for example, Huixian et al. [10] described the consequences of an earthquake on brick chimneys in Tangshan (China) in 1976. In Spain, chimneys suffered damage during an earthquake Mula in 1999 [40]. Chimneys were also found to be damaged after a similar event in Wenchuan (China) in 2008, as described by Zhao et al. [11].

More recently, many chimneys were damaged in the earthquakes in Emilia Romagna in 2012 and a large number had to be demolished [12]. Artoli et al. [12] and Minghini et al. [13] studied in detail the case of a chimney in Ferrara (Italy) that had been damaged by the quake in Emilia Romagna and had to be partially demolished.

A number of groups have focused on how to strengthen chimneys against the effects of earthquakes, including Pallares et al. [24], who studied the benefits of repairing chimneys with FRP, and Longarini & Zucca [26], who studied retrofitting chimneys with tuned mass dampers (TMD).

In order to illustrate the effects of earthquake damage on brickwork chimneys, Fig. 15 shows the state of one in Lorca (Spain) after the Lorca quake in 2011. The most serious damage was in the upper section, as indicated by Ghobarah & Baumber [9], with diagonal cracks. This chimney was strengthened after the earthquake, as shown in Fig 15b.

6. Damage caused by living organisms

This section enumerates and describes the damage caused by living organisms to industrial brick chimneys, which is mainly due to the action of: insects, animals, vegetation, fungi, lichens, but most of all by human beings. Insects can form colonies in chimneys, as they find mortar a suitable place for making nests. The mortar is weakened by the presence of holes, as shown in Fig. 16a, which in turn reduces the chimney's resistance.

Birds are the animals that cause most damage to chimneys. Bird droppings contain nitric acid and phosphoric acid, which reacts with bricks and mortar with deleterious effects. Large birds such as storks can also cause structural damage by building their large nests in the crowns (see Fig. 16b).

Wind-blown seeds often take root in the small transition platforms between the base and the stack, and the roots of the plants so produced can penetrate the mortar and get between the bricks, which may then break up and disintegrate (see Fig. 17).

Other types of organisms include fungi and lichens, which like to settle in damp places such as chimney bases. Ramos et al. [29] found fungi and lichens in a chimney they studied in Guimaraes (Portugal).

Diverse types of damage can be caused by human actions. Some of these may have taken place while the chimney was actually in use as part of a factory. It was quite a frequent practice to support certain elements such as roofs and ceilings against the chimney, and devices such as electric cables and pulleys were often attached to them. When the factory was demolished, these elements added when it was in operation either remained or were eliminated, leaving cavities, remnants of mortar or areas that had suffered damage by having to support heavy components. In Fig. 18a, the remains of a factory roof can be seen attached to the side of a chimney.

Other types of damage can occur when the associated factory has been demolished and the chimney becomes a symbol of the past. Insufficient funds and the difficulty of maintaining such high structures have usually been responsible for the fact that most of the chimneys inspected during this study were found to be in a deficient state of maintenance and conservation.

Vandalism is also to blame for a common and highly visible type of damage: graffiti. Although these do not represent a threat to the chimney's stability, the aesthetic damage they cause should be borne in mind, as they do influence the value of the chimney as part of the national heritage (see Fig.18b).

In recent years another type of damage has been found in the form of a deficient restoration operation or repairs, which may not only affect the chimney's aesthetics but also its structural behaviour.

7. Conclusions

The study described in this paper was based on a detailed inspection of 538 industrial brick masonry chimneys in Spain with the aim of determining their general state of conservation. After these inspections, it was found that most of the chimneys were affected by diverse types of damage and suffered from deficient maintenance and conservation.

The inspections carried out uncovered practically all the possible types of damage that can occur in brick chimneys and identified the most common of these. It was thus possible to classify the most frequent types of damage found in the form of a useful guide for architects, engineers and others involved in chimney maintenance and conservation.

These types of damage were classified according to their origin, each type was described, and its possible causes were identified. The text is supported by photographs taken in the course of the field visits during the study.

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Figure captions

Fig. 1. Location of the 538 chimneys inspected. Source: Google Earth.

Fig. 2. a) Parts of a brickwork chimney; b) Brickwork chimney in Sydney (Australia).

Fig. 3. Damage to bricks: a) Flaking bricks in a chimney in Peñarroya-Pueblonuevo (Spain); b) Efflorescence and superficial spalling in a chimney in Daroca (Spain).

Fig. 4. Damaged stonework in the base of a chimney in Linares (Spain).

Fig. 5. Deterioration and missing mortar. Chimneys in: a) Manzanares (Spain); b) Cinco Casas (Spain).

Fig. 6. Damaged decorative tiles in a chimney in Xàtiva (Spain).

Fig. 7. Damage caused by corrosion of metal components in a chimney in Gandía (Valencia): a) General view; b) Close-up.

Fig. 8. Displacements caused by prevailing winds: a) Chimney in Puertollano (Spain); b) Chimney in Oliva (Spain) with large openings in stack and crown.

Fig. 9. Damage in the form of cracks due to temperature variations and gradients: a) Chimney in Ciudad Real (Spain); b) Chimney in Sueca (Spain).

Fig. 10. Smoke stains on the upper section of a chimney in Segovia (Spain): a) General view; b) Detail of crown.

Fig. 11. Damp stains on the base of a chimney in Alfara del Patriarca (Spain).

Fig. 12. Chimney in Villar del Arzobispo (Spain), part of which collapsed due to strong wind gusts: a) General view; b) Close-up.

Fig. 13. Damage caused by lightning strikes. Chimneys in: a) Casas de Ves (Spain); b) Daimiel (Spain).

Fig. 14. Chimney in Teruel (Spain) damaged by artillery shells.

Fig. 15. Chimney in Lorca (Spain) after the Lorca earthquake (2011): a) General view; b) Diagonal cracks; c) Strengthening.

Fig. 16. a) Chimney in Catarroja (Spain) with mortar affected by the presence of insects; b) Chimney in Puertollano (Spain) weighed down by a large storks' nest in the crown.

Fig. 17. Damage caused by growth of plants in the base of a chimney in Gandía (Spain).

Fig. 18. a) Damage due to having to previously support an auxiliary structure in Foios (Spain); b)

Graffiti on a chimney in Villaluenga (Spain).

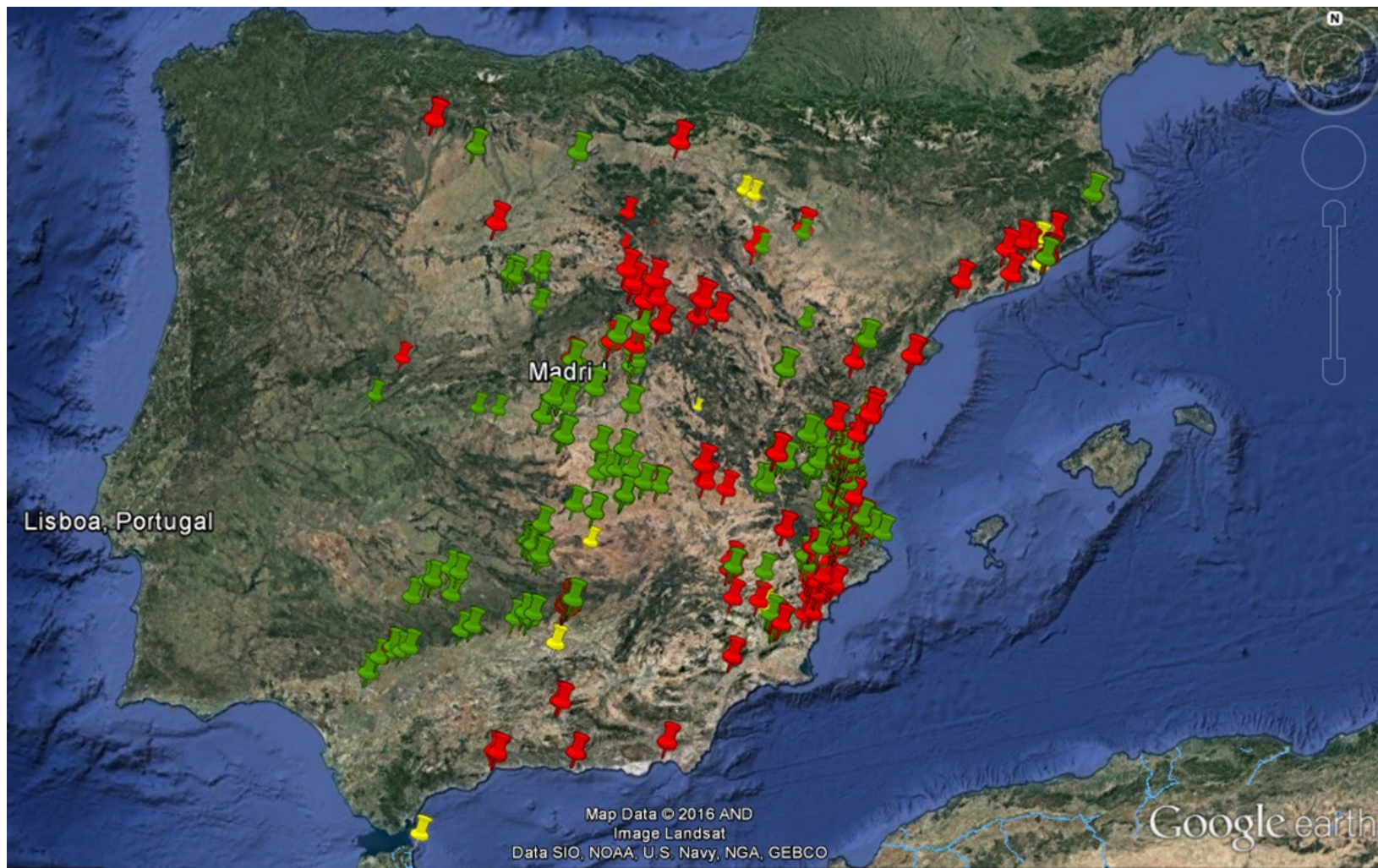


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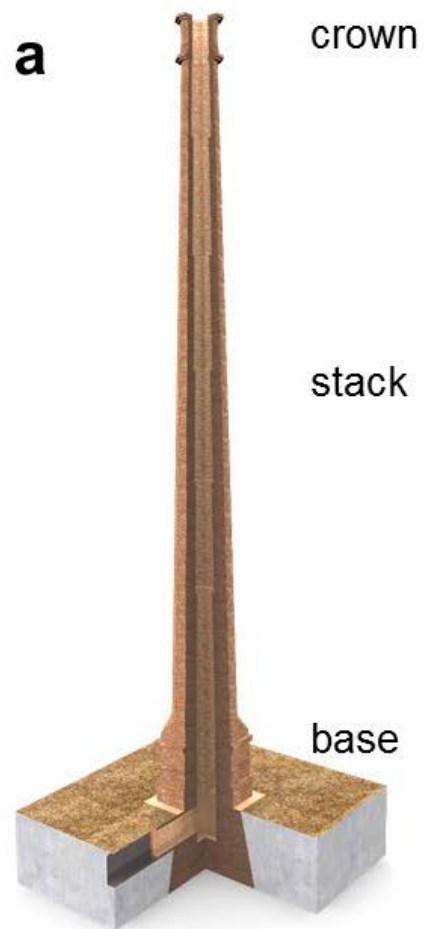


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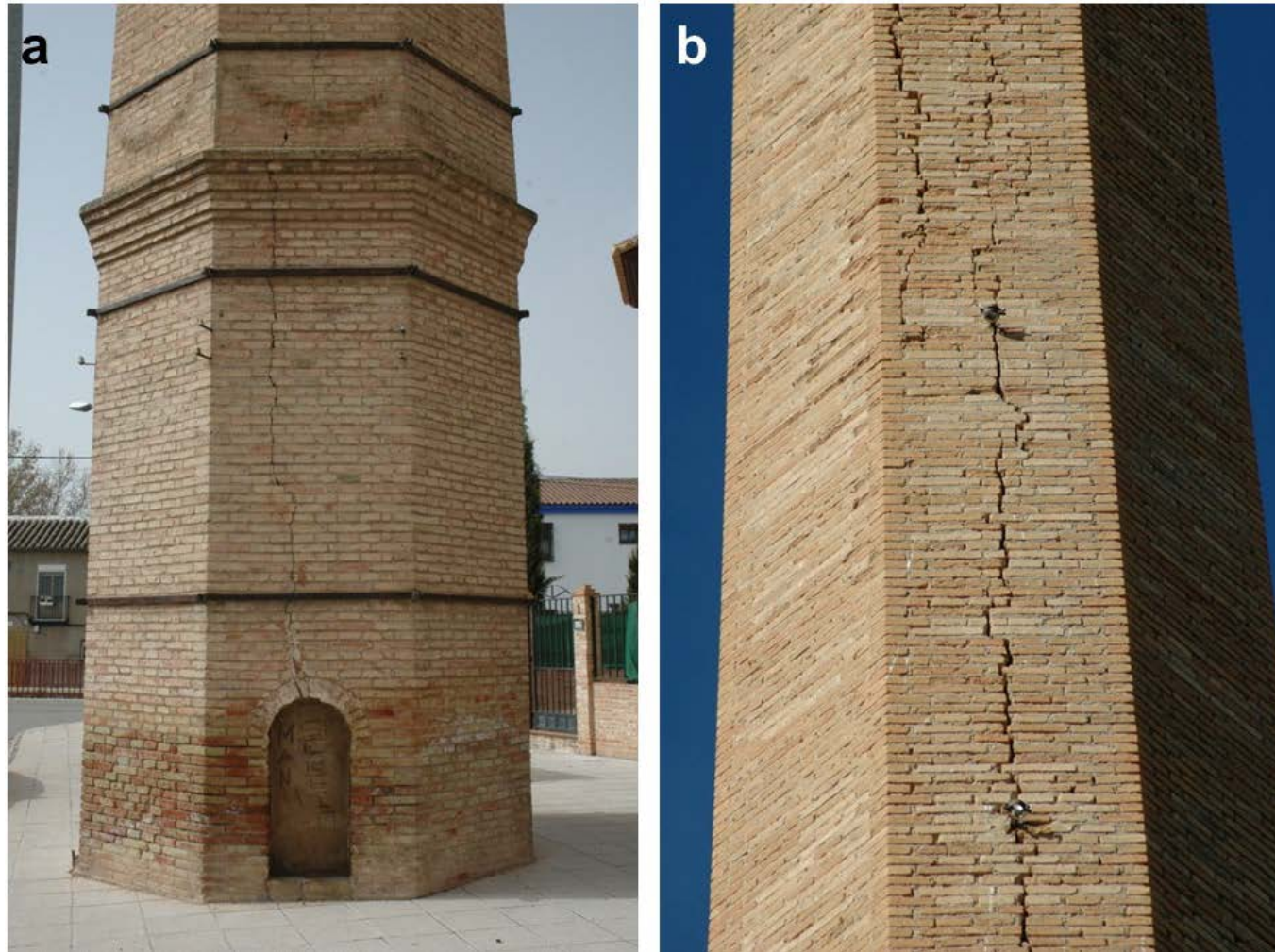


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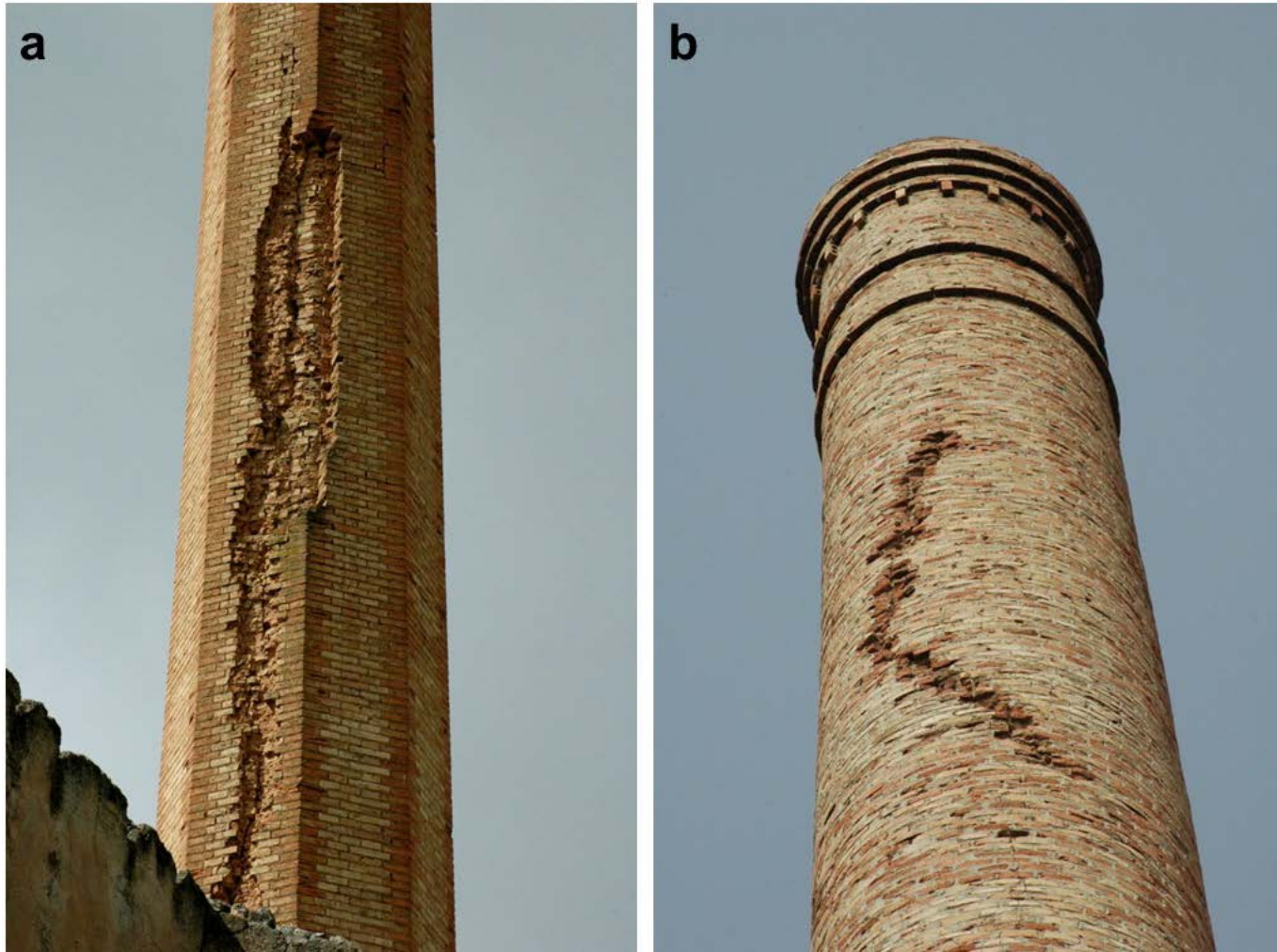


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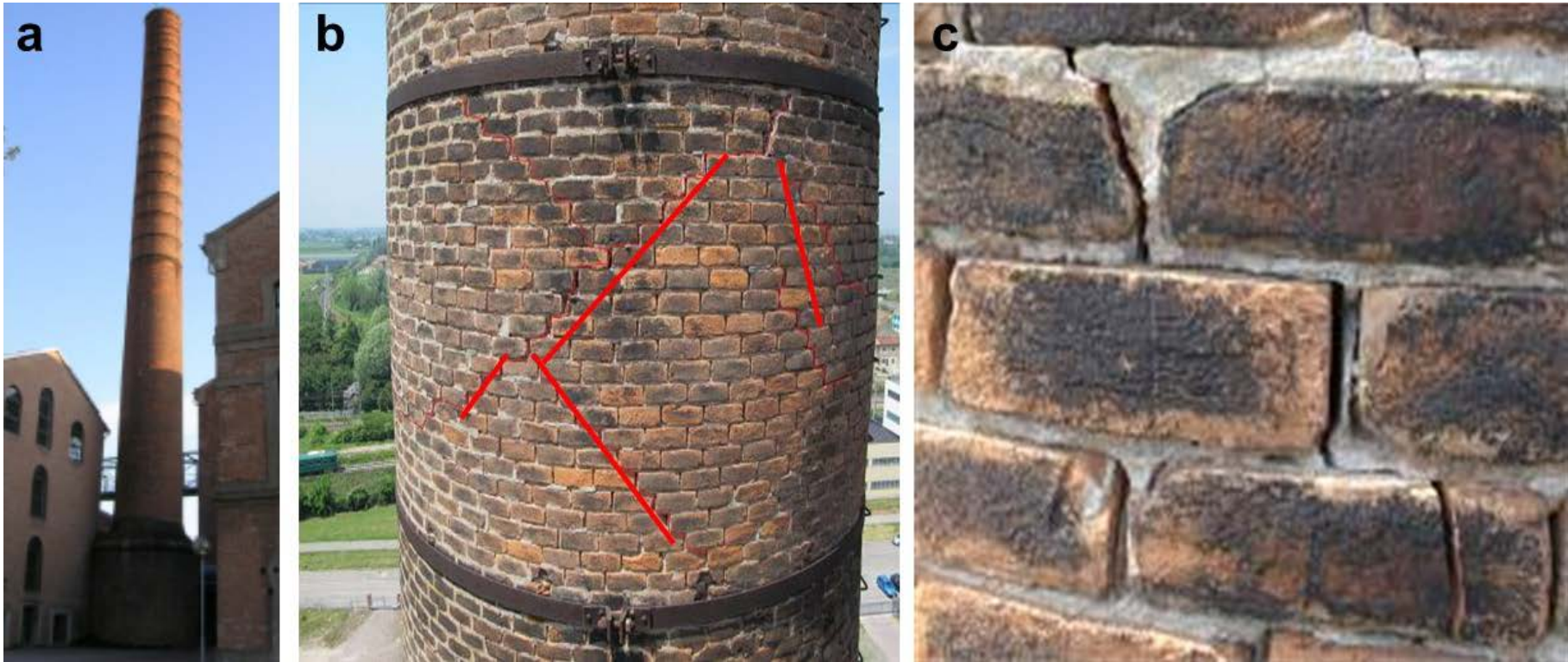


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