The Pombaline Cage ("Gaiola Pombalina"): An European Anti-Seismic System Based on Enlightenment Era of Experimentation

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Abstract. On November 1st, 1755, the lower part of Lisbon, a city of medieval character, was badly destroyed by the action of a violent earthquake, followed by a tsunami and violent fires. At the time, the Marquis of Pombal, ruled Portugal, and took several measures to safeguard the inhabitants and rebuild the city. It was decided to rebuild the city on the same site, according to a new urban plan with orthogonal streets. The conception of the new urban mesh was an Enlightenment Era design. The buildings were endowed with a series of unique characteristics, including an anti-seismic wooden structure - the Pombaline cage. This solution sought to resist earthquakes, making the building structure less rigid, aiming at dissipating the seismic energy through the lower weight and elasticity of the wood, the flexibility of the connections between the elements and even the lightening of the massive elements. This way, the total ruin of the building was avoided, in the event of an earthquake, and an interior area was created that could remain intact, serving as a refuge for the inhabitants. This anti-seismic system had great importance and influence in the panorama of engineering history, considering it could be at the genesis of seismic engineering in Europe. The perception that 18th century engineers had of the system to resist earthquakes through flexibility, should be the object of in-depth study, as it could be adopted in the reinforcement of constructions against possible earthquakes, especially the oldest ones, avoiding the introduction of rigid reinforcements in buildings otherwise characterized by their ductility. The present study seeks to explore the performance of this system, and to better understand how the increase in seismic performance is processed through flexibility, instead of the increase of the buildings stiffness.

Keywords: anti-seismic, wooden structure, earthquake, flexibility, Pombaline cage

1 Introduction

On November 1st, 1755, the city of Lisbon was hit by a violent earthquake, accompanied by a tsunami, followed by large fires that lasted several days [1]. The lower part of the city, with a medieval mesh, built on the unstable embankment's terrain of an old creek, was badly destroyed (see Fig. 1) [2].

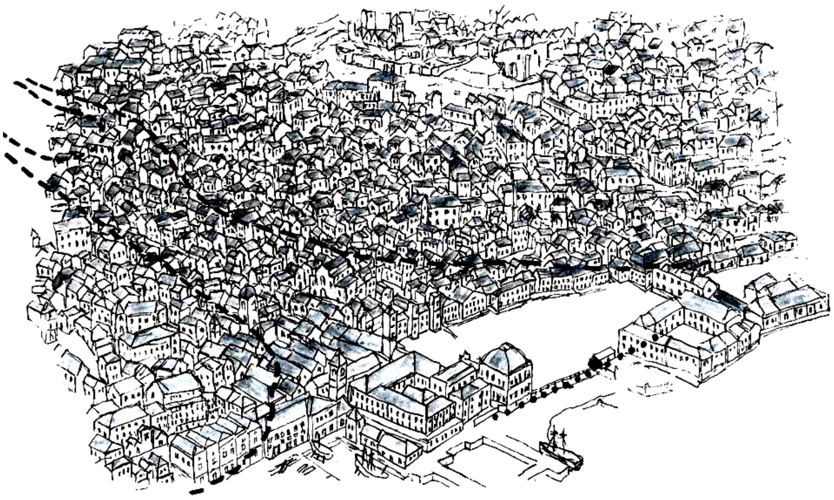

Fig. 1. The city of Lisbon before the earthquake, with the indication (dashed line) of the creek limit.

The Prime Minister of King D. José, the Marquis of Pombal, played a fundamental role in the reconstruction of the city, and marked the beginning of Seismology as a science. Several immediate measures were taken to protect the population, such as burying the dead to avoid epidemics, ensuring the supply of food products to the city and removing debris from the roads, a completely structured process that could be at the genesis of modern civil protection systems [3].

The almost total destruction caused by the earthquake led to the adoption of administrative and legislative measures so that a new Lisbon could be planned and built on the rubble of the old city. It was an extremely innovative decision for the time, implementing a new design plan based on orthogonal streets [4]. The Marquis of Pombal commissioned a group of Portuguese and foreign engineers to outline the new profile for the city of Lisbon [5]. Instead of rebuilding the city, using the old streets as a reference, new streets and squares were designed that would allow, in the event of a new earthquake, escape routes and concentration points for the population. All reconstruction operations were directed by military engineers, who combined their architecture and construction knowledge with cartographic reconnaissance and land use planning. They were led by an experienced military engineer - Engineer Manuel da Maia, who had the full support of the Prime Minister. The city reconstruction posed complex challenges, such as the need to redistribute areas from a medieval grid of narrow streets to a new orthogonal grid of wide streets, the need to erect four-story buildings on the unstable terrain of an ancient creek and also the need to act quickly to accommodate the many displaced people. The most ingenious part of Pombal's plan was that he really took care to build structures that would be able to stand up in the event of another earthquake. The Gaiola Pombalina, a three-dimensional and anti-seismic wooden structure, covered in masonry, was then created, to ensure that both the new buildings and the Lisbon blocks would survive earthquakes and fires. This system, extremely ingenious in its simplicity of principles and its practical realization, was inspired by naval construction, in which the wood frames, being deformable, had a high capacity to resist traction and compression stresses in a constantly agitated environment. On the other hand, masonry was an effective material in fire resistance.

The present study seeks to explore the performance of this system, and to better understand how the increase in seismic performance is processed through flexibility, instead of buildings stiffness increase. All drawings present in this document are originals by the author, and expressly created for this communication.

2 Context

In the last half of the 16th century, the great colonial powers, such as Portugal, Spain and the Netherlands fought over territories in South America. Underlying the economic issues were disputes between Catholics and Protestants. In Portugal and Spain, due to external threats, absolutist power was strengthened and in the face of reform, religious and even superstitious fervor increased. However, in the second half of the 18th century, a great interest in science existing in Europe, motivated by curiosity, associated with new experiences such as the arrival of new animal and plant species from Latin American colonies. In this period, the scientific method experienced great advances with experimentation. The Enlightenment theory, characterized by philosophical rationalism, the exaltation of the sciences and the criticism of the social order was developed. This theory called into question the tyrannical absolutism and the exaggerated splendor of the court and religious intolerance.

The Lisbon Earthquake effects were not confined to Portugal, but they also contributed, in some ways, to change the World. For example, the knowledge and understanding of the earthquake phenomenon in general. The first thought of the Portuguese people, when the earthquake occurred, was that God was punishing them. But, as in the rest of Europe, the Enlightenment era had an impact on the 18th century society. This event led to the first sci-entific studies on the origin of earthquakes, studies that contributed to the foundations of modern seismology de-velopment. The pragmatic approach to Lisbon reconstruction reflects the high value that the Enlightenment era placed on order, reason and knowledge [5]. In Portugal, the minister of the kingdom, Marquis of Pombal, who had been ambassador to England, was imbued with a strong Enlightenment spirit, and responded very correctly to the challenges posed in the reconstruction of the city. For the first time in the history of architecture and engineering, there were city-scale seismic concerns.

3 The Adopted Urban Plan

For the reconstruction of Lisbon, the Marquis of Pombal commissioned several alternative plans. But he chose Manuel da Maia's proposals, the most radical and meticulous plan. An unprecedented urban and architectural plan, influenced by Enlightenment ideas, supported by the architects Eugénio dos Santos and Carlos Mardel, which rebuilt the capital of the kingdom and, at the same time, changed an entire society. Much more than was lost, most of the buildings would be sacrificed to this innovative, geometric, and rationalist design, with wide, aligned streets and homogeneous blocks, and buildings with simple facades repeating a "harmony of proportions" (see Fig. 2). In order to guarantee the safety of the inhabitants in the event of a new earthquake, several measures were adopted in urban terms, namely; to prevent the city from being flooded again by a tsunami, the ground level was raised, using the rubble of the old city; in order to prevent the infiltration of wastewater from causing liquefaction effect on the ground, a sewer system was built; to allow the evacuation of the inhabitants and the easy movement of rescue teams, in the event of a new earthquake, the plan had a clear layout of orthogonal streets; to avoid the obstruction of the streets, in case of building collapse, the street width is equal to the height of the buildings, and clear accesses were established, with alternatives to the two large squares used as an emergency refuge.

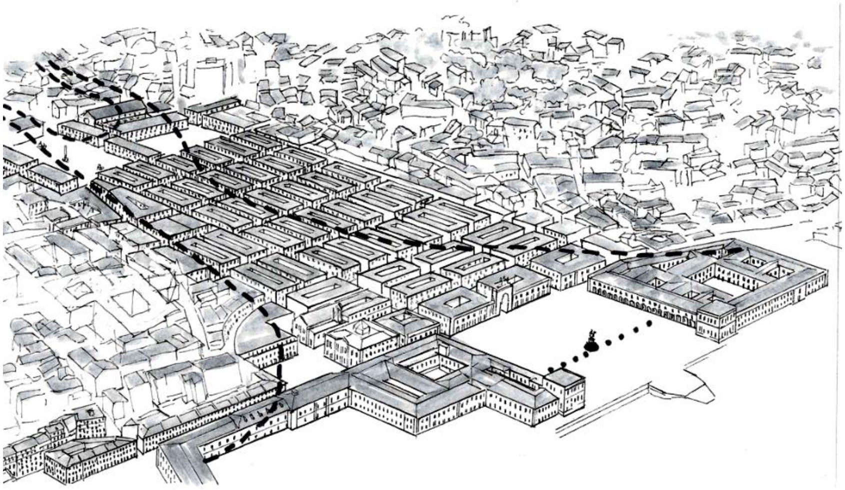

Fig. 2. Reconstruction of the city of Lisbon in the period before the earthquake.

3.1 The Building Blocks

To occupy a smaller land area, thus creating conditions for the construction of wider streets, the buildings were grouped into blocks. At the time, the inconveniences of the non-alignment of the buildings in a block in the event of an earthquake were known (Fig.3a). In a similar way, the existence of buildings in the same block with different heights (Fig.3b), also presented a poor performance. Two other geometric conditions that led to poor performance were the existence of facades perpendicular to the earthquake direction (Fig.3c) or the existence of galleries on the ground floors (Fig.3d).

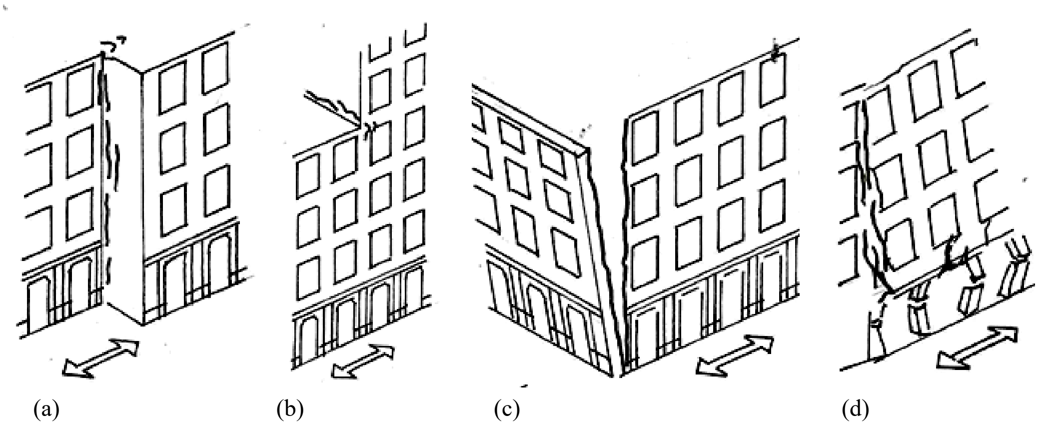

Fig. 3. Types of damage caused by earthquakes.

Thus, for better performance to seismic actions:

The buildings had to be strictly aligned; The corners of the buildings were reinforced with solid stone pilasters; It was imposed that the windows were kept away from the corners; The construction of galleries on the ground floor was also prohibited. - It was tried that in all blocks the buildings had the same height; The blocks were oriented longitudinally in the expected direction of the earthquakes, so that the shorter facades were perpendicular to that direction (Fig. 4). To easy the transfer of the old property to the new grid, a façade pattern was established, and always repeated.

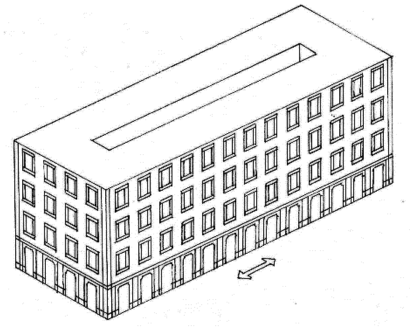

Fig. 4. Building blocks orientation.

4 Pombaline Income Buildings

The buildings, designed by military engineers, in addition to being designed in a standardized way, so that they could easily receive different components, had different constructive provisions, to better resist possible earthquakes and prevent the spread of fires.

4.1 Architectonic Provisions

Knowing that the regularity of the architectural layout was crucial, the designer sought to comply with a set of simple rules when designing the buildings (Fig.5): - The plants, in general, had two symmetrical apartments per floor. - For better stability of the facade, the spans were strictly aligned, both vertically and horizontally. - To facilitate the escape of residents in the event of a catastrophe, the stairs were located next to the facades, and therefore were provided with windows. - To prevent the chimneys from tipping over to the street, the kitchens were located on the side opposite to the street.

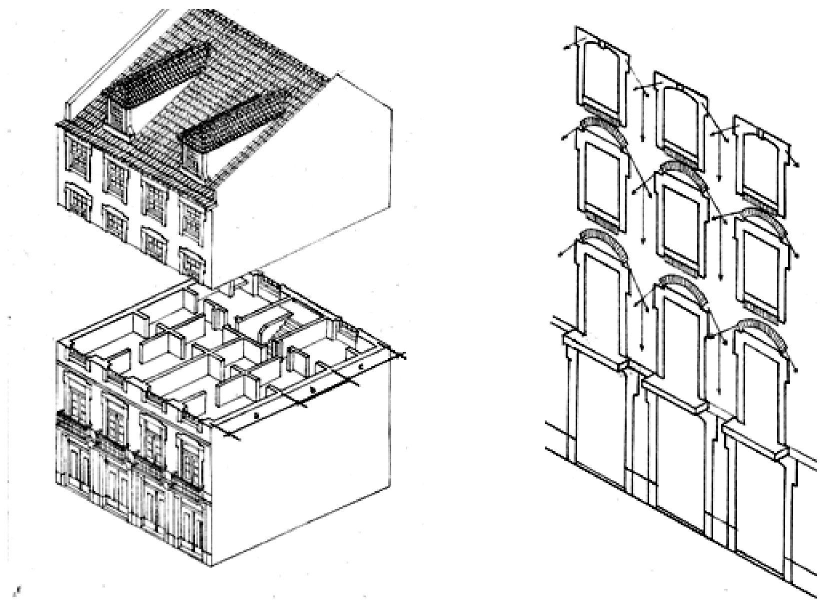

Fig. 5. Perspective of a forementioned architectural dispositions and balance of forces on the façade.

4.2 Constructive Provisons

In constructive terms, a set of rules were systematically implemented, which clearly conferred greater strength against possible earthquakes (Fig.6). As the foundation soil consisted of landfill, the buildings were based on pine piles. The masonry building incorporated an anti-seismic reinforcement wooden structure, known as “the Pombaline cage”, embedded in masonry walls, consisting essentially of a set of props and beams [6]. This was the first structure to be tested for earthquake action. A real model was built in a large square in the city, to which a regiment of soldiers exerted several synchronized movements, simulating an earthquake; Metal elements were used to ensure the connection between the floors, the roof and the timber-framed ‘cage’ walls in order to provide a box-type behavior for the whole building. Vaults covered the ground floor ceiling. These structures provided the structure lower part with greater rigidity and, at the same time, had the function of a fire-resistant element, in case a fire broke out in the stores. The cage structure started above this level. For greater stability, the stairs were developed around a wall, which minimized the risk of smoke rise.

4.3 Performance Against Seismic Acion

A considerable number of provisions were implemented to mitigate the effect of earthquakes in the new buildings (Fig.7).

The cage cloths were filled with small stone masonry, which allowed in the event of an earthquake, could have some movement to dissipate the earthquake energy.- On the facade walls, the cages had a simpler configuration and were located on the interior side of the façade wall, which means that in the event of a violent earthquake, they would allow the release of the heavy masonry wall, which was about 60cm thick [7].

As there were three lines of compartments parallel to the facades, the middle line was a safe area as it was located inside the cage.

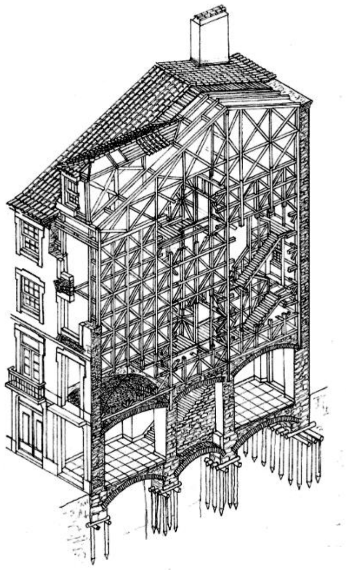

Fig. 6. Perspective view of the aforementioned constructive provisions.

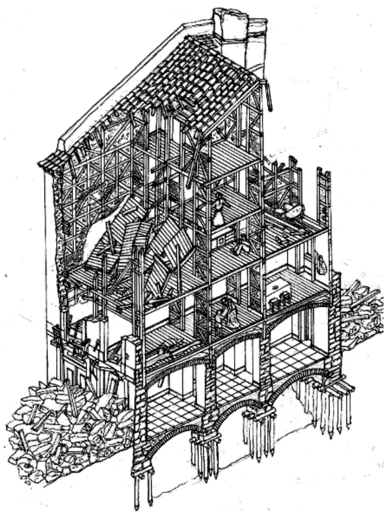

Fig. 7. Perspective view of the construction provisions that allowed to attenuate the effect of earthquakes.

5 The Pombaline Cage – Anti-Seismic Structure

In many countries, such as Greece, Turkey, France, Germany, the United Kingdom and Poland, there are numerous examples of current and historic buildings with mixed (composite) structural systems based on wood, stone, brick and earth collaboration, wood being the toughest element [8].

The cage is a typically Portuguese standardized construction system made of oak, holm oak or pine [9], which was a milestone in the history of national and international construction (Fig.8). It includes details that had not been addressed until then, such as the structural stability of buildings in the face of seismic actions, fire safety and the standardization of construction elements. The Pombaline cage consists of a series of Saint Andrew's crosses, based on the empirical principle of the impossibility of deforming a triangle (Fig.9a). The diagonal arrangement of the wood reinforces the structure and, at the same time, makes it flexible to absorb and dissipate horizontal forces. This structure produces, from the first floor, a three-dimensional locking system, which is then filled with masonry, which provided the set an additional strength [10].

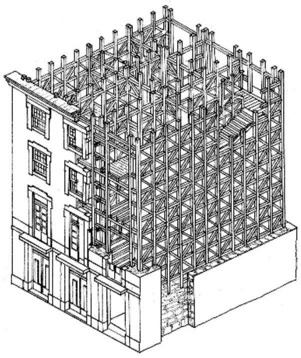

Fig. 8. Perspective representation of the Pombaline cage inside buildings.

The anti-seismic structure of the cage comprised three floors, with a very balanced relationship between height and depth. The props generally had a square section while the transoms and diagonals had a rectangular section (Fig.9). On the first floor, the cage had two modules of crosses and, on each of the upper floors, only one and a half modules (Fig.10) [11].

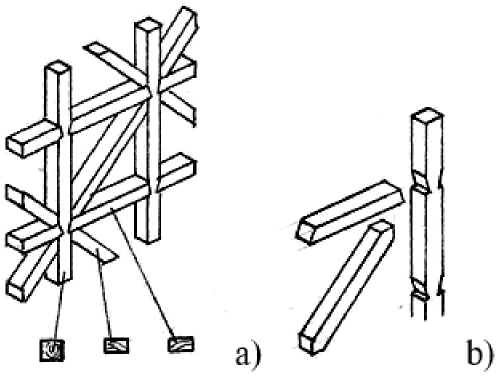

Fig. 9. A) Cage; b) Props.

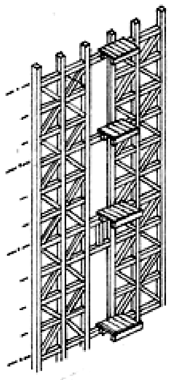

Fig.10. Cage structure development in height.

The spaces between the wooden structure sections of the cage were filled with earth mortar and small stones. The whole materials were covered with a lath (Fig.11a) on which earth mortar was applied. In the event of an earthquake, all the filling and coating material, due to its ductile nature, allowed the cage to move (Fig.11b) [12]. The intersection between cage planes was made by multiplying the plumbs in the intersection zone (Fig.12). The wall around which the stairs were developed always had two continuous props and interlocking sections, diagonally, following the development of the stairs (Fig.13).

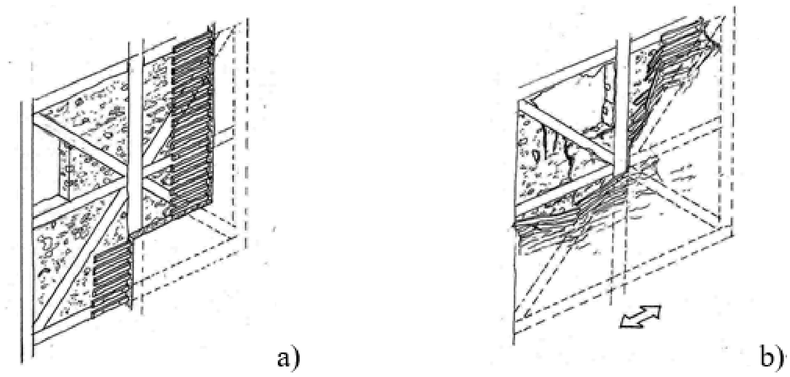

Fig.11. a) Filling of the cage structure; b) cage performance in the event of an earthquake.

In Portugal, traditionally, the thickness of the facade walls decreases with height (Fig.14a). In the case of the Baixa Pombalina, the wall thickness is constant throughout the height. The cage structure, in addition to being simplified, was in the interior face, revealing that this system was designed to free the heavy masonry facades, when a violent earthquake occurred (Fig.14b).

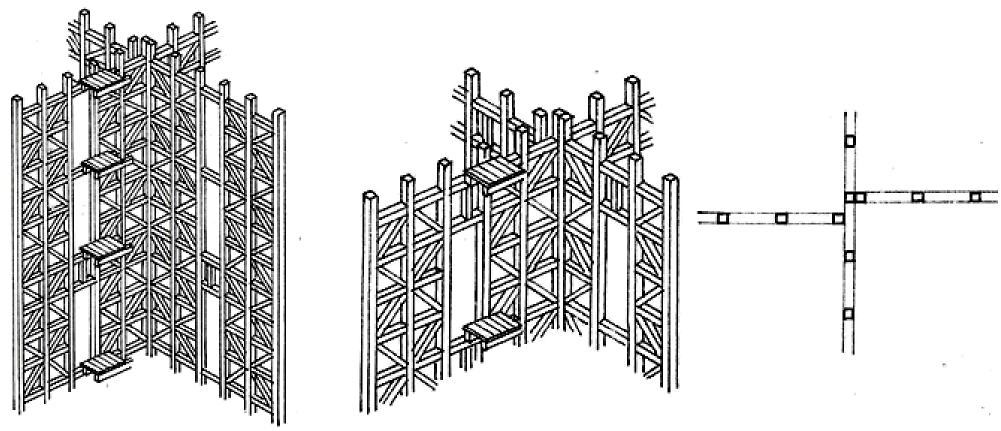

Fig.12. Intersection of cage walls.A

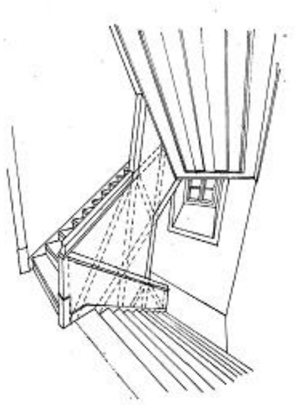

Fig.13. Insertion of stairs.

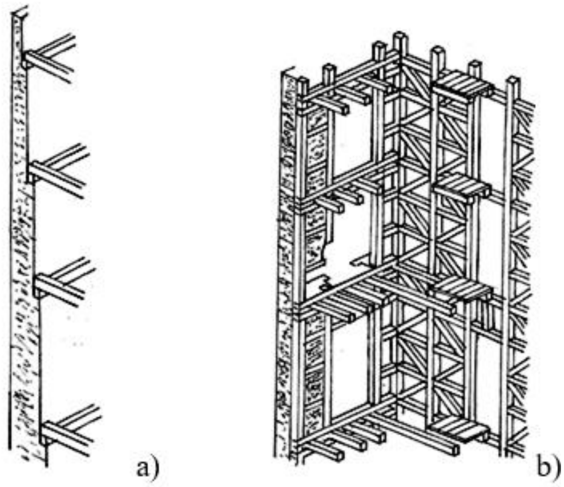

Fig.14. a) Traditional wall; b) Pombaline building wall.

6 Conclusions

Many studies have proven the efficiency of the Pombaline Cage in resisting horizontal forces, such as those induced by seismic action. The cage contributes to a good performance of the building as a whole and limits the horizontal displacements of the whole structure. This system opposes the seismic action due to its ductility, seeking to dissipate energy, allowing small movements, and also relieving excessive loads such as heavy masonry facades. There is no record that these buildings, even those with the altered Pombaline structure, or voted to be abandoned, have collapsed. The same does not happen in buildings built later, with different operating modes.

This interesting heritage, very important in seismic engineering history and technology, has been neglected along time, due to ignorance of the public. This has led to the continued destruction of these buildings.

Acknowledgements

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