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EARTHQUAKE RESISTANT STRUCTURES OF PORTUGUESE OLD 'POMBALINO' BUILDINGS

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SUMMARY

Portuguese 'Pombalino' masonry buildings were built mainly in Lisbon Downtown after the 1755's Lisbon Earthquake. The conception of these buildings included anti-seismic provisions, which are described in this paper. One of the most relevant provisions is the inclusion of an interior three-dimensional braced timber structure named 'gaiola' enclosed in masonry walls above the first floor aiming at providing resistance to horizontal forces. Seismic assessment of one representative 'Pombalino' Building is discussed, where the influence of 'gaiola' walls in its seismic behavior is referred. The expected collapse mechanism of 'Pombalino' buildings is discussed, as well as usual strengthening solutions. Seismic assessment of these buildings is discussed based on their actual conservation state and on structural changes on the original structure.

INTRODUCTION

The Portuguese territory is a seismic prone region. One of the most destructive earthquakes in the history of this country is the Earthquake of the 1st November of 1755. It was a strong earthquake (estimated Richter Magnitude 8.7) and epicenter in the Atlantic Ocean, at approximately 250km south of Lisbon. The 1755 Earthquake destroyed large areas in Lisbon and Algarve, the southern region of Portugal. In Lisbon, the Earthquake was followed by a tsunami and a fire was out of control for several days, as illustrated in Figure 1.

Lisbon Downtown, near Tagus River, was the most destroyed area of Lisbon and was rebuilt following a urban plan. The need of a fast rebuilt and the fear of another earthquake led to the enforcement of new construction rules based on the experience learned from the collapsed buildings due to the earthquake, aiming at providing seismic and fire resistance to the new

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constructions. The new constructions built according to these rules are named 'Pombalino' Buildings (Figure 2), after the 'Marquês de Pombal' that was the king's prime minister responsible for Lisbon reconstruction. The construction rules were not written in a document but they can be considered as the first technical prescriptions regarding seismic resistance of the new constructions and strictly enforced, otherwise the building would be demolished by order of the king.

Figure 1 – Lisbon destroyed by the Earthquake of the 1st November of 1755

The most relevant anti-seismic provision of the 'Pombalino' Buildings is the existence of a three-dimensional timber structure named 'gaiola pombalina' wrapped up inside masonry interior walls above the first floor. The intention of the 'gaiola' three-dimensional timber structure conception was to provide resistance to horizontal forces. There are doubts about the possible intention of allowing the overturning of the façades (masonry walls without timber elements) without the collapse of the building. Another anti-seismic provision was the limit of three stories for the buildings.

Since the fire that followed the 1755 Earthquake caused a large number of deaths, 'Pombalino' Buildings also include anti-fire provisions. One of these provisions is the inclusion of thick masonry walls between adjoining buildings, higher than the roof timber structure, in order to prevent the fire propagation between buildings. The existence of fireplaces at the commercial shops of the ground floor motivated the system of masonry arches and vaults in this floor and the inclusion of the 'gaiola' timber structure only above first floor as another anti-fire provision. Masonry walls at the ground floor level were also adopted aiming at isolating the timber structure from the underground water, since the water table is near the ground surface (Downtown is near Tagus River).

The largest number of buildings with 'gaiola' is located in Lisbon Downtown. However they can also be found at other places in Lisbon and at other less important urban areas of Portugal also destroyed in 1755, like Vila Real de Santo António in Algarve.

As time went by, construction practices changed and timber elements were progressively removed from the three-dimensional structure. Experience shows that masonry buildings built between 1755 and the early 19th century included a complete three-dimensional timber structure ('gaiola') above the ground floor. It is thought that the use of the 'gaiola' construction was completely abandoned by the decade of 1880. A more detailed description of these buildings can be found in Cardoso *et al.* [1].

'POMBALINO' BUILDINGS FROM LISBON DOWNTOWN

Figure 2 presents structural details of 'Pombalino' Buildings, where the presence of the 'gaiola' enclosed in masonry interior walls is identified. The other interior walls (partition walls) are wooden panels that should not be considered having structural functions. Roofs are made with timber truss and ceramic tiles and may include window openings. Floors are timber slabs and can be considered as a flexible diaphragm. Ground floor walls are masonry walls supporting a system of vaults made of blocks of ceramic masonry and stone arches. Foundations include short and small diameter woodpiles connected by a timber grid. The masonry of the exterior walls (thickness 0.80m) is made of irregular blocks of calcareous stone and lime mortar with very poor strength capacity. Masonry infill of the 'gaiola' can be stone rubble, some of it from the earthquake-collapsed buildings, or clay bricks, similar to the bricks used at ground floor vaults. It is usual to find both type of masonry at the interior walls.

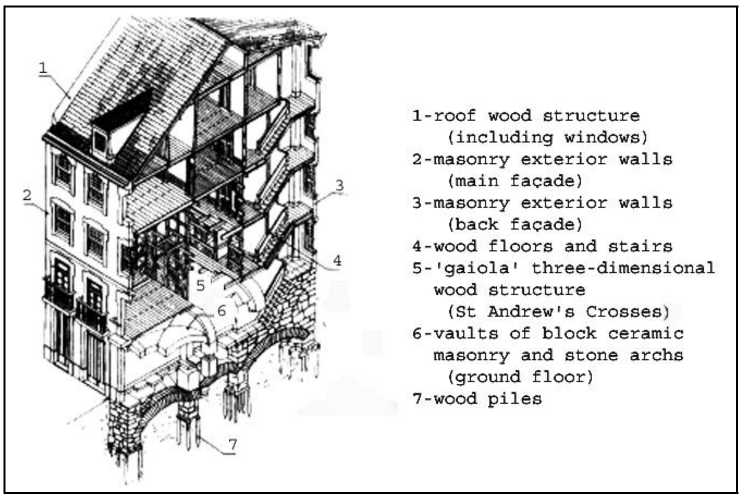


Figure 2 – Structural details of a 'Pombalino' Building (*adapted from* Mascarenhas [2])

In Figure 3, an aerial view of Lisbon Downtown, it can be observed similar regular blocks of buildings as a result of urban planning after 1755. Each building belongs to a given block, being similar to the buildings in the same block, and each block is similar to the other blocks. Most of the structures are 'Pombalino' Buildings. Figure 4 shows a photo of the façades. Original functions of these buildings were commercial at the ground floor and residential at the upper floors, with one or two housing units by story.

The façades architecture (Figures 4 and 5) allows distinguishing 'Pombalino' Buildings from other masonry buildings due to the geometry regularity and symmetry. According to the original conception, dimensions and horizontal spacing of openings are the same for all 'Pombalino' Buildings. Front façades present vertical alignment of the openings, identifying individual vertical and horizontal masonry alignments.

For a typical 'Pombalino' Building, ground floor openings are doors. First floor openings are all of the same type (only doors with balconies or only windows), depending on the importance of the street in front. The other floor openings are windows. At the top floor, openings are included in the roof structure and can be doors or small windows. The number of openings varies from 3 to 6 per story and depends on building dimensions.

Figure 3 – Aerial view of Lisbon Downtown (Santos [3])

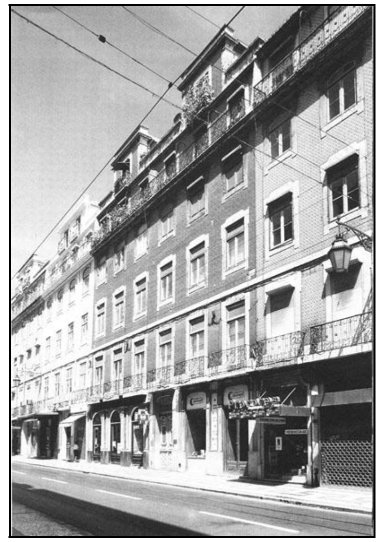


Figure 4 – 'Pombalino' Building from Lisbon Downtown (Prata Street, 210 to 220) (Santos [3])

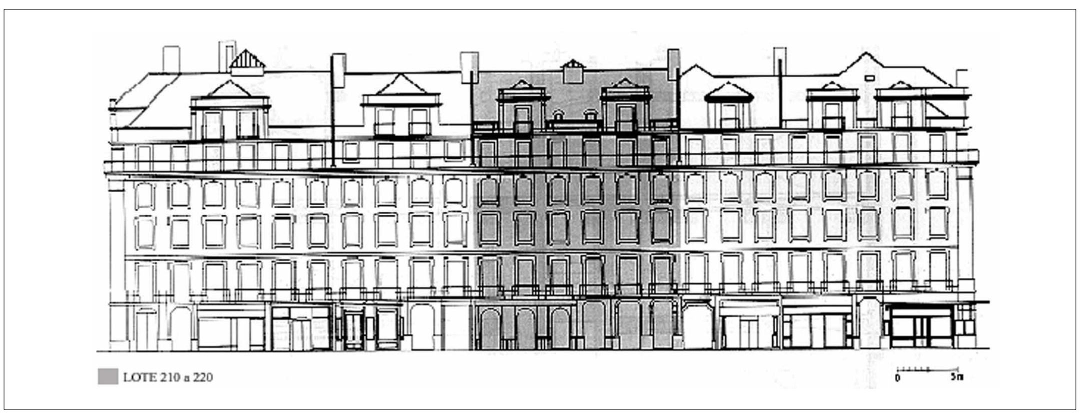


Figure 5 – Façades architecture of a Downtown typical block (Santos [3])

According to Portuguese military/civil experience in construction practice, geometry regularity allowed serial construction, speeding up the construction process. Another provision to speed up the construction was the organization of the construction sequence of 'Pombalino' Buildings: the 'gaiola' and the entire timber structure were the first to be built, masonry infill was placed afterwards, at the same time as exterior masonry walls construction. At the end, windows and doors stones were placed, with finishing work. This sequence allowed different specialists (carpenters and masonry workers) to do their jobs without interferences.

The Downtown reconstruction was slower then expected due to economical reasons and to owners induced delays. The owners wanted more economical benefits from their properties than the ones obtained if the enforced rules were followed. As a result, in spite of three being the maximum number of stories as prescribed, most buildings were built with four stories.

THE STRUCTURE OF 'GAIOLA POMBALINA'

The 'gaiola' three-dimensional timber structure

As previously mentioned, 'Pombalino' Buildings (Figure 2) are old masonry buildings that can be identified by the presence of a three-dimensional timber structure named 'gaiola pombalina' enclosed in masonry interior walls above the first floor (Figure 6). The other interior walls (partition walls) are timber panels and can be distinguished from 'gaiola' walls because 'gaiola' walls are thicker (18 to 25 cm) than partition walls (10 to 15cm).

The timber structure of 'gaiola' is like a birdcage made of vertical and horizontal elements braced with diagonals named St Andrew's Crosses (Figure 6). The connections between the timber elements of 'gaiola' and the exterior masonry walls are performed by iron elements but experience shows that sometimes these elements do not exist. Most of the times, timber elements of 'gaiola' are notched together (Figure 7) or connected by nails or iron ties according to historical information regarding construction techniques. The timber frame conception of 'gaiola' and connections between timber elements were inspired in ship construction, which was an excellent Portuguese expertise.

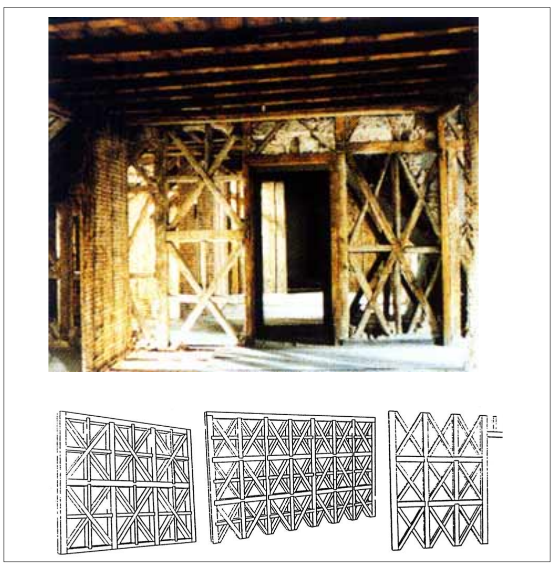


Figure 6 – Timber elements of 'gaiola' enclosed in masonry interior walls (Cardoso [4])

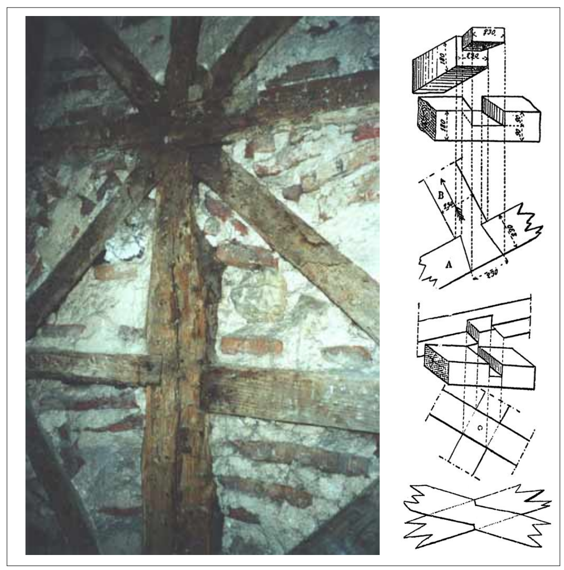
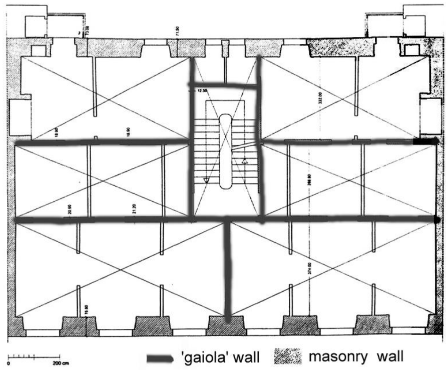


Figure 7 – Connections between timber elements of 'gaiola' (Cardoso [4])

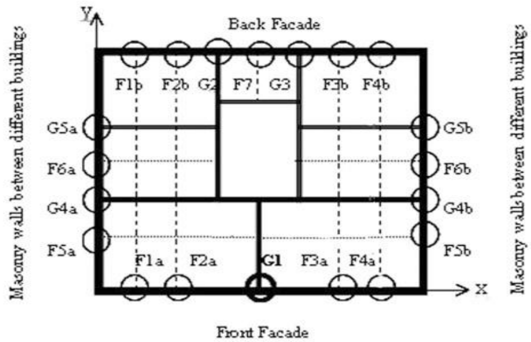
The influence of 'gaiola' in the global behavior of the building

A previous study (Cardoso [4]) was performed to understand the influence of the three-dimensional timber structure in the dynamic global behavior of a 'Pombalino' Building. In this study, a numerical model of a building from Lisbon Downtown (Prata Street, 210) was developed. The plan of an intermediate floor of the building is presented in Figure 8, where the 'gaiola' walls and their connections to masonry walls are identified.

The dynamic behavior of the building with the 'gaiola' structure was compared with the dynamic behavior of the same building without this timber structure. The main conclusion was that 'gaiola' structure increases the building global stiffness because: (i) the frequencies of the building with the 'gaiola' are higher than those obtained in the model of the building without this structure – Table 1; (ii) according to the modal configurations observed for both buildings, the presence of ‘gaiola’ prevents local vibration modes of the masonry walls because the out-of-plane displacements of each masonry wall (façades and masonry walls between adjoining buildings) no longer occur independently from the rest of the structure; (iii) the out-of-plane displacements are equal for parallel masonry walls connected by the same ‘gaiola’ wall.



Plan of a typical floor of the analysed building (*adapted from* Santos [3])



Plan of the numerical model of the building, identifying the different walls and the connections considered (G- ‘gaiola’ walls, F – floors)

Figure 8 – Plan of the analysed building

Table 1- Modal configurations and frequencies for the building with and without ‘gaiola’

Modal configuration	*Building with ‘gaiola’ - f [Hz]*		*Building without ‘gaiola’ - f [Hz]*	
Translation perpendicular to the front façade	Mode 1	0.942	Mode 1	0.398 (local vibration mode)
Translation parallel to the front façade and torsion	Mode 2	1.055	Mode 2	0.695 (local vibration mode)
Translation perpendicular to the front façade	Mode 2	1.196	Mode 3	1.009

For the building without ‘gaiola’, the first modes are local vibration modes, which correspond to independent out-of-plane displacements of each masonry wall. Most of the local modes observed concern the front façade.

Figure 9 presents the out-of-plane displacements of the front façade of the building with and without the ‘gaiola’, obtained in the connection G1 (Figure 8) for the seismic action defined in Portuguese Code of Actions (RSA [5]). The seismic action adopted was defined intending to simulate an earthquake similar to the 1755 Lisbon Earthquake and considering soft soil, according to the soil found in Lisbon Downtown. The maximum displacements were obtained in the top of the building. The local displacements presented in Figure 9 are the displacement corresponding to the real out-of-plane deformed configuration of the front façade, defined by the difference between the displacements obtained in the connection G1 and the one obtained in the corner of the building.

According to the obtained results, the local displacement due to the presence of the ‘gaiola’ is reduced about 70% (from 15.7cm, in the building without ‘gaiola’, to 4.7cm in the building with this timber structure). The study performed allowed understanding the bracing function of 'gaiola' since out-of-plane displacements of masonry walls connected to perpendicular 'gaiola' walls was reduced.

Besides the bracing function of 'gaiola' and the improvement of the building resistance to horizontal forces, this timber structure also affects the dynamic behavior of the building. The hysteretic energy dissipation capacity of 'gaiola' enclosed in masonry walls due to the gaps between the timber elements and crack openings in masonry should be better characterized and accounted for. The presence of steel elements at the connections between timber elements may be responsible for ductility, as observed during tests performed at panels removed from buildings (Alvarez [6]). The mechanical behavior of 'gaiola' needs a more detailed investigation for a better definition of the damping coefficient and ductility of this structure.

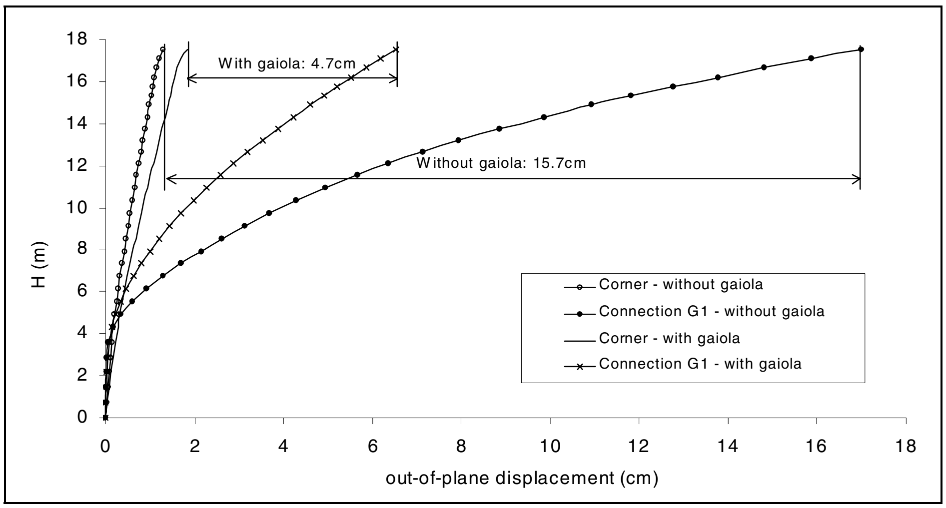


Figure 9 - Out-of-plane displacements of the front façade obtained in the connection G1 for the seismic action defined in Portuguese Rules (RSA [5]).

THE EXPECTED COLLAPSE MECHANISM OF 'POMBALINO' BUILDINGS

Past earthquakes all over Europe showed that the main collapse mechanisms of old masonry buildings are the bending of façades (out-of-plane) or shear at the plane of the walls at ground floor level (global shear mechanism), that leads to a global collapse mechanism (Croci [7]). Masonry low tensile and shear strength may be relevant to determine the kind of collapse mechanism and the level of seismic intensity associated to initiation of damage.

As previously discussed, the 'gaiola' timber structure improves seismic performance of the building but this structure exists only above the first floor. The vertical transition from the ground floor (only masonry) to the first floor (masonry and 'gaiola') may be relevant for seismic collapse mechanism of these buildings because stiffness change and the connections between transition elements are not well known. For example, the formation of the global shear-base (at the plane of the walls) collapse mechanism may be induced due to this transition.

Another example of weakness in these buildings is the bad quality of masonry or the construction of different walls at different times, leading to weak connections between perpendicular masonry walls. Like all masonry buildings, the presence of large openings reduces the strength of façades.

Besides understanding the influence of 'gaiola' in the building global behavior, the study performed (Cardoso [4]) also intended to identify the expected collapse mechanism of the analyzed 'Pombalino' building (Prata Street, 210). This mechanism was identified by adopting an iterative method that allowed considering the main sources of non-linear behavior of these structures, like masonry crack openings and the rupture of connections. The connections considered were the ones between the timber elements of 'gaiola' and those between timber elements ('gaiola' and floors) and masonry walls. A commercial program was used in order to perform linear dynamic modal analyses by response spectrum.

The collapse mechanism obtained for the analyzed building was out-of-plane bending of the front façade. Figure 10 presents the damages that allowed identifying this mechanism. The rupture of the connections G1 between the front façade and the perpendicular 'gaiola' wall and damages in the masonry wall simultaneously allowed identifying this collapse mechanism. The masonry damages considered were due to tension and compression due to bending and shear in and out of plane of the wall.

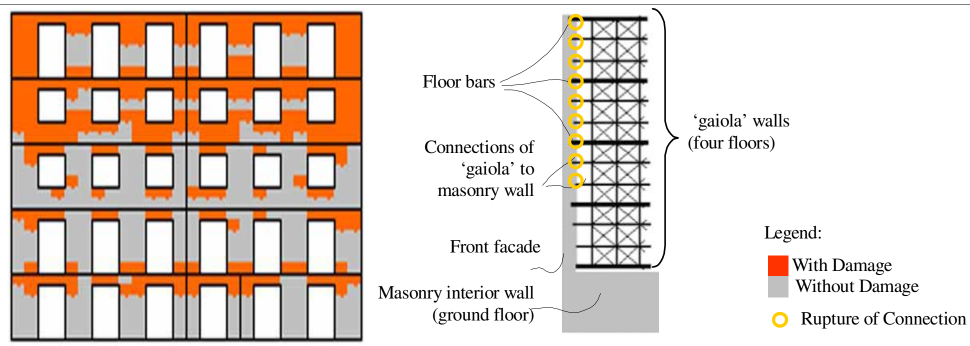


Figure 10 - Masonry damages and the rupture of connections that allowed identifying the bending of the front façade collapse mechanism (Cardoso *et al.* [1])

The collapse mechanism obtained corresponds to the expected one for these buildings according to what may have been their original conception. In fact, this structure would allow the overturning of the façades without the collapse of the building, as presented in Figure 11. This conception may be efficient for one or two floor buildings as it shown in Figure 12 that represents a building whose exterior walls have fallen out-of-plane in the 1998 Azores earthquake. However, there are some uncertainties regarding its efficiency in buildings with more than two floors because the out-of-plane fall of the façades may bring down other parts of the building.

ACTUAL CONSERVATION STATE OF 'POMBALINO' BUILDINGS

Due to their location at Downtown, the center of Lisbon, during the XXth century most of 'Pombalino' Buildings were adapted to new functions (small offices and services instead of housing) or completely occupied by banks and companies. For the buildings that maintain their original conception, the main problems result from deficient/absence of maintenance. Roof broken ceramic tiles that allow water infiltration causing masonry and timber degradation is one of the most common deficiencies found.

When floor and 'gaiola' timber elements are not connected with metallic (steel) elements to masonry walls, degradation of materials may strongly reduce the strength of the connection. Ground settlements due to underground tube construction and changes on the underground water level also caused some masonry cracks, which can be observed near the corners of the openings. Corner elements and connections between interior masonry walls (perpendicular to façades) and facade walls can also present small cracks, showing detachment of façades.

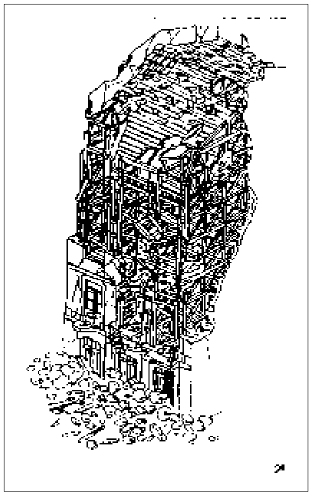


Figure 11 - Collapse mechanism according to original conception

Figure 12 - Fall out the plane of exterior walls without complete collapse (1998 Azores earthquake)

The most relevant changes in these buildings are the inclusion of bathrooms and running water and the opening of larger shop windows at ground floor, sometimes with partial or complete demolishment of exterior masonry walls at this level. The building vulnerability to shear base collapse mechanism is increased after the demolishment of ground floor masonry vertical elements. Figure 13 presents ground floor interventions performed to open larger shop windows.

Advisable *Advisable*
(The continuity of the masonry vertical elements is not interrupted)

Not advisable
(The continuity of the masonry vertical elements is interrupted)

Figure 13 – Usual interventions performed to open larger shop windows

Another important structural change is the demolition of interior walls, the introduction of stairs and elevators and the construction of more stories at the top of the original building. These changes are critical especially when they introduce structural elements that have different properties than the original ones. For example, it is very common to find metallic elements (Figure 14) replacing the demolished masonry walls. The introduction of more stories at the top of the building (Figure 15) is also critical because the mass increases at the top, increasing the effects of the seismic action in the building and the out-of-plane displacements at the top of the façade, which may lead to the collapse of the façades.

The changes described were prescribed after structural design, where the transmission of vertical forces was verified. The most probable, however, is that horizontal forces transmission was not considered in most interventions. For this reason, the buildings seismic vulnerability might have been increased due to changes to the original structures.

Due to the influence of ‘gaiola’ in global seismic behavior of the buildings, the demolition of interior walls reduces the seismic resistance and therefore is not advisable. In fact, the bracing function of the ‘gaiola’ and its contribution to the building global stiffness would be lost. Small changes in ‘gaiola’ structure like removing timber elements or cutting elements for pipe installation (Figure 16) also reduce the bracing capacity of this timber structure. The masonry cover of ‘gaiola’ usually hides these details, which should be investigated and repaired in real rehabilitation. In Figure 16, two examples for pipe installation are presented. One solution is much worse than the other but both should be avoided because they interfere within the timber structure.

Figure 14 – Metallic element replacing demolished wall

Figure 15 - Introduction of more stories in the top of the buildings (each building has different number of stories)

Not advisable:
The timber section was cut/ reduced for pipe installation

More advisable:
The timber section was not cut but is slightly damaged

Figure 16 – Hidden damages in ‘gaiola’ walls

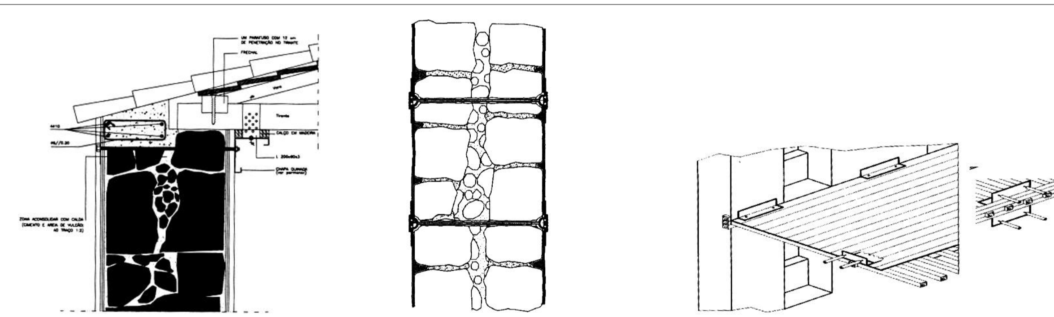
STRUCTURAL STRENGTHENING OF ‘POMBALINO’ BUILDINGS

Most rehabilitation works are performed to adapt old buildings to new functions or to repair damage due to age. Seismic mitigation should be a concern but seismic strengthening is not usual in the rehabilitation works because it has costs and owners are not sensitive to seismic problems. The level of complexity of intervention is high because demolishing is not advisable due to historical importance of these buildings and in many cases because the buildings are occupied during works.

Some structural strengthening techniques of 'Pombalino' Buildings are presented in Table 2. The most used in design practice is the strengthening of the connections between timber elements and masonry walls because it is easier to perform and cheaper than the other kinds of interventions mentioned. Another usual strengthening technique is the introduction of ties connecting façades preventing out-of-plane displacements. Iron ties are often observed in old constructions as being part of the original.

Table 2 - Usual strengthening techniques of 'Pombalino' Buildings (*adapted* from Cardoso *et al.* [1])

Structural Deficiency	*Strengthening provision used*
Low resistance to out-of-plane seismic effects (overturning of façades) and fall of the roof; low resistance of connections between façades and perpendicular masonry walls due to bad quality of masonry at connections.	Introduction of a concrete or steel beam at the top of the building, connecting roof to walls (Figure 17 a)) and confining masonry. The beam is executed along the whole perimeter of the building. Sometimes, these beams are executed at skirting board level of all floors above ground floor. Introduction of steel elements or ties (pre-stressed or not), cables or anchors connecting parallel masonry walls.
Masonry low shear strength may be critical to shear failure of the building due to the formation of a global shear collapse mechanism.	Introduction of a steel mesh confining masonry structural elements of façades (Figure 17 b)).
Settlements due to foundation failure	Micro piles
Low strength connection between timber elements	Use of FRP in the Strengthening of Timber Reinforced Masonry Load-bearing Walls (Cruz *et al.* [10]).
Low strength connection between timber elements and masonry walls	Introduction of steel elements, like ties, that connect timber elements to masonry (Figure 17 c)).
Timber damage due to the presence of water, propitious to fungus attack, termite and timber-fetter presence.	Substitution or repair of broken tiles and measures to water proofing the roof. Sometimes, connections between roof and façades are also reinforced during this type of repairs. Damaged timber elements are removed and substituted by new timber elements of the same geometry.



a) Concrete beam placed at the top of the building connecting the roof to the walls (Costa *et al.* [8])

b) Steel mesh confining masonry structural elements of façades (Costa *et al.* [8])

c) Steel ties connecting timber elements of the floor to masonry walls (Silva [9])

Figure 17 – Most usual strengthening techniques

There is no information available about seismic performance of retrofitted buildings of this type as strong earthquakes do not hit Lisbon since 1755. Some retrofit solutions are being submitted to homologation process so performance evaluation by laboratory testing is being done.

The most common materials used are steel, concrete and pine timber. Mortar materials and proportions must be compatible with old materials. Besides cost, durability and efficiency, the reversibility of the strengthening technique must also be considered. For this reason, in the strengthening and repair of the connections between timber elements, the use of bolts or ties is preferable to the use of glue and other new materials, like Fibber Reinforced Polymers (FRP), for example.

CONCLUSIONS

The expected collapse mechanism obtained in the study of a real 'Pombalino' building from Lisbon Downtown is bending out-of-plane of the front façade. The inclusion of the timber braced structure was proved to be an efficient anti-seismic provision, since 'gaiola' presence increases the building global stiffness to seismic actions and the out-of-plane displacements of the front façade are reduced due to the presence of this structure.

Seismic behavior of these structures under seismic actions is not completely characterized. For instance, the connections between the timber elements of 'gaiola' can be responsible for global ductility, as well as the damping characterization that should be characterized considering masonry cracking characteristics and the detachment of the masonry covering 'gaiola' timber elements.

The introduction of a concrete/steel beam executed at the entire perimeter of the building at top is an efficient strengthening solution because it prevents the out-of-plane mechanism of façades that was the mechanism observed in the study performed. This is a usual strengthening solution due to its relative low cost and medium level of complexity.

The strength increment of the connections of timber elements that compose the 'gaiola' is a provision that may be adopted in design practice, since the presence of 'gaiola' three-dimensional timber structure is quite relevant in the building global behavior.

As consequence of the delay in Lisbon Downtown reconstruction, the buildings from the same block might not have been built at the same time. Since construction practices changed in time, timber elements were progressively removed from the three-dimensional structure. For this reason, in spite of the fact that the exterior of the buildings looks similar identifying them as 'Pombalino' buildings, there are no guaranties they have a complete 'gaiola' structure. For seismic assessment of old 'Pombalino' Buildings, besides considering the recent changes to the original structure, inspection techniques should allow identifying the existence, geometry and conservation of the timber 'gaiola' structure.

Due to their location at Downtown, during the XX^{th} century, most of 'Pombalino' Buildings were adapted to new functions (small offices and services instead of housing) or completely occupied by banks and companies. The importance of the preservation of cultural heritage and the functions that these old masonry structures still maintain in our days justifies the concern about their structural safety, including under earthquake actions. In spite of the presence of the 'gaiola' in the buildings increasing global stiffness and resistance, a bad behavior of these buildings for seismic actions can be expected due to the following reasons: (i) the combined effects of age and of lack of maintenance leading to the degradation of structural materials, that decrease local and global stiffness and strength; (ii) the high number and variety of negative structural changes that these structures suffered during service time.

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