# Characterization of Lisbon Old Buildings

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**SUMMARY:**

This paper focuses on the characterization of old masonry buildings in Lisbon, where four typologies of buildings are typically recognized: buildings built before 1755, 'Pombalino' buildings built after the 1755 Earthquake, 'Gaioleiro' buildings built between 1870 and 1930 and 'Placa' buildings, a short-term structural solution which precedes the reinforced concrete buildings. One major concern for the engineering communities is the seismic susceptibility of this type of buildings and the potential life and property loss. The assessment existing buildings must be supported on their chronologic evolution, including the survey of structural modifications and causes of degradation. Given the cultural and economic value attached, structural interventions and retrofitting schemes may be fitted to the different typologies in order to maintain and emphasize, as much as possible, their original design.

*Keywords: Masonry Buildings, Structural Behaviour, Structural Reinforcement*

## 1. INTRODUCTION

A significant part of the building stock in Portugal (and in Europe) was built before the introduction of adequate seismic code provisions. The functions that old buildings still maintain nowadays support the concern about their structural safety and seismic vulnerability. Four typologies of masonry buildings are usually recognized in the Lisbon County: buildings built before 1755, 'Pombalino' buildings built after the 1755 earthquake, 'Gaioleiro' buildings built between 1870 and 1930 and 'Placa' buildings, a short-term structural solution which precede the reinforced concrete buildings.

In fact, the date of construction might be an indicator of their seismic resistance. For instance, the first anti-seismic construction in Portugal appeared with the 'Pombalino' buildings built after the 1755 earthquake and systematically imposed during the whole reconstruction program. However, during the nineteenth century, these construction methods were gradually abandoned resulting on the design of buildings with inferior constructive quality, known as 'Gaioleiro' buildings. On the other hand, the introduction of reinforced concrete solutions (ring beams and columns) between the 1930-1950 decades represented, in most cases, an improvement to the resistance of the buildings.

The goal of this work is to gather the available information regarding the period of construction, the materials of construction, the structural system and the general state of conservation, aiming at the qualitative evaluation of the buildings expected behaviour when subjected to the action of earthquakes. In addition, an important number of buildings have been subjected to several structural modifications which may have reduced their potential seismic performance. Structural interventions and retrofitting schemes may be fitted to the different typologies in order to maintain and emphasize, as much as possible, their original design and to improve their seismic safety.

## 2. OLD MASONRY BUILDINGS

Old masonry buildings are mainly composed by thick masonry walls arranged in perpendicular planes and relatively flexible wooden floor diaphragms. The irregularity of masonry stones (composition and shape), the quality of the mortar and the workmanship significantly affect the structural performance of the construction (Figure 1). The bearing capacity of masonry walls is mostly guaranteed by the internal compressive stresses and by the friction generated between the elements (cohesion). The mortar was usually made with good quality sand, from the Leiria pine forest, and air lime in a ratio of approximately one part to the double (1:2, 2:5, 5:9) or even stronger (3:5) (Appleton, 2005). The exterior masonry walls have a decreasing thickness from bottom to top; however, over the centuries the wall thickness was also reduced.

**Figure 1.** Rubble stone masonry walls.

According with the period of construction the solution for the interior structure diverges. Reminding the conventional expressions, the ‘frontal’ walls were generally parallel to the main façade wall regarding the support of the floor beams, while the ‘tabique’ walls were considered as partition walls without other structural function.

On the older masonry buildings, ‘frontal’ walls were composed by an irregular timber structure filled by rubble masonry. With the construction of ‘Pombalino’ buildings the conception of ‘frontal’ walls improved to a uniform and repetitive system composed by vertical, horizontal and diagonal joists, filled by rubble masonry (Figure 2 a). By the end of the nineteenth century, the timber structure started to be simplified and the rubble masonry infill replaced by industrial masonry bricks (solid or hollow) (Figure 2 b). The most traditional solution for the partition walls is made of timber laths nailed to vertical joists, filled afterwards by rubble masonry and mortar (Figure 2 c). These walls have a deformable and light structure.

a) b) c)

**Figure 2.** Interior walls: a) Frontal’ walls characteristic of a ‘Pombalino’ building (Appleton, 2003); b) Brick masonry walls characteristic of a ‘Gaioleiro’ building; c) ‘Tabique’ walls.

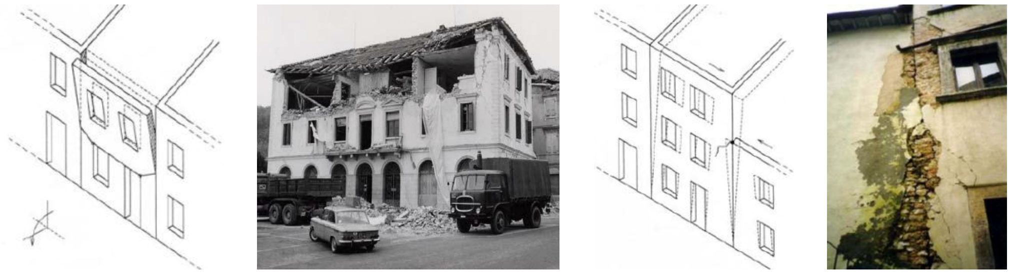
The floors were composed by wooden beams, usually placed perpendicular to the façade walls and braced by smaller beams that prevent the transverse deformation of the main beams. The floors were supported on the interior walls and embedded on the masonry walls. Timber floors are usually very deformable due to the weak connections to the masonry walls and the lack of nailing fixation. With the ‘Placa’ buildings, the floors were replaced by reinforced concrete slabs, acting as rigid diaphragms on the horizontal plan.

## 2.1. Seismic Vulnerability

With the exception of the ‘Pombalino’ buildings old masonry buildings were built before the introduction of adequate seismic code provisions (the first Portuguese modern code that enforces seismic design dates from 1958) and therefore, where based on empirical provisions and on the available natural materials. On one hand, the age of the buildings combined with a reduced maintenance and consequent degradation, support the concern about their structural safety. On the other hand, existing buildings have been subjected to significant structural modifications, diluting their original design.

The seismic resistance of a structure depends on the elements capacity of transferring the inertia forces, imposed by the dynamic actions, directly to the foundation system without collapse of the building (Lopes, 2008). The operation of the structure altogether is essential for the good seismic performance of the buildings and to prevent the overturning of the façade walls, which is the most common collapse mechanism of old masonry buildings (Figure 3 a and b).

The assessment of the seismic vulnerability on historic city centres should consider the structural interaction between buildings as well as the sequence of construction. It is expected that the connection between the existing masonry walls and the façade walls of the former buildings is weaker due to the difficult interlocking of the masonry units. Moreover, during a seismic event the horizontal displacements generated on the more flexible structures are constrained by the structures with superior stiffness within the compound; however, for higher amplitudes the buildings tend to vibrate in a different way resulting on the separation and collision between buildings (Figure 3 c and d).



a) b) c) d)

**Figure 3.** Failure Mechanisms: a) and b) overturning of the façade wall (Lagomarsino, 2007); c) and d) pounding effect between adjacent buildings (Lagomarsino, 2007).

# 3. BUILDINGS BUILT BEFORE 1755

The buildings that remain after the 1755 Earthquake belong to a very heterogeneous group. Actually, it is not possible to define a specific typology of buildings, as they emerged from several centuries of history without a proper urban planning. Though, at Castelo de São Jorge hill (Alfama, Mouraria and Castelo districts) and Bairro Alto, it is still possible to find original architectonic features. For instance, older buildings usually have a narrow front façade and pitched roofs to the side (Figure 4). Access to the upper floors is made next to the side masonry walls through one flight stairs.

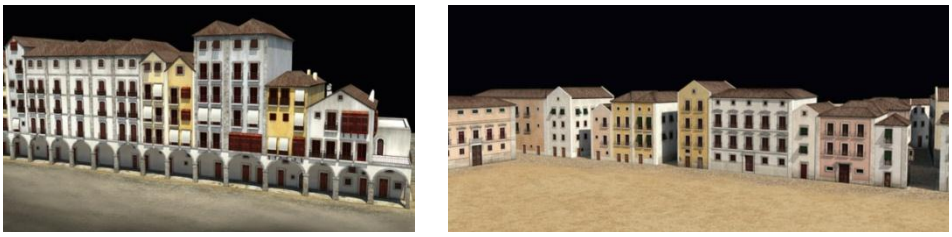


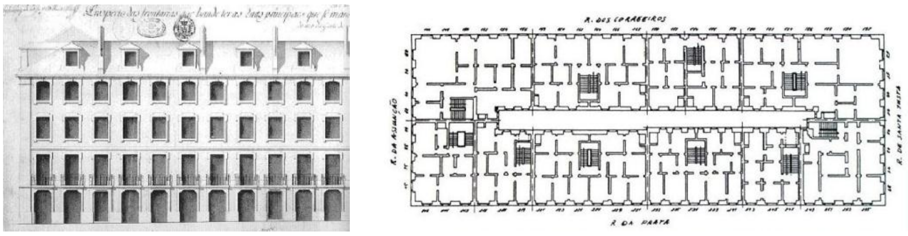
**Figure 4.** Reconstruction Model of the city in 1755 (Museu da Cidade, 2010).

The interior walls are mainly composed by ‘tabique’ walls made of timber laths nailed to vertical joists, filled by rubble masonry and air lime mortar. Their structural role has to be individually assessed, regarding the conservation of the materials and the connection between elements. The floors and roof structure were made of rounded joists and reused wood elements, explaining the diversity of the solutions. Some buildings have a rebounded ground floor, as the upper floors standout on the front façade wall increasing the interior space (Figure 5).

**Figure 5.** Buildings with rebounded ground floor (Museu da Cidade, 2010) (Lopes, 2008).

## 4. ‘POMBALINO’ BUILDINGS

On November 1st, 1755 Lisbon was hit by a very strong earthquake followed by a tsunami that caused great destruction in the city. The new downtown design placed the buildings in rectangular quarters with similar dimension following an orthogonal grid of streets. The ‘Pombalino’ construction represents the first time in history that a city was entirely built making use of solutions designed to withstand future earthquakes. According to Mascarenhas (2005), the structural regularity of the buildings provided a similar performance of the construction within the compound, which besides reinforcing the group effect also gave them superior structural stability (Figure 6).



a) b)

**Figure 6.** ‘Pombalino’ buildings (Mascarenhas, 2005): a) the windows were aligned both vertically and horizontally in order to maintain the balance of forces; b) 1st floor of a ‘Pombalino’ quarter.

The buildings were supported on a timber grid laid on short timber piles intended to stiffen the alluvial soil and to create a working platform above the water level (Appleton, 2003). The general foundation system consisted in continuous masonry walls or caissons filled with rubble masonry covered by a group of arches. The building ground floor was entirely built in stone masonry. Vaults and arches support the first storey floor (Figure 7), while the upper floors were composed by timber beams usually placed perpendicular to the rubble stone masonry façade walls.

**Figure 7.** Masonry crossed vaults, barrel vaults (Appleton, 2003) and arches on the ground floor.

This typology of buildings is characterized by a three-dimensional timber structure (named ‘gaiola pombalina’) enclosed on the walls above the first storey. Vertical and horizontal timber elements were added to the façade walls stiffening the masonry structure around the window openings (Figure 8 a)). The interior structure was composed by timber-masonry walls, timber floors and roof, linked to the exterior walls by timber connecters partially embedded on the masonry and reinforced by metal straps. ‘Frontal’ walls were composed by vertical, horizontal and diagonal elements connected through assemblies and nailing fixation (Figure 8 b and c). The truss structure was then filled by rubble stone masonry. The wood structure results on the buildings strength and energy dissipation capacity, essential to support the seismic actions in any direction (Lopes, 2010).

a) b) c)

**Figure 8.** ‘Gaiola Pombalina’: a) Timber frame on the façade walls and relieving arch lintel above the window (Appleton, 2008); b) ‘frontal’ wall without masonry infill (Lopes, 2010); c) connection between diagonal elements: notch work, assembly and nailing fixation.

The ‘Pombalino’ reconstruction was extended for almost one century; hence structural variations are expected within the uniformity and regularity of the original designs. For instance, it has been reported the discontinuity of the timber structure of the ‘frontal’ walls between floors. From Figure 9 it is possible to realize that, on one hand, there is no connection between the vertical joists that would ensure the direct transition of loads and, on the other hand, the configuration of the truss structure changes between the floors. Moreover, above the doors’ frame, the timber structure is only composed by vertical joists, interrupting once more the truss structure.

**Figure 9.** Structural variations of the ‘frontal’ walls on the building.

Other insufficiencies can be found related with the original design of the buildings. While the ground floor is entirely made in masonry, the upper floors are formed by a much more flexible timber-masonry structure. This stiffness variation in height can actually be prejudicial to the global seismic behaviour of the structure.

## 5. ‘GAIOLEIRO’ BUILDINGS

During the first half of the nineteenth century there were few changes on the urban landscape as the city continued to grow accordingly with the ‘Pombalino’ reconstruction plan. In 1864, a commission was nominated by the Ministry of Public Works to deal with a program of urban improvements and expansion of the city to the north upland (Figure 10). In 1888, the engineer Ressano Garcia developed a new plan regarding the connection between Liberdade Avenue and Campo Grande.

The ‘Gaioleiro’ buildings are related with the construction of Bairro de Camões occupying the hill on the east side of Santa Marta Street and ‘Avenidas Novas’ adjacent to Fontes Pereira de Melo Avenue and República Avenue. The buildings were aggregated in quarters with interior yards and surrounded by a grid of secondary streets, wider than the streets of the ‘Pombalino’ downtown. This typology of buildings is related with the buildings built to be sold or to be rented by flats aiming to sustain the development of the city and the housing needs of an increasing population.

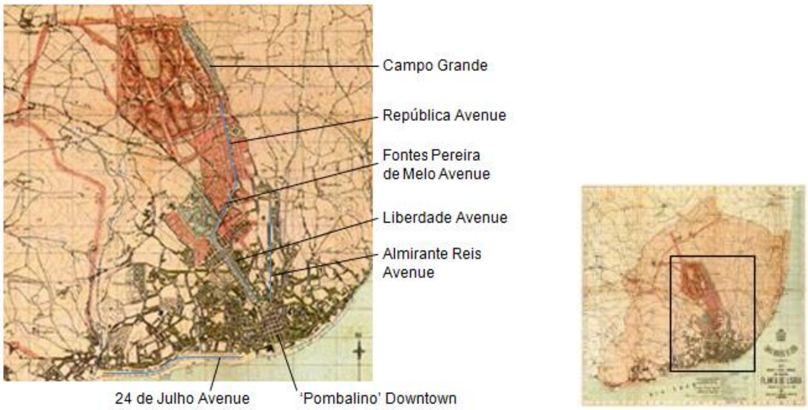



**Figure 10.** Plan of Lisbon in 1903 (adapted from AFML).

The expansion program proposed by Ressano Garcia was very flexible compared with the ‘Pombalino’ plan. The construction was carried out by private entities, and therefore the quality of the buildings is very variable. There were no standards for buildings height or depth, neither for the architectural design of the façade walls. The buildings are usually longer into the backyard and tighter into the façade walls, originally with two flats per storey or only one (Figure 11).

**Figure 11.** ‘Gaioleiro’ buildings with different size and shape.

The side walls are interrupted by light-shafts providing natural light and ventilation to the interior rooms (Figure 12 a). Ventilated masonry boxes on the ground floor prevented the rising moisture from the soil and the rotten of the interior wooden structures (Figure 12 b).

a) b)

**Figure 12.** Ventilation system: a) central light-shafts; b) first flight of masonry staircase gives access to an elevated ground floor with ventilated box underneath (Appleton, 2005).

During the nineteenth century, the cage structure characteristic of the ‘Pombalino’ buildings was progressively simplified. The diagonal elements from the ‘frontal’ walls started to be removed, conditioning the bracing of the timber structure. The rubble infill was then replaced by brick masonry, solid on the lower floors and hollow on the upper, or by ‘tabique’ walls, originally used on ‘Pombalino’ buildings as partition walls. The thickness of the brick masonry walls decreases along the height of the building by changing the position of the bricks (Figure 13). Nevertheless, this variation is also related with the transition between solid masonry bricks on the lower floors and hollow bricks on the upper floors or the replacement of the brick masonry walls by ‘tabique’ walls.

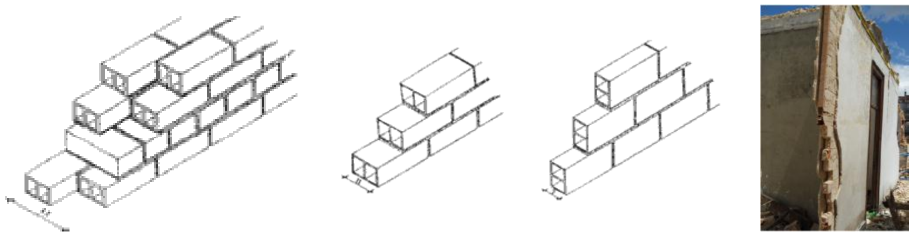


**Figure 13.** Brick masonry walls.

The ‘tabique’ walls assume a structural role on the ‘Gaioleiro’ building as they were copiously used on the upper floors of the buildings. This fact points a major vulnerability of these buildings related with the variation of the type of interior walls along the elevation of the building. As a result, the masonry walls are not continuously laterally supported by the interior structure and are, therefore, prone to out-of-plane failure. The light-shaft and side walls, originally built in rubble stone masonry, were also replaced by brick masonry walls.
Other structural limitations are related with the increasing number of storeys and high ceiling heights. The spans also become more generous, leading to increasing deformations and consequent degradation of ceilings. The weak connections to the masonry walls and the lack of nailing fixation between the beams and the floor boards result on the low horizontal stiffness of the floors.
The back façade walls are recognized by the steel balconies or galleries and service staircases (Figure 14). The balconies were built with iron beams in shape of I or T profile (around 0.20 m height) and brick masonry disposed in vaults, interconnected by air lime mortar or cement. Nonetheless, the degradation of these structures is very common.

**Figure 14.** Metallic structures on the back façade wall (Appleton, 2005) and oxidation problems.

## 6. ‘PLACA’ BUILDINGS

In 1938, a new urbanization plan was commissioned by engineer Duarte Pacheco supporting the urban expansion to the north and the construction of Bairro de Alvalade (Figure 15). The first buildings were built with exterior masonry walls and timber floors strengthened by peripheral concrete beams. With the development of the Bairro de Alvalade, alongside with the construction of Bairro dos Actores and S. João de Deus district, the back balconies and the service rooms (kitchens and bathrooms) started to be built with slender concrete slabs (70 to 100 mm thickness). In fact, the buildings from these new neighbourhoods have a characteristic shape in plan known as ‘Rabo de Bacalhau’ (Figure 16) originated by the expansion of the lateral light-shafts characteristic of the ‘Gaioleiro’ buildings into the back yard of the quarter. The concrete slabs were after extended to the whole floor, supporting the name ‘Placa’ (meaning concrete slab) given to this typology of buildings.

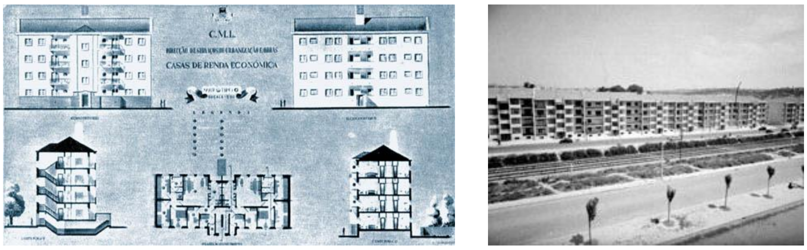
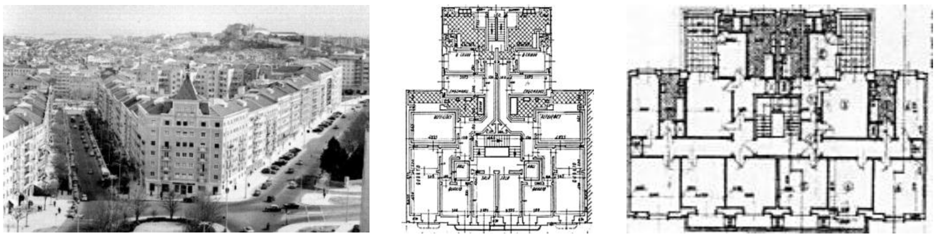



**Figure 15.** Design of the economic rent buildings from Bairro de Alvalade (Alegre, 1999) (AFML).



a) b) c)

**Figure 16.** Bairro dos Actores and S. João de Deus: a) Overview on Guerra Junqueiro Avenue; b) and c) plan design of ‘Rabo de Bacalhau’ shape (Costa, 1997).

The reinforced concrete frame structures started to appear at the ground floor of the buildings for commercial occupation where larger spans on the front wall and open spaces were needed. At this level the exterior walls were also built making use of hollow concrete blocks (Figure 17). The structural differences between the ground floor and the upper floors results in important stiffness variations on the buildings, leading to interruption of the interior walls on the first floor.

**Figure 17.** Front and back façade walls of a ‘Placa’ building in Guerra Junqueiro Avenue (Lopes, 2008).

The concrete frame structure was then extended to the exterior structure, first on the corners of the building making the connection between perpendicular masonry walls and on the back façade wall structure. For instance, on ‘Rabo de Bacalhau’ typology (Figure 16) the prominent shape of the building is made with a reinforced concrete frame structure.
The ‘Placa’ typology of buildings has specific features that should be emphasized, particularly due to the combination of different structural materials and construction solutions. Whereas in old masonry buildings the gravity loads were mostly due to the walls, on the ‘Placa’ buildings, the self-weight of the concrete slabs becomes an important load to the structure. On the other hand, the floors act as horizontal diaphragms collecting and transmitting the inertia forces to the vertical structure.
Associated with the transition period there is an evident absence of specific design features in terms of the amount and detailing of the reinforcement to ensure the ductility of the system. The concrete slabs are slender and lightly reinforced, generally with only one layer of reinforcement for positive moments, where there is no guarantee on the continuity between spans (Alegre, 1999). Moreover, the

concrete used on the buildings has a low to moderate resistance class (C20/25 on the best cases) and was slight compact. There are, in addition, problems of excessive deformability of the slabs, and pathologies related with the corrosion of the reinforcement (Figure 18) and concrete carbonation.

**Figure 18.** The corrosion of the steel is common and leads to the spalling of concrete cover (Lopes, 2008).

## 7. STRUCTURAL MODIFICATIONS AND CONCLUSIONS

Ancient buildings have experienced several structural interventions mostly motivated by different uses and needs of occupation. Numerous 'Pombalino' buildings have now more stories than their original design (five storey height including attic) added at the end of the nineteenth century in reaction to the increasing population in the city (Figure 19 a and b). On the other hand, the 'Gaioleiro' compounds were originally design with no restrictions to the height of the buildings (Figure 19 c). This structural variation brings important irregularities within the group behaviour related with the increment of the plan eccentricity between mass and structural stiffness, which may originate major torsional effects during the action of an earthquake.

a) b) c)

**Figure 19.** 'Pombalino' buildings: a) and b) increasing number of floors; and c) 'Gaioleiro' buildings with different heights in its original conception.

Other common modifications are related with the elimination of interior walls regarding the enlargement of the existing rooms (Figure 20 a) and the elimination of the masonry piers from the ground floor providing larger openings (Figure 20 b). Steel or reinforced concrete beams (pre-fabricated) are usually introduced in the place of the removed walls, supported in new columns (steel or reinforced concrete) or simply supported on the adjacent walls (interior or exterior). Nevertheless, the vertical discontinuous alignment of the walls might result on the excessive deformation of the overlying walls and floor that lose their original support system, and decrease the lateral support of the exterior masonry walls.

The final period of 'Gaioleiro' buildings is characterized by the progressive replacement of the timber floors by steel beams interconnected by ceramic bricks, whereas with the 'Placa' buildings the use of reinforced concrete slabs is generalized to the whole floor. In the meanwhile, several timber floors were replaced by reinforced concrete slabs or, more recently, by composite slabs combining steel plates and reinforced concrete. These new floors have rigid diaphragm behaviour in contrast with the flexibility of the timber-masonry structure, changing the distribution of internal forces. In addition, the weight of structure increases, affecting significantly the dynamic characteristics of the building.

Currently, many old masonry buildings have been replaced by new reinforced concrete structures, coexisting in the same compound buildings with different structural conceptions (Figure 20 c). Even though, there are some cases where the old masonry façade walls are still part of the new building, the new building structure benefit the overall behaviour of the compound and avoid further vulnerabilities to the existing structures (both old and new), at the cost of reducing their own capabilities.

a) b) c)

**Figure 20.** Example of structural modifications: a) elimination of interior walls replaced by steel beams; b) cut of the vertical façade elements on the ground floor; c) new reinforced concrete buildings within the old masonry compounds of buildings.

In general, the most frequent structural modifications are introduced combined with each other in the same building and in several buildings of the compound, changing its characteristic features and structural regularity. However, structural interventions and retrofitting schemes may be fitted to the different typologies in order to maintain and emphasize, as much as possible, their original design and to improve their seismic safety and not the contrary.

As final remarks, the assessment of the seismic vulnerability of old masonry buildings may be based on their chronologic evolution, including the survey of the structural modifications and causes of degradation. As the evolution between types and techniques of construction was progressive, each building as to be evaluated as a whole in order to determine which elements have a structural role.

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