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Seismically Active Areas of the World

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HOUSING REPORT
Historic, braced frame timber buildings with masonry infill ('Pombalino' buildings)

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Important
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Summary

Pombalino buildings (see Figures 1, 2, 3 and 4) are historic masonry buildings that can be identified by the presence of a three-dimensional timber structure (named "gaiola pombalina"), which is enclosed in internal masonry walls above the first floor. The roofs are built with

timber trusses clad with ceramic tiles and the floors are made of timber boards laid on timber joists. Ground floor walls are roughly dressed stone masonry supporting a system of vaults made of clay tiles, with stone arches. Foundations are made of short and small-diameter timber piles connected by a timber grid. These buildings were built after the 1755 earthquake when fear of new earthquakes led to the enforcement of anti-seismic provisions, such as establishing a maximum number of stories and introducing an interior timber structure called "gaiola." The buildings originally were mixed-use with commercial enterprises on the ground floor and residences on the upper floors. During the 20th century, most Pombalino buildings underwent substantial refurbishment when they were converted and occupied entirely by banks and companies. For the buildings that have maintained their original uses, the main problems result from poor maintenance.The expected collapse mechanisms due to earthquake actions are the overturning of facades (out-of-plane) or shear failure at the plane of the walls at ground floor level (global shear mechanism), leading to a global collapse mechanism. Typical seismic strengthening of these buildings includes the introduction of a concrete/steel ring beam at the level of the roof eaves. The introduction of steel elements/pre-stressed cables or of anchors connecting parallel masonry walls is also common. Steel elements are also used to connect detached timber elements from the floors and gaiola to the masonry. New techniques applying new materials like Fibre Reinforced Polymers (FRP) are also used to increase the strength of the connections of timber elements that compose the gaiola.

1. General Information

Buildings of this construction type can be found in downtown Lisbon, in the area near the Tagus River known as Baixa. This type of building can be found elsewhere in Lisbon and in other urban areas in Portugal also destroyed in 1755, such as the Vila Real de Santo António in Algarve (in the southern part of Portugal). Because of its historical relevance, the building example described in this work is from Baixa. This type of housing construction is commonly found in urban areas.

Pombalino buildings were built mainly in the urban areas of regions that experienced the greatest destruction following the 1755 earthquake.

This construction type has been in practice for more than 200 years.

Currently, this type of construction is not being built. As time has passed, construction practices have changed and timber elements have progressively fallen into disuse in the three-dimensional structure. Experience shows that masonry buildings built between 1755 and 1880 included a complete three-dimensional timber structure (gaiola) above the ground floor. Most likely during the 1880's, the practice of gaiola construction was completely abandoned. This time boundary, however, is not very precise because it is possible to find many buildings with incomplete gaiola structures built before 1880.

Figure 1: Typical Building (Santos, 2000)

Figure 2: Typical building from a block of buildings

Figure 3: Typical building from a block of buildings

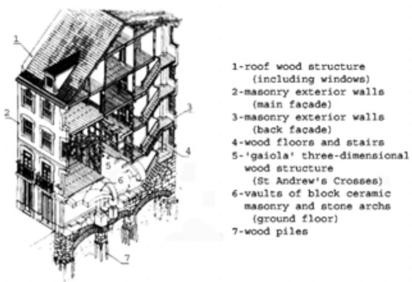

Figure 4: Perspective drawing showing key load-bearing elements (adapted from Mascarenhas, 1994)

2. Architectural Aspects

2.1 Siting

These buildings are typically found in flat terrain. They share common walls with adjacent buildings. Pombalino buildings belong to a block of buildings (see Figures 2 and 3) and they have common walls with adjacent buildings. Common walls are perpendicular to the facades of both buildings. The distance between blocks of buildings varies from 10 meters to 5 meters, corresponding to a street's transverse dimension. Street width depends on its importance (a main street is larger than a secondary one)

2.2 Building Configuration

A Pombalino building's geometry is very regular because these buildings were the result of urban planning in Lisbon after 1755. The need for a quick reconstruction of the city and the fear of a new earthquake led to the enforcement of new construction rules. These rules included not only anti-seismic provisions but also facade architecture, building plan and geometry. A Pombalino building's plan is compact with a rectangular or nearly rectangular shape with symmetrical configuration (see figure 6). There are no isolated buildings as they are part of an urban block which is also symmetrical and with a rectangular plan shape (see Figure 7). A typical block has 7 to 8 buildings, usually a building at each corner and one on each side. Each block has a size of 70x25 m while the streets have width ranging from 5 to 20 m. The interior of each block includes a very small courtyard accessed only by the doors of the back façade. In a typical building (see Figure 5), doors serve as the ground floor openings. First floor openings are all of the same type (either doors with balconies or windows), depending on the importance of the street onto which the facade opens. Windows comprise the openings of the other floors. The eaves of the roof also include openings and these might be doors or small windows. The original plan called for the same dimensions and horizontal spacing of the openings for all Pombalino buildings. Main facades present a regular opening grid with clearly identified masonry piers and spandrels.

The number of openings in each building or on each floor varies from 3 to 6 and depends on the area of the building plan. If the main facade of an original building has 6 openings, approximately 26% of the overall area is for windows and 38% of the overall wall surface area is utilized for doors, measured at the floor above ground level. At the ground floor level of the same original building, the overall door area is 50% of the overall wall surface area. To prevent fire propagation between buildings, which was one of the main causes of death in the 1755 earthquake, the masonry walls between adjoining buildings have no openings and extend beyond the roofs.

2.3 Functional Planning

The main function of this building typology is mixed use (both commercial and residential use). This was the main function at the time of construction. Since then, commerce and offices have taken over larger areas and residential use has decreased. In a typical building of this type, there are no elevators and 1-2 fire-protected exit staircases. Each shop at the ground floor has at least one exit, corresponding to previously mentioned doors at this level, leading outside the building. Access to floors above is accomplished by means of one door and a single set of stairs. Shop extension to the upper floors usually introduces another staircase to the floor above, and sometimes elevators. The internal courtyards of the blocks have no access from the outside so they cannot be used as escape route.

2.4 Modification to Building

The most common modification of Pombalino buildings is the addition of bathrooms. If the floors above ground are used for residences, typically the kitchen has been altered to provide for running water. It is also common to observe the insertion of larger shop windows on the ground floor, which sometimes demolishes all vertical masonry elements in the facades. Behind the buildings, the area at the ground floor level, once used as internal courtyards and free space, has been taken over by shops for their expansion needs. The most common adaptation of the old buildings for their new function is the introduction of elevators and new stairs and the demolition of interior walls (at ground floor and at floors above). The introduction of at least one floor at the top of the building is also common.

Figure 5: Plan of the facades of a typical block of buildings (Santos, 2000)

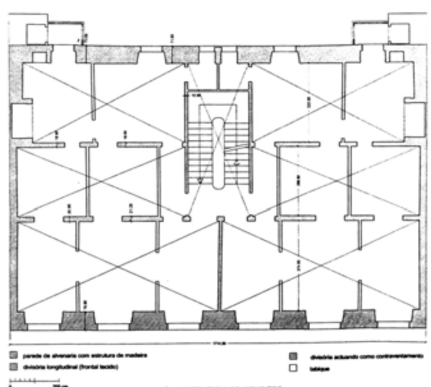

Figure 6: Plan of a typical building (Santos, 2000)

Figure 7: Aerial view of Lisbon Downtown showing similar blocks of 'Pombalino' buildings

3. Structural Details

3.1 Structural System

Material	Type of Load-Bearing Structure	#	Subtypes	Most appropriate type
	Stone Masonry Walls	1	Rubble stone (field stone) in mud/lime mortar or without mortar (usually with timber roof)	☐
		2	Dressed stone masonry (in lime/cement mortar)	☐
	Adobe/ Earthen Walls	3	Mud walls	☐
		4	Mud walls with horizontal wood elements	☐
		5	Adobe block walls	☐
		6	Rammed earth/Pise construction	☐

Masonry	Unreinforced masonry walls	7	Brick masonry in mud/lime mortar	☐
		8	Brick masonry in mud/lime mortar with vertical posts	☐
		9	Brick masonry in lime/cement mortar	☐
		10	Concrete block masonry in cement mortar	☐
	Confined masonry	11	Clay brick/tile masonry, with wooden posts and beams	☐
		12	Clay brick masonry, with concrete posts/tie columns and beams	☐
		13	Concrete blocks, tie columns and beams	☐
	Reinforced masonry	14	Stone masonry in cement mortar	☐
		15	Clay brick masonry in cement mortar	☐
		16	Concrete block masonry in cement mortar	☐
Structural concrete	Moment resisting frame	17	Flat slab structure	☐
		18	Designed for gravity loads only, with URM infill walls	☐
		19	Designed for seismic effects, with URM infill walls	☐
		20	Designed for seismic effects, with structural infill walls	☐
		21	Dual system – Frame with shear wall	☐
	Structural wall	22	Moment frame with in-situ shear walls	☐
		23	Moment frame with precast shear walls	☐
	Precast concrete	24	Moment frame	☐
		25	Prestressed moment frame with shear walls	☐
		26	Large panel precast walls	☐
		27	Shear wall structure with walls cast-in-situ	☐
		28	Shear wall structure with precast wall panel structure	☐
Steel	Moment-resisting frame	29	With brick masonry partitions	☐
		30	With cast in-situ concrete walls	☐
		31	With lightweight partitions	☐
	Braced frame	32	Concentric connections in all panels	☐
		33	Eccentric connections in a few panels	☐
	Structural wall	34	Bolted plate	☐
		35	Welded plate	☐
Timber	Load-bearing timber frame	36	Thatch	☐
		37	Walls with bamboo/reed mesh and post (Wattle and Daub)	☐
		38	Masonry with horizontal beams/planks at intermediate levels	☐
		39	Post and beam frame (no special connections)	☐
		40	Wood frame (with special connections)	☐

		41	Stud-wall frame with plywood/gypsum board sheathing	☐
		42	Wooden panel walls	☐
Other	Seismic protection systems	43	Building protected with base-isolation systems	☐
		44	Building protected with seismic dampers	☐
	Hybrid systems	45	other (described below)	☑

The structural system can be divided into the ground floor system (masonry walls and vaults) and the gaiola system (wooden interior walls) of the floors above the first floor, described as follows: The ground to first floor level is comprised of stone masonry columns supporting stone arches and clay brickwork vaults (see Figure 11). Interior walls above the first floor are part of the gaiola. Masonry infill can be stone or clay bricks like those used at the ground floor vaults. It is usual to find both types of masonry in internal walls (see Figure 10). For the first buildings built after the earthquake, there are reasons to believe that the masonry used was rubble recycled from destroyed buildings. Other internal partitions are the wooden panels without structural function. Exterior walls (facades and walls between adjacent buildings) are stone masonry in lime mortar. Stone masonry walls (ground floor)and wooden frame with masonry infill (floors above the first floor).

3.2 Gravity Load-Resisting System

The vertical load-resisting system is stone masonry walls. Single leaf, irregular block, stone masonry walls. Masonry vaults at the ground floor, with ceramic regular blocks and stone arches (see Figure 11). Usually, the wall thickness of the Pombalino buildings varies from 1.0 to 1.2 meters and is the same for all floors. The Pombalino buildings built towards the end of the nineteenth century may present two or three different wall thicknesses. The usual changes are observed between the ground floor (1.0 to 1.2m) and the first floor (0.8 to 1.0m), and between the upper two floors. The thickness of the top floor may vary between 0.5 and 0.8m.

3.3 Lateral Load-Resisting System

The lateral load-resisting system is stone masonry walls. Masonry walls and a three-dimensional wood frame structure (gaiola) above the first floor, double braced with diagonal timber elements (see Figures 8, 9 and 10), form the lateral load-resisting system. The timber elements are notched together or connected by iron or metal ties, according to historical information about the construction techniques. The results of experimental tests performed on Pombalino panels, and of tests performed on masonry panels without diagonal bracing (Alvarez, 2000 and Lopes, 1986) showed that the gaiola exhibits ductile behavior and allows some energy dissipation. Connections between the timber elements, which sometimes include metallic (iron) elements, probably contribute to the observed ductile behavior. These results may be extrapolated to the performance of the entire structure. According to the construction process (first the entire gaiola was built, then the masonry infill and the exterior walls), there are reasons to believe that interior timber frames are connected to floor elements but these connections must be better characterized. The connections of interior timber frames between stories must also be better characterized.

3.4 Building Dimensions

The typical plan dimensions of these buildings are: lengths between 8 and 16 meters, and widths between 10 and 12 meters. The building has 4 to 5 storey(s). The typical span of the roofing/flooring system is 3.3 meters. Typical Plan Dimensions: The above dimensions were measured in a building with 6 openings per floor at the main facade. The horizontal spacing of openings is approximately 1.5 meters and the width of openings (doors and windows at a floor above ground floor) is approximately 1.2 meters. Typical Number of Stories: Due to the construction regulations of the time, the first Pombalino buildings had a maximum of 4 stories including ground floor, plus an habitable attic under the roof. The restriction on the number of stories was lifted at the request of the developers soon after the reconstruction process started, so that most Pombalino buildings have 5 stories. Typical Story Height: Ground floor height is greater than other floors: 4.5 meters. Typical Span: The distance among load bearing structures is from 2.88 to 3.70 meters. The typical storey height in such buildings is 3.5-4.0 meters. The typical structural wall density is more than 20 %. 6% - 24% Typical wall density is 24% (both ground floor and floors above). Direction parallel to facades: 14% (ground floor) and 18% (other floors) Direction perpendicular to facades: 10% (ground floor) and 6% (other floors) All values relate to the plan area of the floor. Measurements were made considering only masonry and gaiola walls. Wall interior doors are included. The stone arches and masonry vaults at ground floor level support the interior walls of the floors above and therefore the wall density at ground floor level is smaller than at other floors.

3.5 Floor and Roof System

Material	Description of floor/roof system	Most appropriate floor	Most appropriate roof
Masonry	Vaulted	☑	☐
	Composite system of concrete joists and masonry panels	☐	☐
Structural concrete	Solid slabs (cast-in-place)	☐	☐
	Waffle slabs (cast-in-place)	☐	☐
	Flat slabs (cast-in-place)	☐	☐
	Precast joist system	☐	☐
	Hollow core slab (precast)	☐	☐
	Solid slabs (precast)	☐	☐
	Beams and planks (precast) with concrete topping (cast-in-situ)	☐	☐
	Slabs (post-tensioned)	☐	☐
Steel	Composite steel deck with concrete slab (cast-in-situ)	☐	☐
Timber	Rammed earth with ballast and concrete or plaster finishing	☐	☐
	Wood planks or beams with ballast and concrete or plaster finishing	☑	☐
	Thatched roof supported on wood purlins	☐	☐
	Wood shingle roof	☐	☐
	Wood planks or beams that support clay tiles	☐	
	Wood planks or beams supporting natural stones slates	☐	☐
	Wood planks or beams that support slate, metal, asbestos-cement or plastic corrugated sheets or tiles	☐	☐
	Wood plank, plywood or manufactured wood panels on joists supported by beams or walls	☑	☐
Other	Described below	☑	☑

Wood floors can be considered as a flexible diaphragm. The roof timber structure depends on the top floor of the building because it may include windows openings within the timber frame. The number of pitches of the roof depends on the kind of window, which is associated with construction practices at the time the building was built. Connections between timber elements and masonry walls may have metallic elements like anchors. In the absence of these elements, connection forces are transmitted only by friction effect. The characteristics of the connection must be analyzed case by case.

3.6 Foundation

Type	Description	Most appropriate type
Shallow foundation	Wall or column embedded in soil, without footing	☐
	Rubble stone, fieldstone isolated footing	☐
	Rubble stone, fieldstone strip footing	☐
	Reinforced-concrete isolated footing	☐
	Reinforced-concrete strip footing	☐
	Mat foundation	☐
	No foundation	☐
	Reinforced-concrete bearing	☐

Deep foundation	piles	
	Reinforced-concrete skin friction piles	☐
	Steel bearing piles	☐
	Steel skin friction piles	☐
	Wood piles	☑
	Cast-in-place concrete piers	☐
	Caissons	☐
Other	Described below	☐

It consists of wood piles. Masonry placed over a grid of connected timber piles (see Figure 12). Timber piles are very short (generally less than 5 meters), and mobilize only lateral resistance because soil with good strength capacity is usually found at a depth of 15 meters or more. Pile diameter is small (25 cm) and piles form a regular mesh. Piles were completely under water but the current water level is becoming lower and some piles are degraded. There is no evidence of foundation soil instability and some authors maintain that pile degradation is no longer important to foundation strength capacity because the timber mesh acted as soil reinforcement at the time of construction. Baixa was rebuilt over rubble from collapsed buildings during the 1755 earthquake and the timber grid of piles would be a good measure to provide compaction. However, this is still an object of discussion and controversy.

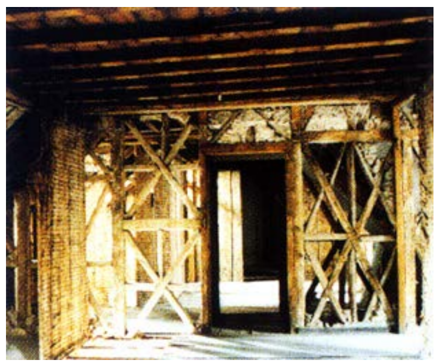

Figure 8: Wood braced frame of 'gaiola' after the removal of cover masonry (Museum of BCP, 2000)

4. Socio-Economic Aspects

4.1 Number of Housing Units and Inhabitants

Each building typically has 5-10 housing unit(s). 3 to 4 housing units in each building, or 6 to 8 housing units in each building. There are 1 or 2 units per floor on above ground floors. The number of units may depend on the area of the building plan: there is only one unit per floor if the number of windows is less than 4; if the number of windows is more than 4, there can be two units per floor. The number of inhabitants in a building during the day or business hours is more than 20. The number of inhabitants during the evening and night is less than 5. Some buildings belong to companies and banks and all floors have been adapted to new functions. In such cases, the number of inhabitants varies from a high number during business hours (40 to 50 workers and clients/costumers), to a small number of inhabitants (mainly security people, less than 5) at night. If buildings were converted into commercial outlets, occupancy might be as high as 200 people depending on time of day and the season.

4.2 Patterns of Occupancy

One family occupies one housing unit.

4.3 Economic Level of Inhabitants

Income class	Most appropriate type
a) very low-income class (very poor)	☑
b) low-income class (poor)	☐

c) middle-income class	☐
d) high-income class (rich)	☑

Most of the residential occupants are very poor old people who have lived in the same house their entire life. When the last resident dies, the building may be abandoned or sold. The housing units are rented at low prices due to housing rent legislation that has not been revised for more than 40 years. Because of low rent rates, these buildings have been very poorly maintained and are often in need of rehabilitation work. Lisbon's City Council has specific programs to finance rehabilitation work and these are being gradually applied throughout the city. The rehabilitation of recently purchased buildings depends of the new owners. Building functions may change but, where residential use is maintained, housing units are adapted to provide good conditions and then rented or sold to wealthy tenants or owners.

Ratio of housing unit price to annual income	Most appropriate type
5:1 or worse	☐
4:1	☐
3:1	☐
1:1 or better	☑

What is a typical source of financing for buildings of this type?	Most appropriate type
Owner financed	☐
Personal savings	☐
Informal network: friends and relatives	☐
Small lending institutions / micro-finance institutions	☑
Commercial banks/mortgages	☑
Employers	☐
Investment pools	☑
Government-owned housing	☐
Combination (explain below)	☐
other (explain below)	☐

Originally, mainly financed by private developers, perhaps with some governmental contribution. Presently, most of the work for rehabilitation and reuse are financed by banks or by the owners. The nature and cost of the work depends of the intended use of the building. Small lending institutions and microfinance institutions finance the work of small offices and the rehabilitation of residential rented units. If the building is going to be adapted for companies or for completely new apartments, refurbishment is more expensive and financed by commercial banks and mortgage lenders. There is a large variation in the costs depending on the degree of intervention: they can vary from 75euros/m2 for small interventions (wall painting and repair, waterproofing), to 400euros/m2 for other kind of interventions (floors replacement, bathrooms and other refurbishment). These prices do not include structural interventions, which are more expensive. In each housing unit, there are 1 bathroom(s) without toilet(s), 1 toilet(s) only and 1 bathroom(s) including toilet(s).

Banks and companies may have more than one latrine per floor/housing unit. Commercial ground floors may also have more than one latrine per shop. .

4.4 Ownership

The type of ownership or occupancy is renting, ownership with debt (mortgage or other) , individual ownership , ownership by a group or pool of persons and long-term lease.

Type of ownership or	Most appropriate type

occupancy?	
Renting	☑
outright ownership	☐
Ownership with debt (mortgage or other)	☑
Individual ownership	☑
Ownership by a group or pool of persons	☑
Long-term lease	☑
other (explain below)	☐

Buildings adapted for banks and for other organizations that occupy entire buildings are owned by a group or pool. Ground floor shops are usually held by long-term lease. Commercial functions at the ground floor sometimes occupy the first floor. The floors above are residential units or small service offices (doctors, lawyers, specialized shops, etc), rented or owned individually.

5. Seismic Vulnerability

5.1 Structural and Architectural Features

Structural/ Architectural Feature	Statement	Most appropriate type		
		Yes	No	N/A
Lateral load path	The structure contains a complete load path for seismic force effects from any horizontal direction that serves to transfer inertial forces from the building to the foundation.	☑	☐	☐
Building Configuration	The building is regular with regards to both the plan and the elevation.	☑	☐	☐
Roof construction	The roof diaphragm is considered to be rigid and it is expected that the roof structure will maintain its integrity, i.e. shape and form, during an earthquake of intensity expected in this area.	☐	☑	☐
Floor construction	The floor diaphragm(s) are considered to be rigid and it is expected that the floor structure(s) will maintain its integrity during an earthquake of intensity expected in this area.	☐	☑	☐
Foundation performance	There is no evidence of excessive foundation movement (e.g. settlement) that would affect the integrity or performance of the structure in an earthquake.	☑	☐	☐
Wall and frame structures- redundancy	The number of lines of walls or frames in each principal direction is greater than or equal to 2.	☑	☐	☐
Wall proportions	Height-to-thickness ratio of the shear walls at each floor level is: Less than 25 (concrete walls); Less than 30 (reinforced masonry walls); Less than 13 (unreinforced masonry walls);	☑	☐	☐
Foundation-wall connection	Vertical load-bearing elements (columns, walls) are attached to the foundations; concrete columns and walls are doweled into the foundation.	☑	☐	☐
Wall-roof connections	Exterior walls are anchored for out-of-plane seismic effects at each diaphragm level with metal anchors or straps	☐	☐	☑
	The total width of door and window openings in a wall is: For brick masonry construction in cement mortar : less than ½ of the distance between the adjacent cross			

Wall openings	walls; For adobe masonry, stone masonry and brick masonry in mud mortar: less than 1/3 of the distance between the adjacent cross walls; For precast concrete wall structures: less than 3/4 of the length of a perimeter wall.	☑	☐	☐
Quality of building materials	Quality of building materials is considered to be adequate per the requirements of national codes and standards (an estimate).	☐	☑	☐
Quality of workmanship	Quality of workmanship (based on visual inspection of few typical buildings) is considered to be good (per local construction standards).	☐	☑	☐
Maintenance	Buildings of this type are generally well maintained and there are no visible signs of deterioration of building elements (concrete, steel, timber)	☐	☑	☐
Additional Comments	The original conception of the gaiola was to resist seismic actions and this supports the prediction of a good response for this type of building. Vertical transition from the ground floor (masonry walls) to the first floor (gaiola wood frame walls) may be a specific deficiency for the seismic behavior of these buildings due to a step change in stiffness and the unilateral behavior of connections. The presence and performance of metallic (iron) elements at the connections between timber elements and masonry walls in the roof and floors are not entirely clear. In fact, some cases were found where the connection between timber elements and masonry depended only on the length of the joist seat inside the masonry. In that case, the strength of the connection depends only on the friction between the materials and would be smaller if there was a metallic element. The uneven quality of the original masonry or the construction of different walls at various times also led to poor strength and stiffness properties. Construction practices were not the same for buildings built in the same period, which might indicate that the quality of workmanship was not the same. As an example, it is possible to find different geometries of gaiola in the same building and there are several gaps in the connections between timber elements, which may or may not have nails. The quality of workmanship also decreased over time, as the first Pombalino buildings show better quality then those built in the nineteenth century. Like all masonry buildings, the presence of large openings reduces the lateral stiffness and load capacity of facades. Another significant uncertainty is how important a role the structural interventions had on buildings because the exterior may look original but the interior can be completely modified. Removal of internal gaiola walls greatly increases the seismic vulnerability of Pombalino buildings.			

5.2 Seismic Features

Structural Element	Seismic Deficiency	Earthquake Resilient Features	Earthquake Damage Patterns
Wall	Low resistance to out-of-plane seismic effects (overturning of facades) and collapse of the roof; Low resistance of connections between facades and perpendicular masonry walls due to bad quality of masonry at corners, that can be associated to construction of connected walls at different times; possibility of formation of a global collapse mechanism due to masonry low shear strength; Large openings reduce lateral capacity of facades. Connections between 'gaiola' walls and masonry walls may have low strength connections if there are no metallic elements; timber decay due to water ingress.	Three-dimensional braced structure that reduces out-of-plane horizontal displacements of facades, contributing to reduced seismic vulnerability of Pombalino buildings; it displays ductile behavior.	Some crack openings and fall of external plaster. No detailed information available. In poorly connected facades, out-of-plane mechanism expected.
Frame (Columns, beams)			
Roof and floors	Low strength connections between timber elements of roof and floor and masonry walls; timber decay due to water ingress.	A good connection between roof/floor timber elements and masonry walls may reduce seismic vulnerability because they can contribute to reduced out of plane horizontal displacements.	Mainly fall of chimneys. No detailed information available.
Foundations	Timber pile damage due to water level changes may cause building settlements.		No information available.

Some buildings may have metallic elements connecting timber elements (roof, floor and 'gaiola') to the facades that are not visible from the outside because the wall thickness covers them. Each building must be evaluated individually or integrated in a block of buildings. It is important to consider block behavior in case of relevant stiffness differences between the buildings of the same block (see Ramos and Lourenço, 2003 and Silva et al., 2001). Past earthquakes (see

Section 6) caused only light damage to buildings in Baixa. The damage levels were so small (Baixa was far from epicentre) that the information was not worth recording.

5.3 Overall Seismic Vulnerability Rating

The overall rating of the seismic vulnerability of the housing type is B: MEDIUM-HIGH VULNERABILITY (i.e., poor seismic performance), the lower bound (i.e., the worst possible) is A: HIGH VULNERABILITY (i.e., very poor seismic performance), and the upper bound (i.e., the best possible) is C: MEDIUM VULNERABILITY (i.e., moderate seismic performance).

Vulnerability	high	medium-high	medium	medium-low	low	very low
	very poor	poor	moderate	good	very good	excellent
Vulnerability Class	A	B	C	D	E	F
	☑	☐	☑	☐	☐	☐

5.4 History of Past Earthquakes

Date	Epicenter, region	Magnitude	Max. Intensity
1856	37.10 -10.50 (Atlantic Ocean, Southwest of Portugal)	6	
1909	38.95 -8.82 (Benavente (Centre of Portugal)	7	MMI IX (at epicenter)
1969	35.99 -10.81 (Atlantic Ocean, Southwest of Portugal)	7.5	

The 1909 earthquake was felt in Lisbon and caused light damage to buildings in Baixa, mainly crack openings and the fall of chimneys and external plaster. The intensity shown in the table for this earthquake is the epicentral one, in Benavente, some 40 km from Lisbon. On the basis of damage observed in Pombalino buildings and in ordinary masonry structures, it is not possible to conclude whether the Pombalino buildings performed better because all the observable damage was light. For the other earthquakes shown in the table, with epicentres either in continental Portugal or in the Azores Islands, there is no record of significant damage to buildings in Lisbon, due to the long distance from the epicentre.

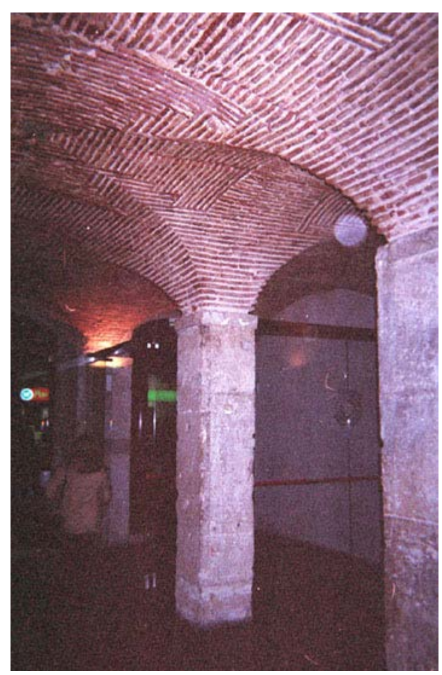

Figure 9: Timber structure enclosed in interior masonry wall

Figure 10: Timber structure enclosed in interior masonry wall (detail)

Figure 11: Masonry vaults at ground floor

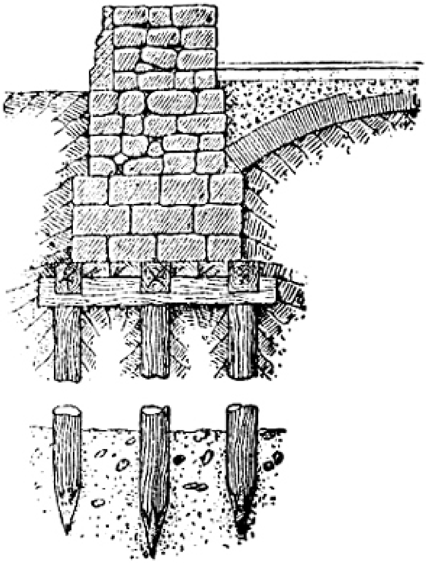

Figure 12: Wood pile foundations (Santos, 2000)

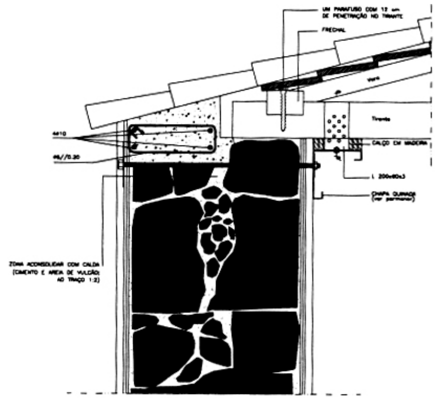

Figure 13: Reinforcement of the connections between roof and masonry walls by a concrete beam (Costa et al, 2001)

6. Construction

6.1 Building Materials

Structural element	Building material	Characteristic strength	Mix proportions/dimensions	Comments
Walls	Irregular blocks of calcareous masonry set in lime mortar	Low tensile and shear strength characteristics, values not known precisely	Not known	(see Cardoso et al., 2001)
Foundation	Short and small diameter timber piles (pine)	Strength values not known		(see Alvarez, 2000)
Frames (beams & columns)	Timber-braced frame (pine and oak) gaiola	Strength values not known precisely	Not known	(see Cardoso et al., 2001)
Roof and floor(s)	Timber elements (pine and oak)	Strength values not known		

6.2 Builder

Originally built by developers. None self built.

6.3 Construction Process, Problems and Phasing

Due to time constraints, the construction process was highly organized. The gaiola and the entire wood structure were built first, then the masonry infill was placed at the same time as the exterior masonry walls were constructed. Finally, windows and doors stones were placed with the finishing work. This sequence allowed different specialists (carpenters and masonry workers) to do their jobs without interference. The construction of this type of housing takes place incrementally over time. Typically, the building is originally not designed for its final constructed size. The reconstruction of Lisbon after the 1755 earthquake was slow due to financial and economic constraints, and it is likely that buildings in the same urban block might have been built in different years. The time gap in the construction of individual buildings may explain some of the observed architectonic variances, as seen in the roof structure and lighting for the stair wells, for example. Very often an extra floor was built at the same time as the rest of the building.

6.4 Design and Construction Expertise

The idea of using timber frames for the gaiola and for the connections between timber elements was inspired by ship construction, in which the Portuguese had great expertise. Engineers and architects had a very important role in planning the reconstruction of the city. The plans included not only the new urban layout but also functional and architectural aspects. Structural features were also examined and seismic considerations were a main concern as the introduction of the gaiola in these buildings shows.

6.5 Building Codes and Standards

This construction type is addressed by the codes/standards of the country. A written document has never been found but construction rules were practiced and transmitted between carpenters and masonry workers so it is assumed that there was a code of practice. The year the first code/standard addressing this type of construction issued was 1755-1758. N/A. The most recent code/standard addressing this construction type issued was There is no mention of regulations for this type of construction in modern building codes or seismic codes. Title of the code or standard: A written document has never been found but construction rules were practiced and transmitted between carpenters and masonry workers so it is assumed that there was a code of practice. Year the first code/standard addressing this type of construction issued: 1755-1758 National building code, material codes and seismic codes/standards: N/A When was the most recent code/standard addressing this construction type issued? There is no mention of regulations for this type of construction in modern building codes or seismic codes.

Beginning in 1758 and during the Marquês de Pombal's governance, the penalty for failing to follow construction rules was the demolition of the building by order of the king.

6.6 Building Permits and Development Control Rules

This type of construction is an engineered, and authorized as per development control rules.

Historical information indicates that the owners of the buildings which collapsed during the 1755 earthquake contracted builders, who supervised the construction. They had to respect all rules imposed by the Marquês de Pombal. Engineers and architects established these rules, as mentioned in section 7.6. Building permits are required to build this housing type.

6.7 Building Maintenance

Typically, the building of this housing type is maintained by Owner(s), Tenant(s) , No one and others. When building owners cannot afford the maintenance of the building (low rents, etc.), they may require financial support from the City Council. The City Council has a special spending program that was developed to allow improvements in old masonry buildings. In most cases, these improvements do not include strengthening buildings.

6.8 Construction Economics

Since this is a construction method that is no longer practiced, values for construction costs are not available. The actual commercial value of Pombalino buildings varies and depends on whether they have been abandoned or upon how difficult it would be to get authorization to perform structural/functional changes: if the building still maintains its original structure and use, the approximate cost may be from 400 to 450 euro/m2 depending on the level of deterioration. If the building has been refurbished, the value depends on its current use. For residential use, values ranging from 1000 to 2500 euro/m2 are usually quoted. Commercial values are not related to construction values. In fact, Baixa is located in the most central part of Lisbon and this justifies the high prices quoted. This information is not available.

7. Insurance

Earthquake insurance for this construction type is typically unavailable. For seismically strengthened existing buildings or new buildings incorporating seismically resilient features, an insurance premium discount or more complete coverage is unavailable. Until 2001, earthquake insurance was available. Now companies avoid this type of insurance, but this may be a temporary situation caused by the redefinition of policy in this sector. It is part of a group of risks related to housing that optionally may cover damage caused by earthquakes. Insurance cost depends on seismic zone, age, and the number of stories in a building.

8. Strengthening

8.1 Description of Seismic Strengthening Provisions

Strengthening of Existing Construction :

Seismic Deficiency	Description of Seismic Strengthening provisions used
Low resistance to out-of-plane seismic effects (overturning of facades) and roof collapse; low resistance of connections between facades and perpendicular masonry walls due to the bad quality of the masonry at the connections.	Introduction of a concrete or steel beam at the top of the building, connecting the roof to walls (see Figures 13 and 14) and confining masonry. The beam is executed along the whole perimeter of the building. Sometimes, these beams are executed at the 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 collapse mechanism.	Introduction of steel mesh, confining masonry structural elements of facades (see Figure 15).
Settlement due to foundation failure	Micro piles
Low strength connection between timber elements	Use of steel rods and traditional techniques for strengthening timber element connections, such as the nails and bolts. Use of FRP in the strengthening of timber reinforced masonry load-bearing walls (see [Cruz et al., 2001]).
Low strength connection between timber elements and masonry walls	Introduction of steel elements, such as ties, which connect timber elements to masonry (see Figure 16).
Timber damage due to water ingress, creating favorable conditions for fungi and insect attack.	Substitution or repair of broken tiles and measures to waterproof the roof. Sometimes, connections between roof and facades are also reinforced during repair. Damaged timber elements are removed and replaced with new timber elements of the same geometry.

The most common construction materials are steel, concrete and pine. Mortar mixes and proportions must be compatible with original materials. Besides the cost, efficiency, and durability of the strengthening solution, the feasibility of removing it from the structure without destruction must also be considered. The complexity level of any intervention is high because demolition is not desirable due to the historical importance of these buildings. Most interventions must be performed in occupied buildings, thus increasing the execution time and complexity. There is little information available about the expected effectiveness of the seismic strengthening provisions listed above.

8.2 Seismic Strengthening Adopted

Has seismic strengthening described in the above table been performed in design and construction practice, and if so, to what extent?
The usual seismic strengthening technique utilized in design practice is to improve the connections between the timber elements and the masonry walls because this is easier to perform and is cheaper than the other interventions mentioned. Another common strengthening technique is the introduction of ties which connect the facades and prevent out-of-plane displacements.

Was the work done as a mitigation effort on an undamaged building, or as repair following an earthquake?
The objective of most rehabilitation work is to adapt old buildings to new uses or to repair damage due to age. When intervention is going to be done, seismic mitigation should be a concern but seismic strengthening is not the current

practice because of the added cost and lack of awareness on the part of owners to seismic risk.

8.3 Construction and Performance of Seismic Strengthening

Was the construction inspected in the same manner as the new construction?
Inspection techniques for old masonry buildings are different from the techniques used in new buildings because the materials and construction techniques are not the same. Inspection of new construction to evaluate seismic vulnerability follows code provisions, whereas inspection of older buildings relies much more on the expertise of individuals and on professional advice.

Who performed the construction seismic retrofit measures: a contractor, or owner/user? Was an architect or engineer involved?
At the time of the construction of Pombalino buildings, contractors performed construction according to current earthquake technical provisions. At the present time, contractors, following engineering advice, usually include some seismic strengthening in the construction. Generally, architects are involved when construction includes not only repair but also modification, which happens in most cases.

What was the performance of retrofitted buildings of this type in subsequent earthquakes?
There is no information available about seismic performance of retrofitted buildings of this type since strong earthquakes have not hit Lisbon since 1755. Some retrofit solutions are being submitted to a homologation process so performance evaluation through laboratory testing is being done. These techniques are recent and there has been no opportunity to confirm their effectiveness. Most of them were developed after observation of damage due to recent earthquakes, such as the 1998 earthquake in Azores, Portugal, and the 1997 earthquake in Umbria, Italy. The results of numerical models of masonry buildings also provided information related to their expected collapse mechanism and they inspired the design of some reinforcement solutions (see Croci, 1988).

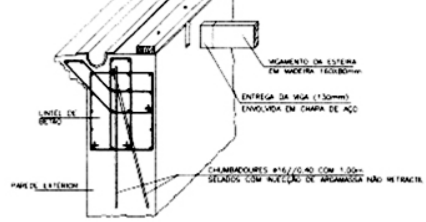

Figure 14: Reinforcement of the connections between roof and masonry walls by a concrete beam (Appleton and Em

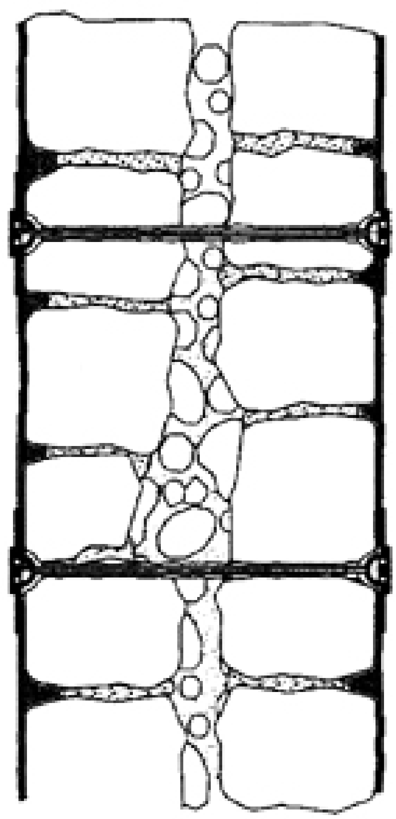

Figure 15: Shear reinforcement of masonry structural elements using steel elements (Silva, 2002)

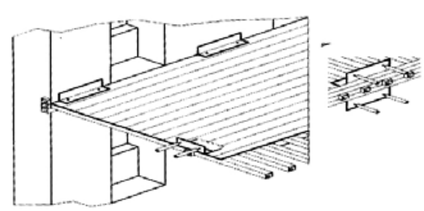

Figure 16: Reinforcement of the connections of wood floors to masonry walls by steel elements (Silva, 2002)

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