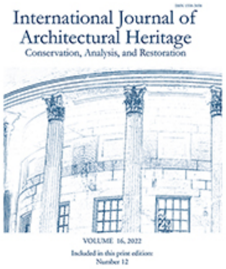
Taylor & Francis
Taylor & Francis Group



International Journal of Architectural Heritage
Conservation, Analysis, and Restoration

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/uarc20

Historic Appraisal Review and Geometric Characterization of Old Masonry Buildings in Lisbon for Seismic Risk Assessment

V. Bernardo, R. Sousa, P. Candeias, A. Costa & A. Campos Costa

To cite this article: V. Bernardo, R. Sousa, P. Candeias, A. Costa & A. Campos Costa (2022) Historic Appraisal Review and Geometric Characterization of Old Masonry Buildings in Lisbon for Seismic Risk Assessment, International Journal of Architectural Heritage, 16:12, 1921-1941, DOI: 10.1080/15583058.2021.1918287

To link to this article: https://doi.org/10.1080/15583058.2021.1918287

Published online: 16 May 2021.

INTERNATIONAL JOURNAL OF ARCHITECTURAL HERITAGE
2022, VOL. 16, NO. 12, 1921–1941
https://doi.org/10.1080/15583058.2021.1918287

Historic Appraisal Review and Geometric Characterization of Old Masonry Buildings in Lisbon for Seismic Risk Assessment

V. Bernardo[a], R. Sousa[b], P. Candeias[a], A. Costa[c], and A. Campos Costa[a]

[a]Earthquake Engineering and Structural Dynamics Unit Structures Department, National Laboratory for Civil Engineering, Lisbon, Lisbon, Portugal; [b]CDRSP - Polytechnic of Leiria, Leiria, Portugal; [c]Department of Civil Engineering, University of Aveiro, Aveiro, Portugal

ABSTRACT

The Metropolitan Area of Lisbon (MAL) has the highest population and building density in Portugal, and is exposed to medium to high magnitude earthquakes due to its geographical location. Currently, the MAL housing stock is constituted by approximately 35% of masonry residential buildings with a large variability of materials and construction techniques, as a result of many centuries of history. Most of these buildings were built before the introduction of the first design code for building safety against earthquakes (RSSCS) in 1958 and therefore were only designed to support gravity loads. Given the presence of these buildings in areas of significant seismicity, a comprehensive research is needed to assess the seismic risk and define mitigation policies for this population of unreinforced masonry buildings. The main purpose of this work is thus to geometrically characterize these typologies, through an exhaustive survey of dozens of masonry buildings collected from original drawings and identify the most important aspects that can influence their seismic behavior. After a compressive historical background, the information collected is statistically analyzed and expressed through probability distributions that can be used for the development of numerical models and derive seismic vulnerability functions, fundamental to conduct seismic risk analyses.

ARTICLE HISTORY
Received 2 February 2021
Accepted 13 April 2021

KEYWORDS
Geometry data collection; historic context; Old Masonry Buildings (OMB); seismic vulnerability; statistical analysis

1. Introduction

The regions of Lisbon and south of Portugal are considered the areas with the highest seismic hazard in Portugal mainland. Located on the Eurasian plate, in the vicinity of the southern boundary with the African plate, Lisbon is susceptible to strong offshore earthquakes, originated in the fault between these two plates, and medium to strong onshore earthquakes resulting from the Holocene deformation in the Tagus Lower Valley, as reported in Vilanova and Fonseca (2007). Most of the events registered in Portugal occurred between the 18th and 19th centuries, including the 1755 Lisbon earthquake, with an estimated magnitude around 8.5 (Richter scale). The "Great Lisbon earthquake", as is known, and the subsequent tsunami and fires destroyed about 85% of the buildings and killed about 30,000 to 40,000 people, which represented approximately 20% of the people living in Lisbon in that period. Aside from this major historical earthquake, the 6.3 magnitude Benavente (Tagus Valley, approximately 60 km north-east from Lisbon) onshore earthquake in 1909 (43 deaths) and the 7.8 magnitude offshore earthquake, associated to the Horseshoe fault in the Atlantic Ocean (150 km of southwest Cape São Vincente in Algarve — south of Portugal) in 1969 (13 deaths) are considered the most relevant reported earthquakes in the instrumental period of the national seismic catalog for Portugal mainland in the last century.

The 1909 Benavente earthquake mostly affected the oriental part of Lisbon, where around 40% of the dwellings collapsed. Among the surveyed damages in masonry buildings, the partial collapse of the building's corner and vertical cracks were the main reports (Choffat, P. and Bensaúde 1912). In general, minor cracks were also reported in other parts of the city.

On the other hand, the 1969 Algarve earthquake mainly affected the south of Portugal, where about 400 buildings collapsed or partially collapsed, namely the clay and stone masonry buildings (Miranda, J. and Carrilho 2014). In Lisbon, the collapse of several chimneys was the main damage identified.

Even though Portugal has not been the target of high-magnitude earthquakes in recent years, it remains susceptible to this natural phenomenon.

The Metropolitan Area of Lisbon (MAL) is composed by 18 municipalities and 211 parishes, Figure 1, with a total area of 2957.5 km^2 and a population density of around 950 inhabitants/km^2 (Statistics Portugal 2012).

CONTACT V. Bernardo vbernardo@lnec.pt National Laboratory for Civil Engineering Av. do Brasil, 101 1700-066 Lisboa Portugal

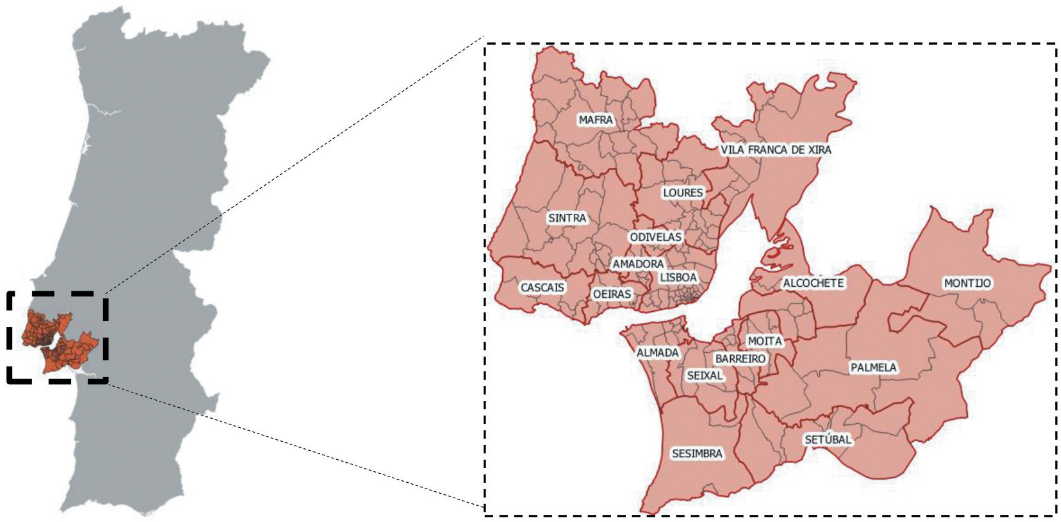


Figure 1. Metropolitan area of Lisbon (MAL).

The masonry buildings stock in the MAL is around 35% and is mostly used for residential purposes (Statistics Portugal 2012). In this region, four main typologies of masonry buildings are typically identified: (i) "Pre Pombalino", constructed before 1755, characterized by heterogeneous and irregular geometry and poor quality masonry; (ii) "Pombalino", erected after the 1755 Earthquake and characterized by regular geometry and by the introduction of a set of features designed to improve their seismic performance; (iii) "Gaioleiro", built between 1870 and 1930, which represent a downgrade of the construction and the progressive disappearance of the seismic concepts previously implemented; (iv) "Placa", constructed between 1930 and 1960, and represent the introduction of reinforced concrete (RC) in the Portuguese construction, namely by replacing the timber floors, common in the previous typologies, by concrete slabs. Moreover, it is also worth pointing out that no impact of earthquake has been considered in their design as the First Code for Building Safety Against Earthquakes (RSCCS 1958) was introduced only in (1958).

In the last decades, the performance of buildings under seismic action deserved special attention due to the increasing public earthquake awareness related to the protections of human life and architectural heritage. In order to minimize losses against future seismic events and reduce potential damage in the structures, several studies have been performed at different scales aiming to assess their seismic vulnerability and seismic risk. At the global scale, reference is made to a research developed by the Global Earthquake Model (GEM) Foundation (Crowley et al. 2013; Silva et al. 2018), the research project RISK-UE (Mouroux and Le Brun 2006), LESSLOSS (Flesch 2007) and PERPETUATE (Lagomarsino and Cattari 2015). At the national level it should be mentioned the seismic risk studies carried out by Sousa (2006) and Silva et al. (2014) together with other local studies at the urban scale in the MAL region (Costa et al. 2010; Tang et al. 2012); Coimbra (Vicente et al. 2011); Faro (Vicente, Ferreira, and Maio 2014) and Seixal (Ferreira et al. 2013). Most of these studies employed some statistical data combined with expert opinion to characterize the building stock and derive vulnerability functions.

In the region of Lisbon, and based on analytical approaches (D'Altri et al. 2020; Roca et al. 2010), the main types of existing masonry buildings have been investigated by several authors: "Pombalino" (Meireles and Bento 2010; Lopes et al. 2014), "Gaioleiro" (Candeias 2008; Mendes 2012; Simões et al. 2018) and "Placa" (Ferrito, Milosevic, and Bento 2016; Lamego 2014; Milosevic 2019). Although these important studies provide a significant improvement in the knowledge regarding the seismic response of these typologies, they were mainly focused in particular cases, which cannot be assumed as representative of the general building's stock in the framework of seismic risk analysis. In this context, the main objective of this work is to characterize the geometry of the masonry buildings in the MAL region until the appearance of RSCCS, hereinafter named as Old Masonry Buildings (OMB).

The first part of this work presents a historic review about the evolution of OMB in the city of Lisbon, providing a brief overview and describing their main features. Based on this, the geometry of dozens of OMB was collected from the original drawings (blueprint) and statistically analyzed through probability distributions.

This information will be most useful for the development of numerical models and to support similar studies about the vulnerability and seismic risk assessment.

2. Historic context of the building stock and urban planning

On the 1st of November of 1755, All Saints Day, Lisbon was shaken by a devastating earthquake with estimated magnitude around 8.5 (Richter scale) that almost destroyed the downtown part of the city and surroundings. This event represents a milestone in the history of construction and engineering in Portugal: before the earthquake, the urban center of Lisbon was very dense and poorly organized, mostly distributed along the Tagus river, without any urban planning over the centuries. The city was the political and commercial center, where the royal palace was located and surrounded by medieval streets, with traditional shops full of the new products that came into the country, fruit of the Discoveries and Portuguese trade with the Indies. At this time, the so-called "Pre-Pombalino" buildings (see section 3.1) prevailed in the old city center.

Following the earthquake, the city was rebuilt under the orders of the prime minister *Sebastião José de Carvalho e Melo*, known by Marquis of Pombal ("Marquês de Pombal" in Portuguese), which appointed the Engineer and Architect *Manuel da Maia* for the urban plan design. During the reconstruction of the city, several innovative solutions were employed, such as: road infrastructures, public health measures and sewerage, pile foundations and building safety for fires and earthquakes, influencing the construction of many new cities in the world. Herewith, a new typology of building emerged, called "Pombalino" (see section 3.2) 2014). This typology was standardized during more than one century. Figure 2(a) shows the downtown street plan for the reconstruction of Lisbon after the earthquake.

In 1852, an improvement policy for the urban development reveals the intention to expand the city to the North, delimited by the Lisbon ring road ("Estrada da Circunvalação" in Portuguese), Figure 2b). By this time, the population who was living in urban areas with more than 2000 inhabitants was only 10.4% of the country's total population.

In the second half of the 19th century, there is an expansion of the urbanization area in Portugal: in 1864 the publication of the Decree-law no.10 of December 31st, introduced modifications and restrictions on urban plans. This law brought advantages leading to the urban area expansion, headed by the engineer *Frederico Ressano Garcia*. Figure 3 presents some of these improvements on the urban plan: the construction of Lisbon's main boulevard — Liberty Avenue ("Avenida da Liberdade" in Portuguese) in 1879 and "Almirante Reis" Avenue in 1888, with the respective connections to "Baixa Pombalina".

The construction of new buildings resulted in the spread of other parts of the city, which followed by the political reforms, modernization of transport system and Industrial Revolution, attracted the population. At the end of the 19th century, the substantial increase of the number of inhabitants, accompanied by socio-economic crisis in the country after the implementation of the First Portuguese Republic in 1910, affected the construction and the real estate market, forcing the contractors to adopt more simplified construction techniques and low-quality materials. This period was marked by the decline of construction quality in Portugal and a new typology, called "Gaioleiro" (see

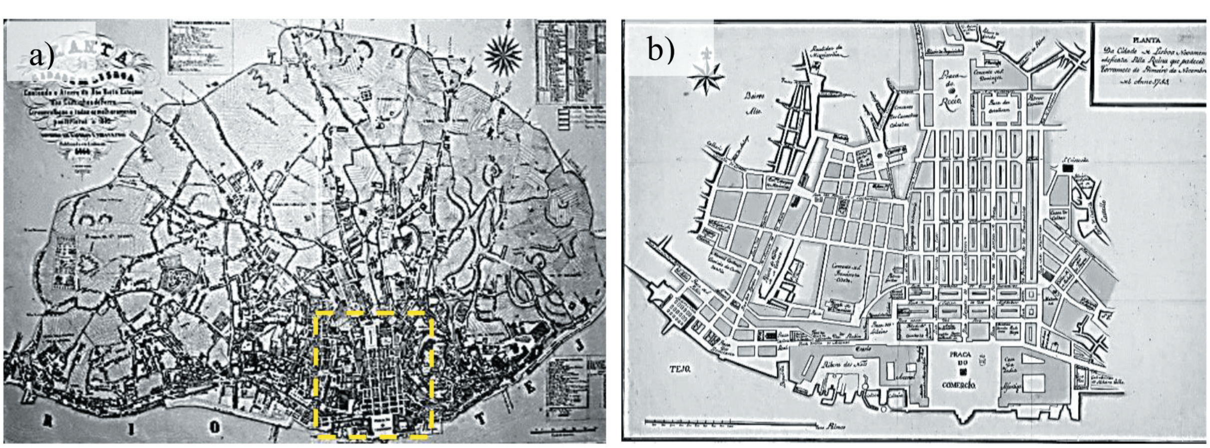


Figure 2. Lisbon in two periods: (a) Map of Lisbon in 1863 and "Baixa Pombalina" downtown highlighted (AFML — Lisbon Municipal Archive: Photographic collections); (b) "Baixa Pombalina" downtown street plan for the reconstruction after 1755 earthquake (Van Der Krogt 2008).

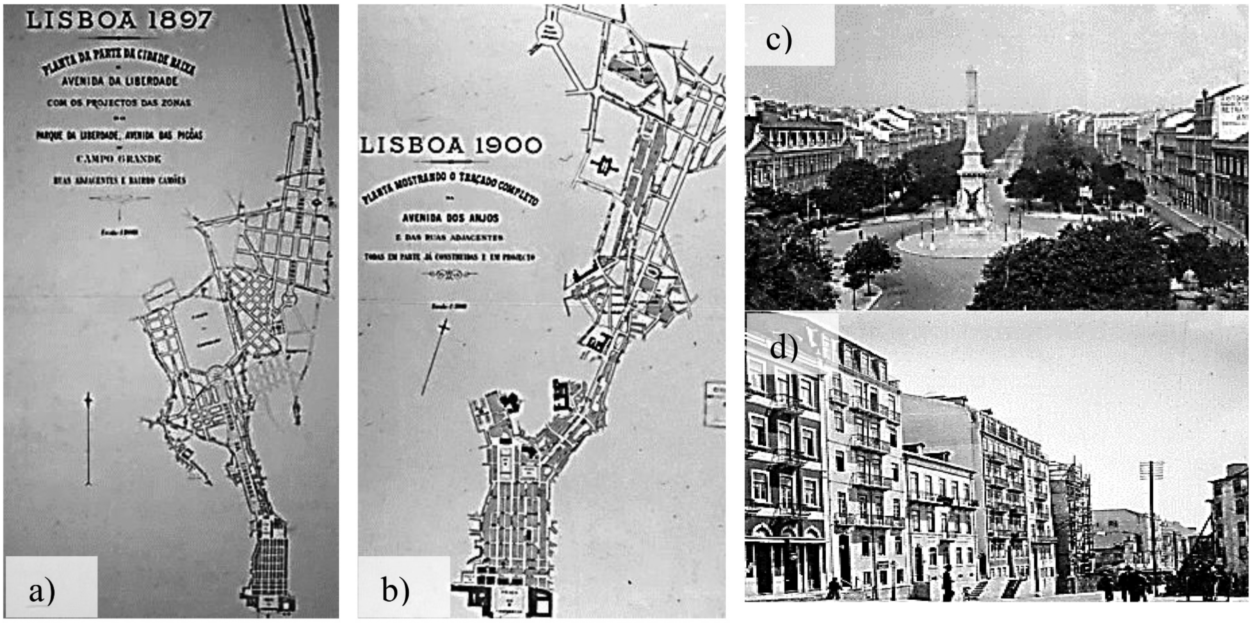


Figure 3. New avenues in Lisbon: (a) Plan to connect "Avenida da Liberdade" to "Baixa Pombalina"; (b) Plan to connect "Avenida Almirante Reis" to "Baixa Pombalina"; (c) "Avenida da Liberdade" (1900); (d) "Av. Almirante Reis"(1908) (AFML — Lisbon Municipal Archive: Photographic collections).

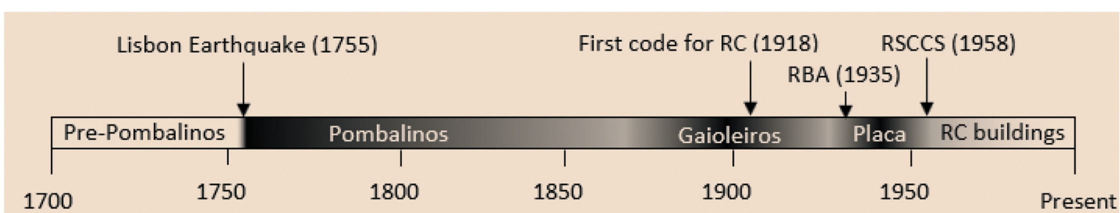


Figure 4. Temporal evolution of the typologies in Lisbon and design codes for old masonry buildings.

section 3.3) 2018), emerged as a result of the progressive adulteration of the main characteristics found in the previous typology, including the abandonment of the main seismic resistant features. Most of these buildings were acquired in the final stage of construction by the *bourgeoisie* class and rented flat by the landlords — rentable buildings.

The second decade of the 20th century was marked by the appearance of the RC in Portugal. Regulatory Instructions for the use of RC was first published in 1918 as a code to regulate its use. Later, in 1930 was approved the General Regulation of Urban Construction (RGCU 1930) and in 1935 the Portuguese Reinforced Concrete Code (RBA), which revoked the code announced in 1918. This period is characterized by the introduction of RC in the construction and by the associated improvement of design techniques, regulated by the new codes. Throughout the 1930s decade the reinforced concrete became gradually more common. The old timber floors, characteristic of the previous typologies, starts to be progressively replaced by RC slabs: first in humid places (bathrooms and kitchens), balconies and terraces, and later on entire floors, giving rise to a new typology called "Placa" buildings (see section 3.4) 2019). This typology remains until the end of the 1950s and was typical on many neighborhoods promoted by a set of social housing policies during the National Dictatorship ("Estado Novo" in Portuguese). In the decade of 1950s, the use of reinforced concrete framed structures became more common, namely to overcome larger spans. In 1958, the seismic action is included in the design of structures with the publication of the First Code for Building Safety Against Earthquakes (RSCCS 1958). This period represents the transition between the "Placa" buildings and the reinforced concrete buildings.

Figure 4 summarizes the time evolution of masonry buildings in Lisbon and the appearance of the first codes to guide structural safety.

3. Building description and main features

According to the aforementioned, four main types of masonry buildings can be identified in the MAL region: "Pre-Pombalino" (before 1755), "Pombalino" (1755 to 1870) (Lopes et al. 2014), "Gaioleiro" (1870 to 1930) (Simões 2018) and (Candeias 2008), and "Placa" (1930 to 1960) (Milosevic 2019) and (Lamego and Lourenço 2012). However, these typologies can also be found in other urban centers in the country. Below is presented an overview of the main geometric and structural characteristics of these building typologies.

3.1. "Pre Pombalino" buildings

The "Pre-Pombalino" buildings (Figure 5a) are a Portuguese typology characteristic before the 1755 Lisbon earthquake. In general, they are recognized by the irregular geometry, reduced dimensions in plan, narrow facades, up to four stories high, high density of walls made with poor quality masonry and reduced number of openings. In residential buildings, the access to upper floors was materialized with a single flight of stairs, next to the side walls in buildings with narrow facades, or at the center in buildings with longer facades. The ground floor was usually reserved for commerce and, in some cases, setback with respect to the upper floors (Figure 5b). In this period, the buildings did not provide any sanitary facilities.

Regarding the construction process, the walls were generally made with: (i) regular stone masonry, more common in important and historical buildings; (ii) rubble stone masonry, constituted by small to medium

Figure 5. "Pre-Pombalino" typology: (a) and (b) example of building facades aesthetic; (c) "Tabique" in exterior walls supporting the timber floor; (d) "Tabique" in partition walls.

stones or even pieces of bricks connected with earth-based mortar or lime mortar; (iii) rammed earth masonry, common in rural buildings or millennial constructions; (iv) “tabique” walls. In “Pre-Pombalino” buildings the “tabique” walls were very common in partition walls (Figure 5c) — a set of vertical long boards connected by horizontal small wood stripes, normally filled with pieces of bricks and lime mortar — or even in interior or exterior structural walls, constituted by a timber framed structure filled with rubble stone or brick pieces of masonry and lime mortar (Figure 5d).

The ground floor was typically made with stone whilst the upper levels were made with wood planks, supported by timber beams, fixed or simple supported on the facades and interior walls.

Currently, “Pre-Pombalino” buildings can be found in older neighborhoods of the city but only few remain in their original state due to material deterioration and adulteration of their characteristics promoted by the rehabilitation interventions over the years.

3.2. *“Pombalino” buildings*

The “Pombalino” typology (Figure 6a) emerged after Lisbon earthquake and is particularly known by the innovative seismic design introduced in that period. These buildings usually have up to five stories and regular geometry. The ground floor is dedicated for commerce and the remaining ones for residential purpose. The main facade walls present large windows, when comparing with the previous typology, and the presence of mansards or attics was common. One interesting aspect of this typology was the construction method, which was standardized and replicated in the city after the earthquake. Moreover, they were designed to present identical properties within the same block, contributing for a better overall seismic performance.

The main innovative feature of this typology is the “Gaiola Pombalina” present in the load bearing walls. The “Gaiola” (cage in English) is a set of plane wood trusses, called “Frontal” walls, connected at the corners by vertical studs. The “Frontal” walls are assembled by wood studs, forming a triangular geometry — Saint Andrew’s cross, and filled with weak masonry (Figure 6 (b,c,d)). The partition walls were in “tabique”

Figure 6. “Pombalino” typology: (a) aesthetic of the building; (b) “Frontal” wall exhibited during rehabilitation works works; (c) “Gaiola Pombalina” timber frame after removed the finishing material; (d) typical node connection detail.

Figure 7. “Gaioleiro” typology: (a) aesthetic of the building; (b) “tabique” partition walls; (c) timber floor supported on the adulterated “frontal” walls or brick masonry; (d) brick masonry interior walls.

(described in section 3.1). The facade and side walls were usually constituted by rubble stone masonry, with better quality in the wall-corners and ground floor.

The floors were made of wood planks supported on timber beams, which were connected to the facade and “frontal” walls through embedded anchors. The foundation system was also advanced: for hard soils, masonry arches with masonry bricks or regular stones were adopted to support the buildings’ walls. In case of soft soils, commonly present in the downtown of Lisbon, the foundation system included a timber frame formed by horizontal wood beams supported by wood piles embedded in embankments, normally formed by debris of the buildings collapsed during the earthquake.

3.3. “Gaioleiro” buildings

The “Gaioleiro” buildings (Figure 7a) were famous during the expansion of the city in the beginning of the 20th century. The quality of construction was very poor when compared with the previous one, being observed many buildings collapses during the construction.

In general, they have up to six stories, rectangular shape in plan and are distinguished from the other typologies by the decorative elements exhibited on the facades. The existence of light-shafts in the center of the building to provide natural light and ventilation were common on these buildings, as well the metallic balconies and service staircases on the back facades.

The facade walls were usually constituted by rubble stone masonry with lime mortar. The side walls were also in rubble stone masonry or brick masonry, but normally with constant thickness along the height. The wood trusses used in the interior walls of the “Gaiola Pombalina” were progressively adulterated and simplified, with the removal of the diagonal elements. The partition walls were in “tabique” (Figure 7b) or brick masonry (solid or hollow bricks) (Figure 7c)(Figure 7b).

The floors were composed by timber beams supported on the facades and covered by wooden planks (Figure 7d)(Figure 7c). The transverse deformation of

Figure 8. "Placa" typology: (a) aesthetic of the building; (b) rubble stone masonry wall; (c) brick masonry wall; (d) concrete slab simple supported on the masonry walls.

the main beams were often restrained by smaller perpendicular beams. In the final period of "Gaioleiro" buildings it is observed the use of composite floors (steel beams and ceramic bricks) on balconies, kitchens and bathrooms. The weak connections between the exterior and interior load-bearing walls and to the wooden floors were very common.

In Lisbon, where most of these buildings were built on soft soils with low strength, the foundation system is composed by masonry arches or continuous foundations in limestone masonry.

3.4. *"Placa" buildings*

Finally, the "Placa" typology (Figure 8a) corresponds to a combination of masonry walls with RC slabs and is characterized by the introduction of the RC as a structural element. Most of these buildings were designed for lower class population, with small interior compartments. The main entrance is generally placed at the center of the building, typically providing access to two apartments per floor, through two-flight staircase.

The vast majority of these buildings were, built before the decade of 1960, have regular geometry and have up to five stories (Statistics Portugal 2012). The "Placa" aesthetic is more simplistic when compared to "Gaioleiro", following the modern architecture. The use of prefabricated elements was also common in balconies, staircases and openings, resulting in less expensive constructions.

The facade walls were usually in rubble stone masonry (Figure 8b) or brick masonry (Figure 8c) with hydraulic lime or cement mortar and often present a progressive decrease in thickness along the height. The side walls were made with the same material or concrete blocks, but usually with constant thickness along the height. The interior and partition walls were made with (solid or hollow) brick masonry or concrete blocks.

The typical wooden floors, presented in the previous typology, were gradually replaced by concrete slabs of poor concrete and one single reinforcement layer for positive bending moments (Figure 8d) (Figure 8b). The slabs were usually simple supported on the masonry walls without continuity. Later, reinforced concrete beams and columns were incorporated in the facades or in the interior partitions to overcome larger spans. The foundations were continuous and made with stone or brick masonry or concrete.

Table 1. Resume of the main structural elements for old masonry buildings in MAL.

Typology	Element	Type/Material	Dimensions	Remarks
"Pré Pombalino" (up to 1755) 	Foundations	stone or brick masonry; dry stone masonry	≥ thickness wall	Continuous foundations with enlargement at the base; stone masonry walls under masonry arches
	Exterior walls	Rubble stone or brick masonry with lime or earth-based mortar; dry stone or rammed earth masonry; "tabique"	Stone or brick masonry: 0.40 to 0.80 m Rammed earth masonry: 0.40 to 0.65 m "Tabique": 0.15 to 0.20 m	"Tabique" used in exterior walls or interior structural walls
	Interior walls		stone or brick masonry: up to 0.30 m "Tabique": 0.10 to 0.20 m	
	Partition walls	"Tabique"	0.07 to 0.10 m	"Tabique" in partition walls — set of vertical long boards connected by horizontal small wood studs
	Floors	Wood (in general)	0.18 to 0.24 m	Wood planks (~0.02 m) supported by timber beams, spaced between 0.20 m to 0.40 m and simple supported or fixed on masonry walls; ground floor in stone
	Roof	Wood (in general)	-	Simple triangular timber truss
	Staircase	Wood or stone	-	Single flight staircase next to side walls or in the center in large facade buildings
"Pombalino" (1755–1870) 	Foundations	Stone or brick masonry; wood piles	≥ thickness wall	Medium to hard soils: good quality masonry (brick or regular stone) and masonry arches; Soft soils: wood piles with diameter around 0.15 m to 0.20 m and maximum length of 5.0 m
	Exterior walls	Rubble stone masonry with lime mortar or regular stone masonry	0.60 to 0.90 m	Good quality masonry in ground floor and wall-corners
	Interior walls	"Frontal"	0.15 to 0.20 m	"frontal" walls assembled with wood studs and connected by means of iron nails to form a triangular geometry. Placed parallel to the main facades to receive the floors mass
	Partition walls	"Tabique"	up to 0.10 m	Perpendicular to "frontal" walls
	Floors	Wood	Total thickness: 0.18 to 0.24 m	Wood planks (0.02 m) supported by timber beams (0.10x0.20 m^2) anchored to the facade and "frontal" walls with steel rods
	Roof	Wood	-	Double pitched roof formed by timber trusses. Existence of mansards
	Staircase	Wood or stone	-	Constituted of three parallel "Gaiola" type walls; stone masonry on the ground level
Typology	Element	Type/Material	(continue) Dimensions	Remarks
"Gaioleiro" (1870–1930) 	Foundations	Limestone or brick masonry	≥ thickness wall	Continuous foundations with enlargement at the base or masonry arches
	Exterior walls	Rubble stone masonry or brick masonry with lime mortar	Facade: 0.50 to 0.90 m Side walls: 0.30 to 0.50 m	Facade walls in general with rubble stone masonry and decreasing thickness in height; side walls with rubble stone or brick masonry with constant thickness
	Interior walls	Timber frame or brick masonry with lime mortar	Brick masonry: up to 0.30 m Timber frame: up to 0.20 m	Weak timber frame structure without diagonal truss
	Partition walls	"Tabique"	Up to 0.10 m	"tabique" walls substituted by brick masonry in the period of transition
	Floors	Wood or steel	Total thickness: 0.18 to 0.24 m	Wood planks supported by timber frame beams; presence of balconies and marquees in steel with brick masonry
	Roof	Wood	-	Double pitched roof formed by timber trusses. Existence of mansards
	Staircase	Wood or stone	-	Main stairs in wood and located on the building center. In narrow shapes are located near to side walls; presence of steel fire escape stairs on the back facade

(*Continued*)

Table 1. (Continued).

Typology	Element	Type/Material	Dimensions	Remarks
"Placa" (1930–1960) 	Foundations	Stone or brick masonry; reinforced concrete	≥ thickness wall minimum depth of 0.30 to 0.50 m	Continuous foundations
	Exterior walls	Rubble stone or brick masonry with hydraulic or cement mortar	Rubble stone masonry: 0.40 to 0.90 m Brick masonry: 0.25 to 0.60 m	Solid or hollow brick masonry; possible concrete blocks in side and interior walls; wall thickness may decrease along height in buildings with more than 5 stories
	Interior walls	Brick masonry with hydraulic or cement mortar	Up to 0.35 m	
	Partition walls		Around 0.12 m	Solid or hollow brick masonry and equal thickness along the height of the building
	Floors	Wood or reinforced concrete	Timber floors: 0.18 to 0.28 m concrete slabs: 0.07 to 0.12 m	C16/20 concrete class and single layer of reinforcement for positive moments (A235); slabs simple supported on the walls
	Roof	Wood or reinforced concrete	-	Timber frame composed by parallel trusses and purlins to support the Portuguese tiles; RC terraces can be found
	Staircase	Wood, reinforced concrete or steel	-	Main stairs in wood or concrete located on the middle of the building; service staircases in concrete or steel located in the back
	Others	Reinforced concrete	Minimum dimensions for gravity loads	RC beams at floor level to interlock the exterior masonry walls; RC frame to overcome larger spans, namely at the ground level

A detailed summary of properties of the main structural elements of the aforementioned typologies is presented in Table 1. Comparison matrix for the main features of OMB is presented in Table 2.

4. Masonry building stock in Lisbon

According to the last Census carried out in 2011 (Statistics Portugal 2012), the building stock in the MAL is constituted by 448.957 buildings, where the RC typology is predominant (65%) as shown in Figure 9. The masonry buildings — Unreinforced Masonry (URM) and Rubble Stone Masonry (RSM) — represents around 34% of the existing buildings, wherein 21.6% have concrete slab and the remaining timber floors. The pre-seismic code masonry buildings, constructed before 1960, correspond to 63,526 buildings, approximately 14.2% of the housing stock in the MAL and around 60% of the existing masonry buildings (Figure 10).

The disaggregation of the building stock in the MAL in terms of period of construction (Figure 11), typology and number of floors was performed for three different periods up to 1960s. Before the decade of 1920, most of the housing stock corresponds to masonry buildings up to four stories without RC slabs (URM1). In the second period (1919 to 1945), after the dissemination of the RC, it is notorious a decrease in the construction of URM1 typology and the appearance of masonry buildings with concrete slabs (URM2) and RC structures, mainly up two stories. Note that a major part of the RC buildings built before the 1960s are masonry buildings confined by slender RC frames. In the last period (1945 to 1960), it was observed a clear boost in the construction, predominantly constituted by RC and URM2 buildings, with increasing number of floors, mostly up to four stories, influenced by the supply and demand increases in the real estate market.

The geographical distribution of old masonry buildings (built before the decade of 1960) across the various municipalities of the MAL, based on the Census 2011 (Statistics Portugal 2012), is presented in Figure 12. The higher concentration of both typologies (URM1 and URM2) is evident in the municipality of *Lisbon*, followed by *Sintra, Setúbal* and *Almada*. Moreover, most of the buildings in the municipality of Lisbon are constituted by timber floors, represented by the "Pre-Pombalino" and "Pombalino" typology, namely located in Lisbon downtown, and by the "Gaioleiro" that appear later in the urban expansion of the city. This information was useful to collect the data of the building stock analyzed in the following section, which were obtained in the most representative regions of Lisbon.

Table 2. Comparison matrix for the main features of old masonry buildings.

Main features	*Pre-Pombalino*	*Pombalino*	*Gaioleiro*	*Placa*
Geometry				
Irregular	X	N/A	O	O
Regular	N/A	X	X	X
Construction and materials quality				
Low	X	N/A	X	O
Medium to heigh	O	X	O	X
Foundations				
Stone masonry	X	X	X	X
Brick masonry	O	X	X	X
Concrete	N/A	N/A	N/A	O
Exterior walls				
Regular stone masonry	O	O	O	O
Rubble stone masonry	X	X	X	X
Brick masonry w/lime mortar	O	X	X	O
Brick masonry w/cement or hydraulic mortar	N/A	N/A	O	X
Tabique	O	N/A	N/A	N/A
Concrete blocks	N/A	N/A	N/A	O
Interior walls				
Rubble stone masonry	X	N/A	N/A	N/A
Brick masonry w/lime mortar	N/A	N/A	X	O
Brick masonry w/cement or hydraulic mortar	N/A	N/A	O	X
Tabique	X	N/A	N/A	N/A
Frontal Walls	N/A	X	O (*)	N/A
Concrete blocks	N/A	N/A	N/A	O
Partition walls				
Tabique	X	X	X	O
Brick masonry	N/A	N/A	O	X
Floors				
Timber structure	X	X	X	O
Steel beams and brick masonry	N/A	N/A	O	O
Reinforced concrete	N/A	N/A	O	X
Others				
Reinforced concrete frame	N/A	N/A	O	X
Rigid diaphragms	O	X	O	X
Timber roof	X	X	X	X
Presence of concrete on the roof	N/A	N/A	N/A	O

"X" — Present and most common; "O" — present but less common; "N/A" — Not Apply (*) without timber truss.

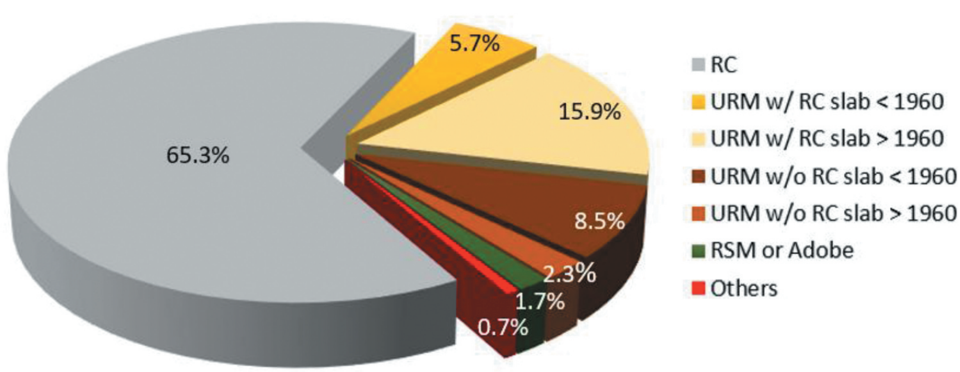


Figure 9. Overview of the Building stock in MAL in 2011 and distribution of the masonry pre-code buildings.

5. Statistical characterization of old masonry building geometry

5.1. General considerations

The geometric characterization was based on the information available in detailed drawings from the original projects (blueprint) and collected in the municipal services. The data collection refers mainly to "Gaioleiro" and "Placa" buildings built between 1900 and 1960 and up to five stories. Figure 13 presents some examples of the data collected from these typologies. The information available before this period is poor or absent. Furthermore, these are the most representative typologies in the MAL, since the others are mainly concentrated in downtown and require a more detailed analysis considering the advanced state of degradation and adulteration from the

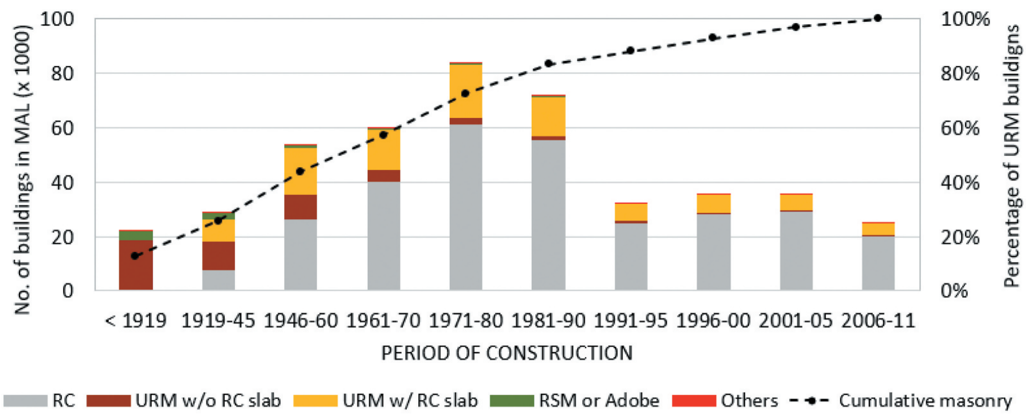


Figure 10. Building stock in MAL and evolution of URM buildings by period of construction up to 2011.

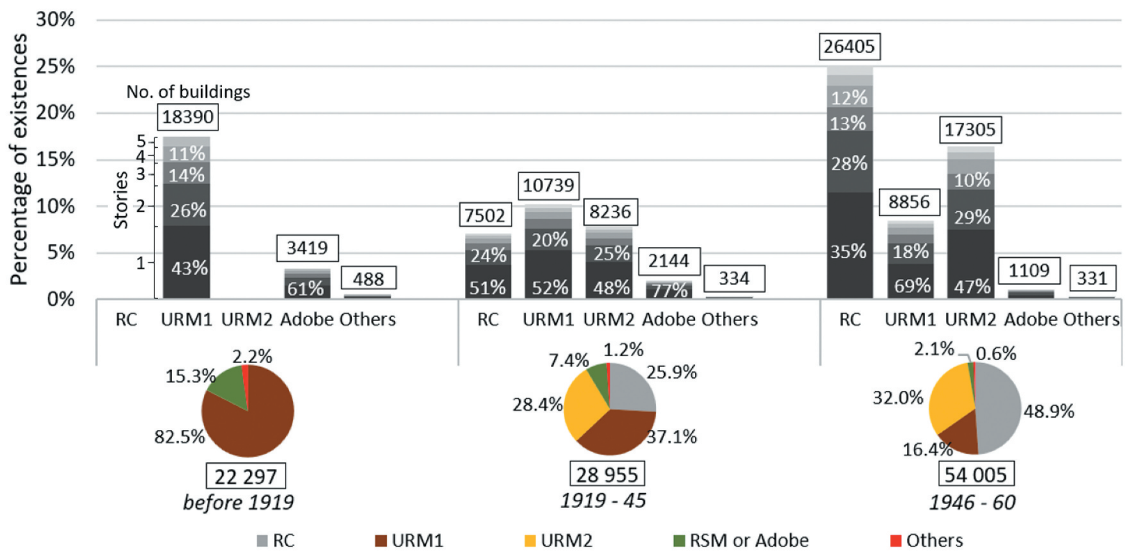


Figure 11. Disaggregation of the buildings in MAL up to 1960 by period of construction, typology, and number of floors.

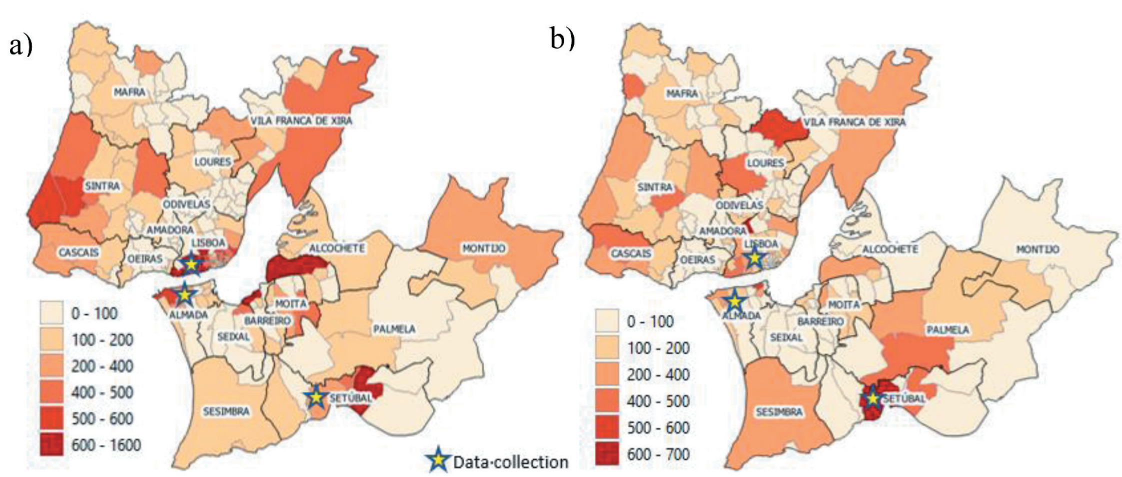


Figure 12. Distribution and number of old masonry buildings in MAL up to 1960 with the location of data collection: (a) URM1 and (b) URM2.

original, as a result of rehabilitation works carried out in the recent years.

The geometric characterization comprises the parameters listed in Table 3 for a population of 100

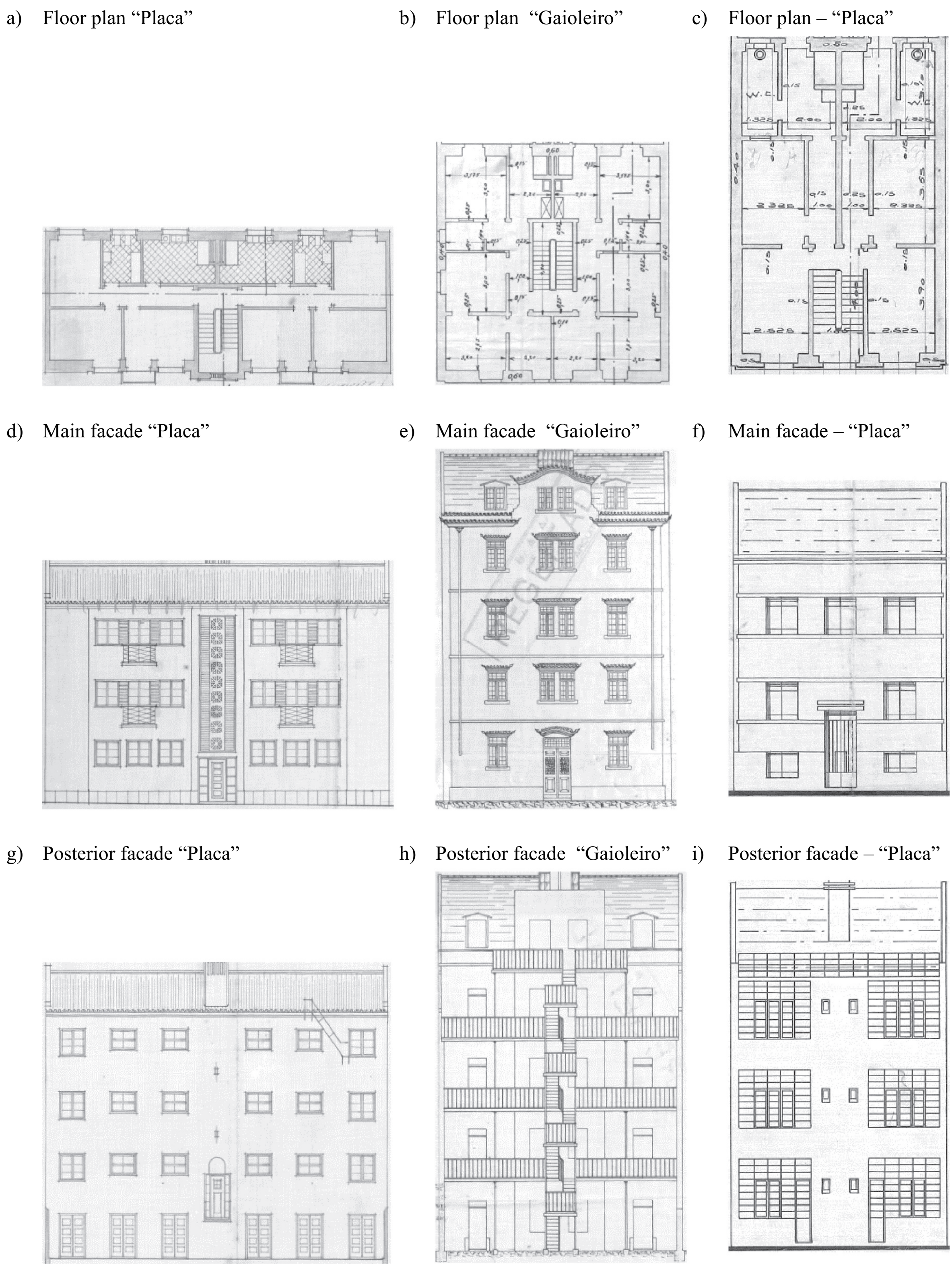


Figure 13. Example of data collection to characterize the population of old "Placa" and "Gaioleiro" masonry buildings.

samples. For a real population of around 63.526 (Figure 9), these results have a margin of error of 10%, for a confidence level of 95%. The respective descriptive statistic was computed quantitatively using the method of moments to estimate the sample mean and variance of the observed data. In some cases, probability distribution functions were also fitted to describe the available data. In order to provide reliable information, the

Table 3. General scheme and geometric parameters collected to characterize the old masonry buildings.

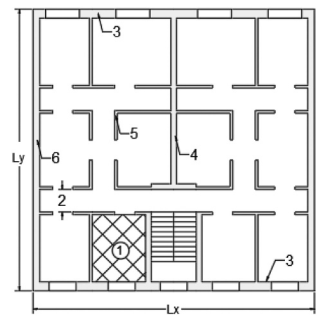
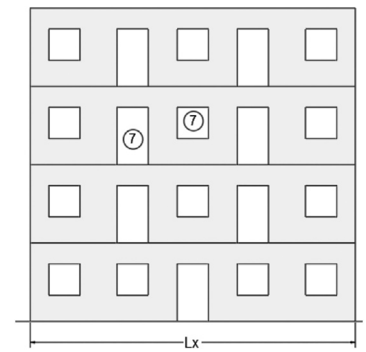
Legend/Parameter	Plan view	Facade view
Plan dimensions Building height Stories height Number of partitions (1) Hall dimension (2) Wall thickness: facades (3); interior (4), partition (5), side walls (6) Openings dimensions (7) Interior walls length Floor (type and thickness)		

Table 4. Statistical properties associated with the geometric parameters collected.

Parameter	Unit	Distribution	Mean	C.O.V.	Mode	1st quartile	Median	3rd quartile
Length Lx	m	LogNormal	12.6	0.40	-	7.3	12.1	17.6
Length Ly	m	LogNormal	12.1	0.34	-	8.2	11.2	14.3
Plan area	m^2	Gamma	151.6	0.60	-	82.6	130.3	197.0
Lx/Ly ratio	-	LogNormal	1.36	0.58	-	0.76	1.11	1.95
Ground floor height	m	LogNormal	3.23	0.13	-	2.96	3.20	3.50
Upper stories height	m	LogNormal	3.01	0.08	-	2.80	3.00	3.25
Openings ratio (ground floor)	-	LogNormal	0.26	0.38	-	0.20	0.23	0.27
Openings ratio (front facade)	-	LogNormal	0.23	0.35	-	0.17	0.21	0.26
Openings ratio (rear facade)	-	Normal	0.21	0.38	-	0.16	0.21	0.25
Interior walls density	-	Normal	0.054	0.19	-	0.047	0.055	0.061
Compartments Area	m^2	Normal	13.7	0.22	-	11.6	13.95	15.59
Walls thickness (Facade)	m	LogNormal	0.47	0.30	-	0.40	0.50	0.60
Walls thickness (Side walls)	m	LogNormal	0.34	0.32		0.25	0.30	0.40
Walls thickness (interior)	m	-	0.14	0.15	0.15	0.125	0.15	0.15
Walls thickness (exterior)	m	-	0.21	0.24	0.25	0.15	0.25	0.25
Average wall thickness reduction	m	-	0.11	0.51	0.10	0.10	0.10	0.10
Floor thickness (RC)	m	-	0.10	0.10	0.10	-	-	-
Floor thickness (timber)	m	-	0.20	0.05	0.20	-	-	-

more adequate distributions were validated using common goodness-of-fit tests, such as Kolmogorov-Smirnov (K-S) test for a significance level of 5% and testing the null hypothesis. Classifying a building according to its typology from a structural point of view is a difficult task, which involves the characterization of the type of floor, load bearing walls and materials, in addition to architectural and geometrical aspects. Considering the enormous variability in the materials, the combined solutions found and the uncertainty in their characterization in terms of typology, the geometry was analyzed independently

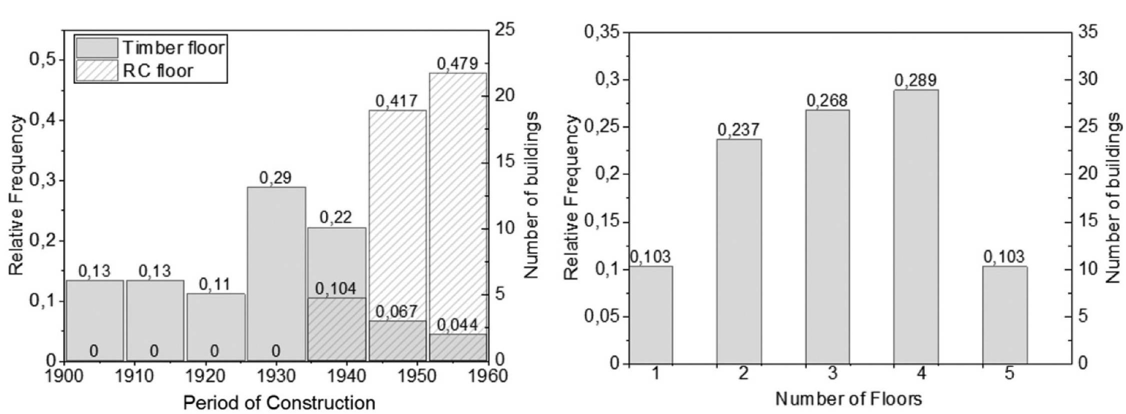


Figure 14. Distribution of buildings collected by period of construction (left) and number of floors (right).

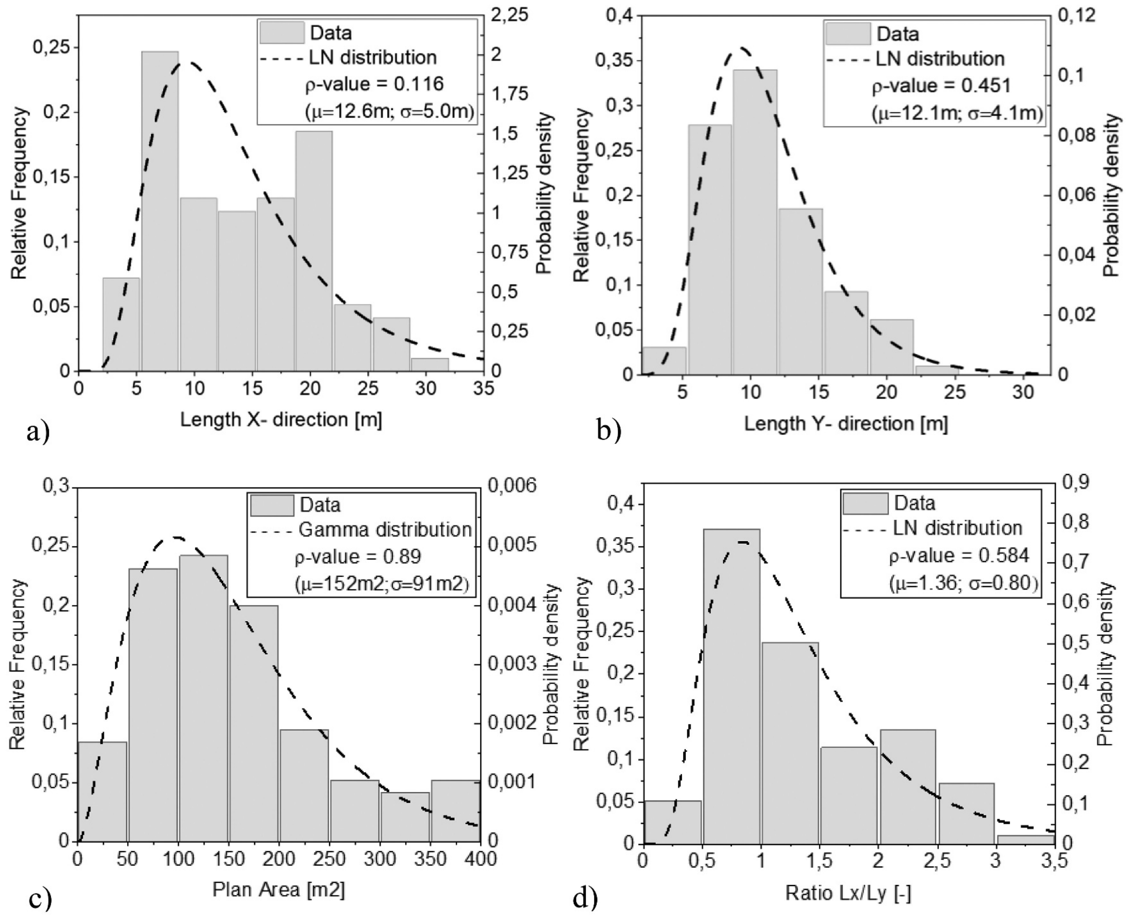


Figure 15. Plan dimensions of the buildings: (a) length X; (b) length Y; (c) area of implantation; a) Relation Lx/Ly.

of the typology attributed and confirmed by one-way analysis of variance (ANOVA).

5.2. Global geometry characterization

The geometric survey is presented by the respective histograms in terms of relative frequency and number of buildings. Alternative distributions, namely Normal (N), LogNormal (LN) and Gamma, were best fitted to data based on Kolmogorov-Smirnov (K-S) tests, which are represented on the histograms figures related to each parameter. The statistical properties for the parameters collected are summarized in Table 4.

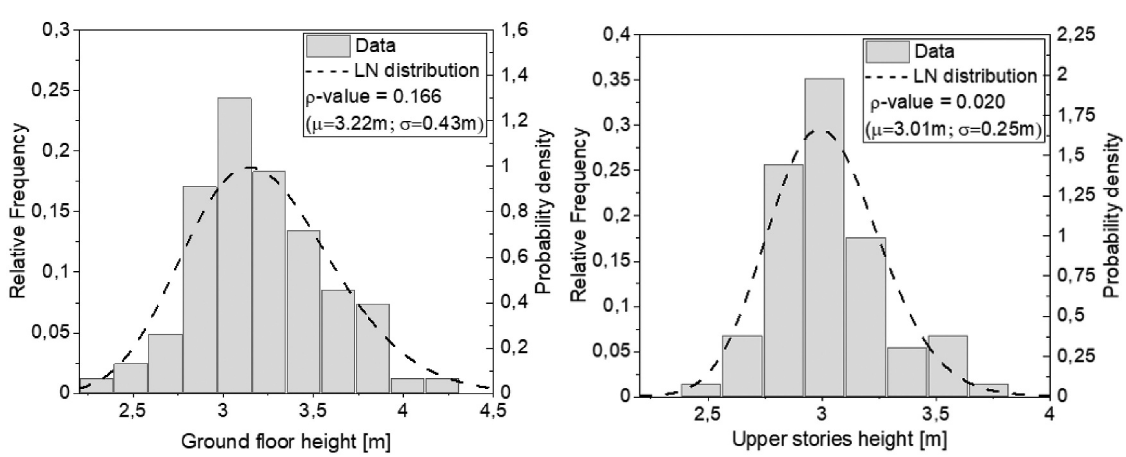


Figure 16. Building floor elevation: (a) ground floor height; (b) upper stories height.

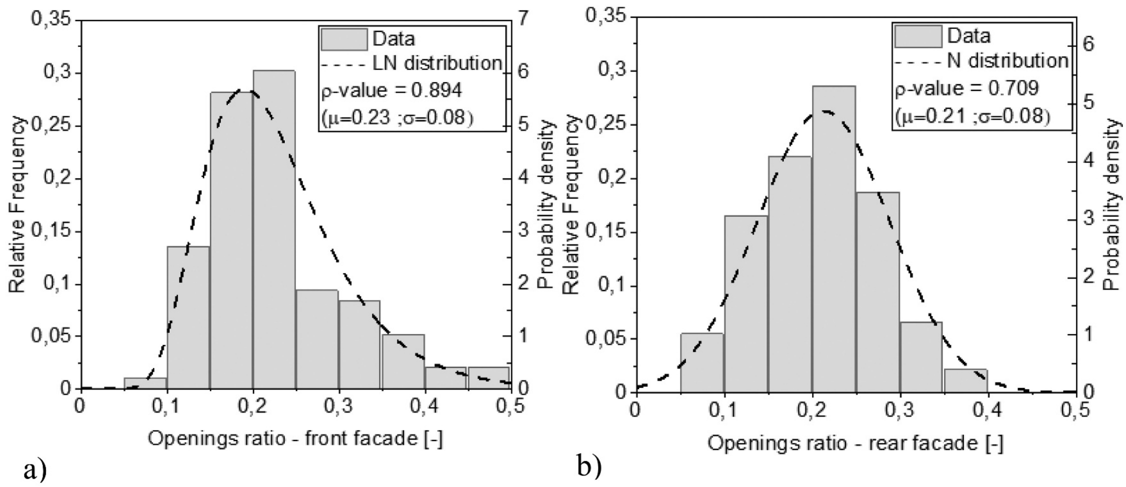


Figure 17. Opening ratio on upper floors: (a) front facade; (b) rear facade.

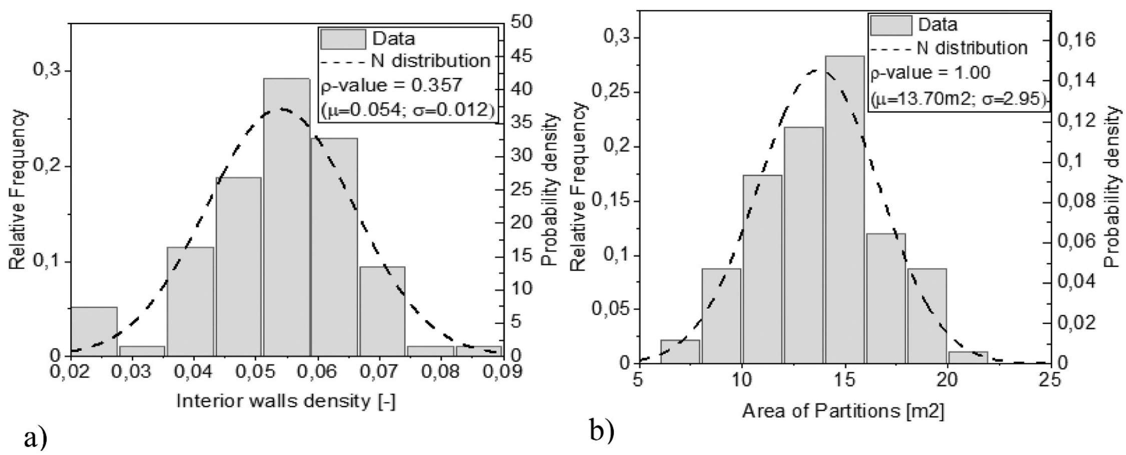


Figure 18. Interior wall characterization: (a) wall density, (b) area of partitions.

The distribution of the data by period of construction is shown in Figure 14 (left)(Figure 14a), where is clearly identified the transition between the timber floor and the RC slabs between the 1930s and 1940s. Figure 14 (right) Figure 14b) presents the number of buildings collected by number of floors.

The plan dimensions of the buildings are presented in Figure 15a) and Figure 15b) for the main facade (length X) and perpendicular direction (length Y), respectively. The range of the area in plan and the ratio between both directions are shown in Figure 15c) and Figure 15d), respectively. The corresponding probability density for the fitted distributions is presented on the secondary y-axis.

The histogram for the ground floor and upper stories height is presented in Figure 16, showing that the ground floor height is relatively higher than in the upper stories, reflecting the common use of the ground floor for commercial purposes.

The number and type of openings (windows and doors) and respective dimensions were also collected for ground and upper floors. The values are relatively similar and summarized in Table 4. Figure 17 shows the openings ratio in the front and rear facade on the upper floors.

To define the distribution of interior walls, the respective density of walls and area of compartments were collected and shown in Figure 18.

Considering that old masonry buildings present an enormous variability in the type of material and arrangement, and that this information is mostly absent in the design documents, the geometric properties of the walls are analyzed only in terms of mean thickness. However, in practice, the uncertainties thickness of walls can be tackled with the uncertainty in the material properties,

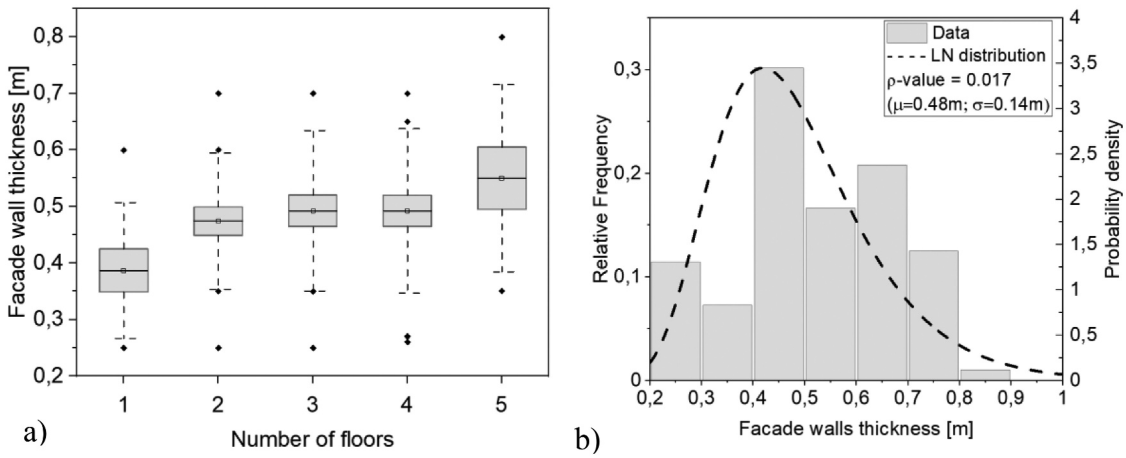


Figure 19. Facade wall thickness: (a) box plot considering the number of floors; (b) histogram with goodness-of-fit.

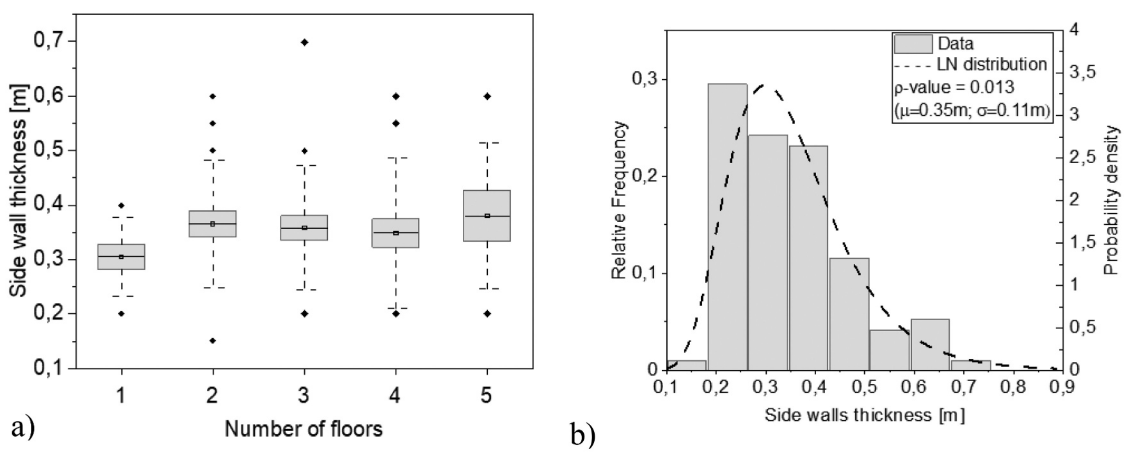


Figure 20. Lateral side wall thickness: (a) box plot by number of floors; (b) histogram with goodness-of-fit.

reducing or increasing, the shear/axial force capacity and deformability of the walls in the framework of upcoming seismic reliability and seismic risk studies.

The wall thickness was firstly examined based on ANOVA tests to examine the influence of the number of floors. The results are presented in a box-and-whisker plot, with mean value and standard error of the mean represented in the box and one standard deviation by the whiskers with the values of the outliers for this bound. As can be seen in Figure 19a) and Figure 20a), for the facade and lateral side walls, respectively, the populations mean is not significantly different for

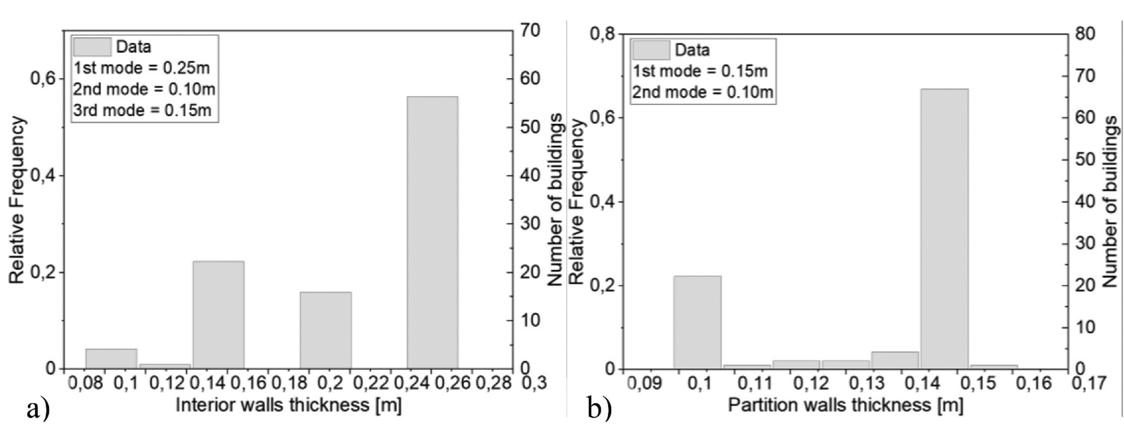


Figure 21. Interior wall thickness: (a) box plot considering the number of floors; (b) histogram with goodness-of-fit.

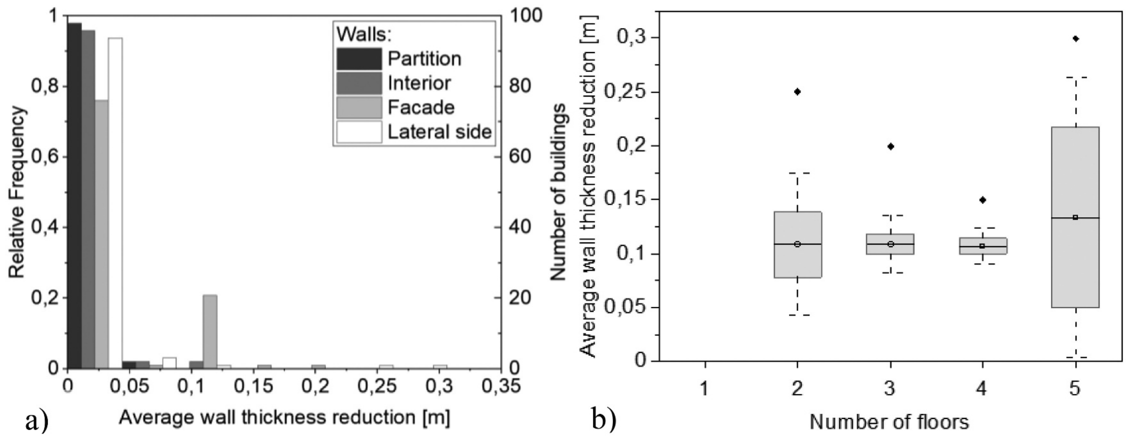


Figure 22. Mean wall thickness reduction: (a) histogram for different type of walls; (b) dispersion of the mean reduction per building height.

a significance level of 5%, so the data set was statistically evaluated.

The histograms for the thickness at ground level are presented in Figure 19b) and Figure 20b), together with the fitted distribution. The goodness-of-fit of the LogNormal distribution is rejected for a significance level of 5% for both types of walls. These results reflect the huge variability of the materials and constructive methods employed in the facade walls. Referring to brick masonry is usually found between a single-leaf arrangement (0.23 m) and three brick-leaf arrangement (0.69 m). On the other hand, for stone masonry the thickness may vary according to the type and quality of material, reaching up 0.80 m for current buildings and minimum thickness of 0.40 m. For high-quality stone masonry (i.e., regular surface, uniform size, good arrangement and good mechanical properties, such as ashlar masonry and perpend stone) the thickness may be less.

The lateral side walls are usually thinner when compared to the facades. The thickness may vary between 0.20 m and 0.70 m (Figure 20b) and depends on the type of material (stone, brick masonry or concrete blocks).

Concerning the interior and partition walls (schematically identified in Table 3), there is no significant variability in the total thickness, as observed in Figure 21. The thickness is around 0.10 m or 0.15 m, or more commonly 0.25 m in case of interior walls. The thickness depends on the type of wall (e.g. *tabique, frontal* walls, brick), their function or even brick dimensions and arrangement (in case of brick masonry walls).

The reduction of the wall thickness along the height is evident in approximately 30% of the buildings analyzed, wherein most of the cases correspond to the facade walls, as seen in Figure 22a). According to Figure 22b), the mean wall reduction per floor is around 0.10 m, independently of the building height.

Regarding floor thickness, it is naturally dependent on the type of floor: for RC floor the majority has 0.10 m

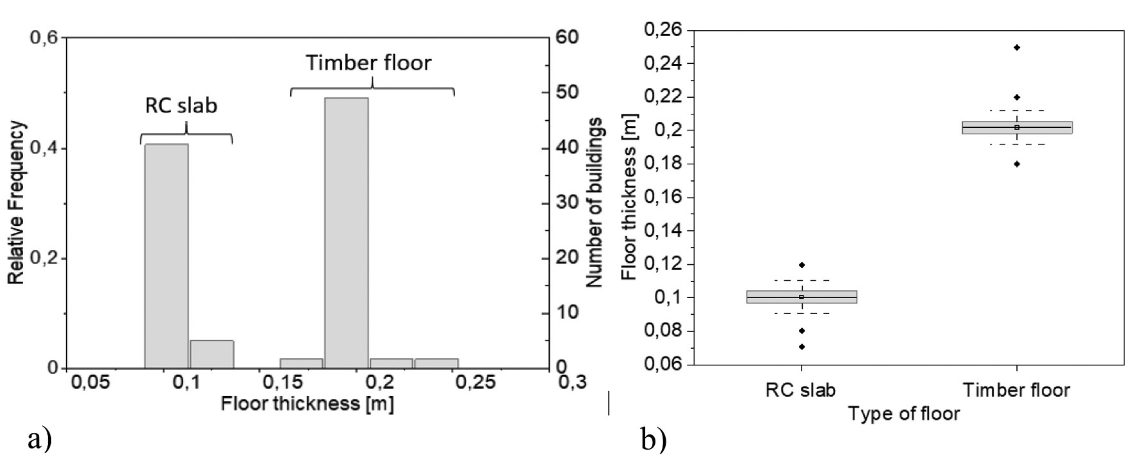


Figure 23. Floor thickness: (a) histogram for the different type of floor; (b) box plot with mean value and dispersion.

and for timber floors the total thickness is around 0.20 m (Figure 23). According to the information collected, the timber floors are usually constituted by wood planks with 0.022 m of thickness, supported by timber beams with 0.10 × 0.20 m, 0.08 × 0.16 cm or 0.07 × 0.18 cm spaced of 0.20 m to 0.40 m.

To summarize, the properties collected and treated above are summarized in Table 4. Considering a mean reference value and the standard deviation for the parameters assessed, stands out: in terms of plan dimensions, the facade length (length X) and the perpendicular length (length Y) have between 7.6 m to 17.6 m and 8.0 m to 16.2 m, respectively. The area in plan is around 60 m^2 to 240 m^2, with a proportion (length X/Y) approximately equals to 0.60 to 2.15. The compartment area is around 13.7 m^2 (cov = 0.22), normally with size 3 x 4, 4 x 4, 3 × 5. The interstory height tends to be higher in the ground floor than the upper floors, approximately 3.20 m (cov = 0.13) and 3.00 m (cov = 0.08). For opening ratio, there is evidence of higher percentage in main facades, around 0.26 (cov = 0.38) and 0.23 (cov = 0.35) on the ground floor and upper floors, respectively, compared to rear facades, with approximately 0.21 (cov = 0.38).

The mean thickness of exterior walls is around 0.47 m (cov = 0.30) and 0.34 m (cov = 0.32), for the facades and side walls, respectively. For the interior and partition walls, the mean thickness is approximately 0.14 m (cov = 0.15) and 0.21 m (cov = 0.24), respectively. The mean density of interior walls is around 0.054 (cov = 0.19). The thickness decreased in the height of the building were observed in 30% of the data analyzed, and correspond to an average of 0.11 m (cov = 0.51) per floor.

Recently, a relevant study, in line with present work, has been carried out by Lovon et al. (2021) to characterize the geometry of limestone and granite masonry buildings in Portugal, namely the size dimensions, floor height, wall thickness (only facade) and thickness reduction, opening ratio and interior wall density were also surveyed. Although the granite masonry buildings are more concentrated in the north of Portugal (Vasconcelos 2005) and the limestone masonry buildings does not cover all the masonry typologies in the MAL, some similarities can be noticed on the average for limestone masonry and the results provided by the present work (underlined): ground- and upper-floor height, respectively, (<u>3.23 m</u> *vs* 2.98 m) and (<u>3.01 m</u> *vs* 2.90 m); opening ratio (<u>0.23</u> *vs* 0.26); mean walls thickness reduction (<u>0.11 m</u> *vs* 0.15 m). However, for the building plan dimensions, the mean size reported in the aforementioned study is around 6.70 m (length X) and 8.20 m (length Y), which roughly corresponds to the 1st quartile for the data analyzed in the present study (Table 4).

Finally, the wall thickness (facade) was assumed independently of the material type; thus, a higher dispersion was attained when compared to Lovon et al. (2021) results. This indirectly reflects the uncertainty of the facade wall thickness geometrical values obtained in the present study.

The discrepancy found between the results obtained in this survey and the ones compiled in (Lovon et al. 2021) may result from the differences in the architectural surveyed databases; the masonry buildings in MAL region tend to be larger in plan dimensions, comparing to the buildings in the north of Portugal, leading to more interior load bearing walls, which is reflected by the approximately double percentage interior density walls (<u>0.054</u> vs 0.026).

6. Final comments and conclusions

The main purpose of the present paper was to present and analyze the results of a survey study carried out to characterize the architectural geometric properties of the most vulnerable typologies of buildings (unreinforced masonry buildings — URM) in Metropolitan Area of Lisbon (MAL), which is the region of Portugal with high seismic risk, given the coexistence of a moderate to high seismic hazard, with a high population density and high building stock exposure.

The MAL is constituted by a total of approximately 63 520 URM buildings which are only designed for gravity loads. The characteristics of these buildings are marked by their period of construction and construction practice resulting from the available materials, available techniques, and society needs. One of the greatest innovations in the history of engineering and construction, perhaps the most notable improvement in the behavior of buildings to seismic loads, was the "Gaiola Pombalina" (Pombaline Cage in English) present in "Pombalino" typology and standardized in the construction of the buildings for more than one century after the Lisbon earthquake, influencing the construction practices around the world.

On the other hand, the rapid expansion of the urban center and the housing demand in the transition period between the 19th and 20th centuries, led to the adoption of more simplified construction techniques and the use of low-quality materials. This is the case of "Gaioleiro" buildings, which are significantly more vulnerable from a seismic point of view.

The last generation of old masonry buildings — "Placa" typology — emerged before the enforcement of the first seismic-code in 1958 and introduced the use of reinforced concrete slabs at the floor level. The high mass of the RC slabs, the low capacity of the load bearing walls to horizontal forces and the weak connections between these elements result in an unsatisfactory structural behavior.

Considering the absence of seismic design considerations in these buildings located in areas of high seismic risk as Lisbon, the information collected and the statistics presented are of paramount importance to characterize the building stock and to generate a large sound database. The main procedures adopted in this survey study are summarized in the following points:

(i) The database refers essentially to the old masonry buildings, up to five stories, built between 1900 and 1960 (hence pre-seismic code), namely the "Gaioleiro" and "Placa" typologies;
(ii) The number of buildings surveyed was randomly selected for a population of 100 masonry buildings (around 10%, 24%, 27%, 29% and 10%, for 1 to 5 stories height, respectively);
(iii) For each group of buildings, blueprint drawings and design notes were selected randomly. The representativeness of the collected information follows, in a reasonable manner, the actual distribution of the building stock in MAL municipalities, namely, in Lisbon, Almada and Setubal;
(iv) The geometrical characterization was based on the following parameters collected: plan dimensions, elevation, stories height, number of partitions, hall dimensions, wall thickness (facade, interior, partition and lateral side walls), opening dimension, interior walls length and type/thickness of floors (RC and timber);
(v) The distribution of the parameters collected was represented by histograms. For some parameters, probability density functions were fitted to the data and evaluated using K-S tests;
(vi) Table 4 summarizes the results of the statistical analysis, where the first and second moments are quantified and the respective fitted distributions do the data.

The comparison between the present results and the ones presented in (Lovon et al. 2021) was also assessed. In short, there is most likely a bias between the different population of buildings surveyed in each study.

Moreover, further studies underway, based on the statistics reported in this study, will cover the entire geometrical variability presented in both studies; the adoption of different representative archetypes (Bernardo et al. 2020), with customized capacity curves and fragility distributions associated to the median, first and third quartiles, presented in Table 4, may deal with that geometrical variability.

Thus, the information provided by this work will be essential to develop structural numerical models and to conduct seismic vulnerability analyses and more detailed seismic risk studies.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Foundation for Science and Technology (FCT) under Grant number PD/BD/135325/2017 in the scope of the InfraRisk Doctoral Programme – Analysis and Mitigation of Risks in Infrastructures;Fundação para a Ciência e a Tecnologia [PD/BD/135325/2017];

ORCID

A. Costa http://orcid.org/0000-0001-8950-4843

References

AFML - Lisbon municipal archive: Photographic collections. http://arquivomunicipal.cm-lisboa.pt/

Bernardo, V., A. Campos Costa, A. Costa, J. M. Catarino, and P. Candeias. 2020. Métodos expeditos para avaliação sísmica de edifícios de alvenaria com pavimentos rígidos. Revista Portuguesa de Engenharia de Estruturas. Ed. LNEC. Série III. n.º 14. ISSN 2183–8488. (november 2020) 111–128 [in Portuguese]

Candeias, P. 2008. Avaliação da vulnerabilidade sísmica de edifícios de alvenaria. PhD Thesis. University of Minho Minho, Portugal [in Portuguese].

Choffat, P., and A. Bensaúde. 1912. *Estudos sobre o sismo do Ribatejo de 23 de Abril de 1909*. in Portuguese. Lisbon, Portugal: Imprensa Nacional.

Costa, A. C., M. L. Sousa, A. Carvalho, and E. Coelho. 2010. Evaluation of seismic risk and mitigation strategies for the

existing building stock: Application of LNECloss to the metropolitan area of Lisbon. *Bulletin of Earthquake Engineering* 8 (1):119–34. doi:10.1007/s10518-009-9160-3.
Crowley, H., Pinho, R., Pagani, M., Keller, N. (2013) "Assessing global earthquake risks: the Global Earthquake Model (GEM) initiative," in Handbook of seismic risk analysis and management of civil infrastructure systems, Ed. Tesfamariam, S. and Goda, K., Woodhead Publishing
D'Altri, A. M., V. Sarhosis, G. Milani, J. Rots, S. Cattari, S. Lagomarsino, E. Sacco, A. Tralli, G. Castellazzi, and S. de Miranda. 2020. Modeling strategies for the computational analysis of unreinforced masonry structures: Review and classification. *Archives of Computational Methods in Engineering* 27 (4):1153–85.
Ferreira, T. M., R. Vicente, J. A. R. Mendes Da Silva, H. Varum, and A. Costa. 2013. Seismic vulnerability assessment of historical urban centres: Case study of the old city centre in Seixal, Portugal. *Bulletin of Earthquake Engineering* 11 (5):1753–73. doi:10.1007/s10518-013-9447-2.
Ferrito, T., J. Milosevic, and R. Bento. 2016. Seismic vulnerability assessment of a "Placa" building aggregate by linear and nonlinear analysis. *Bulletin of Earthquake Engineering* 14:2299–327. doi:10.1007/s10518-016-9900-0.
Flesch, R. 2007. Lessloss: Risk mitigation for earthquakes and landslides. In *European manual for in-situ assessment of important existing structures*.
Lagomarsino, S., and S. Cattari. 2015. PERPETUATE guidelines for seismic performance-based assessment of cultural heritage masonry structures. *Bulletin of Earthquake Engineering* 13:13–47. doi:10.1007/s10518-014-9674-1.
Lamego, P. 2014. *Reforço sísmico de edifícios de habitação. Viabilidade da mitigação do risco*. in Portuguese. Portugal: University of Minho.
Lamego, P., and P. Lourenço. 2012. Caracterização e comportamento sísmico de edifícios de placa. In *Construção 2012*, 1–11. Coimbra, Portugal. University of Minho, Portugal.
Lopes, M., H. Meireles, S. Cattari, R. Bento, and S. Lagomarsino. 2014. Pombalino constructions: Description and seismic assessment. In *Structural rehabilitation of old buildings*, 187–233.
Lovon, H., V. Silva, R. Vicente, T. M. Ferreira, and A. A. Costa. 2021. Characterisation of the masonry building stock in Portugal for earthquake risk assessment. *Engineering Structures* 233:111857. doi:10.1016/j.engstruct.2021.111857.
Meireles, H., and R. Bento. 2010. COMPORTAMENTO CÍCLICO DE PAREDES DE FRONTAL POMBALINO. In *Sísmica 2010-8° Congresso de Sismologia e Engenharia Sísmica*.Aveiro University, Portugal.
Mendes, N. 2012. Seismic assessment of ancient masonry buildings: Shaking table tests and numerical analysis (PhD Thesis). University of Minho Minho, Portugal. [in Portuguese].
Milosevic, J. 2019. *Seismic vulnerability assessment of mixed masonry-reinforced concrete buildings in Lisbon*. Lisbon, Portugal: Technical University of Lisbon. in Portuguese.
Miranda, J., and F. Carrilho. 2014. *45 ANOS DO SISMO DE 28 DE FEVEREIRO DE 1969*. in Portuguese. Lisbon, Portugal: IPMA.
Mouroux, P., and B. Le Brun. 2006. Presentation of RISK-UE project. *Bulletin of Earthquake Engineering* 4:323–39. doi:10.1007/s10518-006-9020-3.
National standard: General regulation of urban construction for the city of Lisbon (Original title: Regulamento geral da construção urbana para a cidade de Lisboa – RGCU). 1930.
Roca, P., M. Cervera, G. Gariup, and L. Pela'. 2010. Structural analysis of masonry historical constructions. Classical and advanced approaches. *Archives of Computational Methods in Engineering* 17 (3):299–325. doi:10.1007/s11831-010-9046-1.
RSCCS. 1958. National standard: Code for building safety against earthquakes (Original title: Regulamento de Segurança das Construções contra os Sismos – RSCCS).
Silva, V., H. Crowley, H. Varum, and R. Pinho. 2014. Seismic risk assessment for mainland Portugal. *Bulletin of Earthquake Engineering 13*(2): 429–457. d oi: 1 0.1007/s1 0518-014-9630-0
Silva, V., M. Pagani, J. Schneider, and P. Henshaw 2018. Assessing seismic hazard and risk globally for an earthquake resilient World.
Simões, A. 2018. *Evaluation of the seismic vulnerability of the unreinforced masonry buildings constructed in the transition between the 19th and 20th centuries in Lisbon*. Portugal: Technical University of Lisbon.
Simöes, A. G., R. Bento, S. Lagomarsino, S. Cattari, and P. B. Louren O. 2018. The seismic assessment of masonry buildings between the 19th and 20th centuries in Lisbon-evaluation of uncertainties. In: Proceedings of the International Masonry Society Conferences.Guimarães, Portugal
Sousa, M. 2006. *Seismic risk in Mainland Portugal*. Lisbon, Portugal [in Portuguese]: Technical University of Lisbon.
Statistics Portugal. 2012. *Censos 2011 Resultados Definitivos*. in Portuguese. Lisbon, Portugal.
Tang, Y., Y. Yin, K. Hill, V. Katiyar, A. Nasseri, and T. Lai 2012. Seismic risk assessment of Lisbon metropolitan area under a recurrence of the 1755 earthquake with tsunami inundation. In: 15th World Conference on Earthquake Engineering (15WCEE). Lisbon, Portugal [in Portuguese].
Van Der Krogt, P. 2008. Mapping the towns of Europe: The European towns in Braun & Hogenberg's Town Atlas, 1572-1617. BELGEO. Belgium. *Belgeo* 371–98. doi:10.4000/belgeo.11877.
Vasconcelos, G. 2005. Experimental investigations on the mechanics of stone masonry: Characterization of granites and behavior of ancient masonry shear walls.
Vicente, R., S. Parodi, S. Lagomarsino, H. Varum, and J. A. R. M. Silva. 2011. Seismic vulnerability and risk assessment: Case study of the historic city centre of Coimbra, Portugal. *Bulletin of Earthquake Engineering* 9:1067–96. doi:10.1007/s10518-010-9233-3.
Vicente, R., T. Ferreira, and R. Maio. 2014. Seismic risk at the urban scale: Assessment, mapping and planning. *Procedia Economics and Finance* 18:71–80. doi:10.1016/S2212-5671(14)00915-0.
Vilanova, S., and J. Fonseca. 2007. Probabilistic seismic-hazard assessment for Portugal. *Bulletin of the Seismological Society of America* 97:1702–17. doi:10.1785/0120050198.