Geometric characterization of pre-code masonry buildings in Lisbon for seismic risk assessment

Caraterização geométrica de edifícios antigos de alvenaria em Lisboa para avaliação do risco sísmico

Vasco Bernardo
Romain Sousa
Paulo Candeias
Aníbal Costa
Alfredo Campos Costa

Abstract

The Metropolitan Area of Lisbon housing stock is constituted by approximately 35% of masonry residential buildings. Most of them were built before the introduction of the first design code for building safety against earthquakes (RSSCS) in 1958. Given the presence of these buildings in areas of significant seismicity as Lisbon, a comprehensive research is needed to assess the seismic risk and define mitigation policies for this population of buildings. The main purpose of this work is to characterize the geometry of those 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. The information collected is statistically analyzed and expressed through probability distributions that can be used to develop numerical models and derive seismic vulnerability functions that are fundamental to conduct seismic risk analyses.

Resumo

A Área Metropolitana de Lisboa é constituída por cerca de 35% de edifícios de alvenaria, tendo sido a maioria apenas dimensionada para ações gravítica, uma vez que o primeiro regulamento contra a ação dos sismos (RSSCS) só surgiu em 1958. Dada a presença destes edifícios em zonas de sismicidade moderada/elevada, como Lisboa, a avaliação do risco sísmico é um processo fundamental para a definição de estratégias de mitigação. O objetivo do presente estudo é caracterizar a geometria dos edifícios de alvenaria, construídos antes da introdução do RSSCS, através de um levamento das propriedades geométricas que podem influenciar o seu comportamento sísmico. A informação obtida foi estatisticamente analisada, podendo ser utilizada para a definição de modelos numéricos representativos do parque habitacional e respetiva vulnerabilidade sísmica.

Keywords: Pre-code masonry buildings / Geometry data collection / Statistical analysis / Seismic vulnerability

Palavras-chave: Edifícios antigos de alvenaria / Propriedades geométricas / / Analise estatística / Vulnerabilidade sísmica

Vasco Bernardo

LNEC-NESDE
Lisboa – Portugal
vbernardo@lnec.pt

Romain Sousa

Polytechnic of Leiria
Leiria – Portugal
romain.r.sousa@ipleiria.pt

Paulo Candeias

LNEC-NESDE
Lisboa – Portugal
pcandeias@lnec.pt

Aníbal Costa

University of Aveiro
Aveiro – Portugal
agc@ua.pt

Alfredo Campos Costa

LNEC-NESDE
Lisboa – Portugal
alf@lnec.pt

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1 Introduction

The regions of Lisbon and south of Portugal are considered the areas with the highest seismic hazard in Portugal mainland, given its geographical location.

The Metropolitan Area of Lisbon (MAL) is composed by 18 municipalities and 211 parishes, with a total area of 2 957.5 km^2 and a population density of around 950 inhabitants/km^2 [1].

The masonry buildings stock in the MAL is around 35% and is mostly used for residential purposes [1]. 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 [2] was introduced only in 1958.

The main objective of this work is to characterize the geometry of the pre-code masonry buildings in the MAL region until the appearance of RSCCS. The geometry of dozens of buildings 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. Further details can be found in Bernardo *et al*. [3].

2 Buildings description and features

Four main types of masonry buildings can be identified in the MAL region: "Pre-Pombalino" (before 1755), "Pombalino" (1755 to 1870) [4]"Gaioleiro" (1870 to 1930) [5]–[7], and "Placa" (1930 to 1960) [8], [9]. Below, is presented an overview of the main geometric and structural characteristics of these building typologies.

2.1 "Pre Pombalino" buildings

The "Pre-Pombalino" buildings (Figure 1a) 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. The ground floor was usually reserved for commerce and, in some cases, setback with respect to the upper floors. In this period the buildings did not provide any sanitary facilities.

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 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 – a set of vertical long boards connected by horizontal small wood stripes, normally filed 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.

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.

2.2 "Pombalino" buildings

The "Pombalino" typology (Figure 1b) 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 of the city after the earthquake. Moreover, they were design 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. The partition walls were in "tabique". 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.

2.3 "Gaioleiro" buildings

The "Gaioleiro" buildings (Figure 1c) 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.

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" or brick masonry (solid or hollow bricks).

The floors were composed by timber beams supported on the facades and covered by wooden planks. The weak connections between the exterior and interior load-bearing walls and to the wooden floors was very common.

2.4 "Placa" buildings

The "Placa" typology (Figure 1d) corresponds to a combination of masonry walls with RC slabs and is characterized by the introduction of the RC as a structural element.

The vast majority of these buildings were, built before the decade of 1960, have regular geometry and have up to five stories [1]. The "Placa" aesthetic is more simplistic when compared to "Gaioleiro",

a) "Pre-Pombalino" b) "Pombalino" c) "Gaioleiro" d) "Placa"

Figure 1 Pre-code masonry buildings in MAL 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 or brick masonry 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, was gradually replaced by concrete slabs of poor concrete and one single reinforcement layer for positive bending moments. Later, reinforced concrete beams and columns were incorporated in the facades or in the interior partitions to overcome larger spans.

3 Statistical characterization of geometry

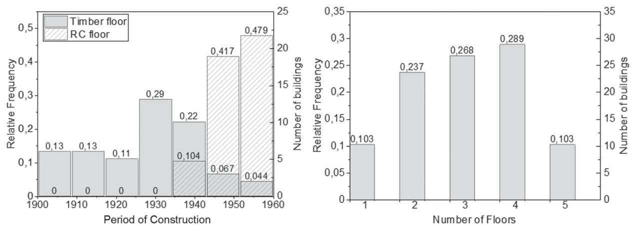
3.1 Survey procedures

The geometric characterization was based on the information available in detailed drawings from the original projects (blueprint) and collected in the municipal services of Lisbon, Almada and Setubal, where the major part of the typologies aforementioned are located [1]. The data collection refers mainly to "Gaioleiro" and "Placa" buildings built between 1900 and 1960 and up to five stories. 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 original, as a result of rehabilitation works carried out in the recent years. The geometric characterization comprises the parameters listed in Table 1 for a population of 100 samples. For a real population of around 63.526 in the MAL region [1], these results have a margin of error of 10%, for a confidence level of 95%. The 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 data based on Kolmogorov-Smirnov (K-S) test.

3.2 Geometry characterization

The geometric survey is presented by the respective histograms in terms of relative frequency and number of buildings. Alternative distributions were fitted and included on the histograms to represent the sample. At the end of this chapter, Table 4 summarizes the statistical properties collected.

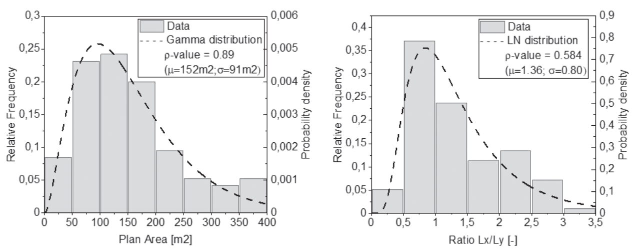
The distribution of the data by period of construction is shown in Figure 2a, where is clearly identified the transition between the timber floor and the RC slabs (rigid floors) between the 1930s and 1940s. Figure 2b presents the number of buildings collected by number of floors. In the presence of buildings in which the coexistence of wooden floors and concrete slabs was observed, namely in the transition period, where the timber floors started to be replaced by concrete slabs in humid zones, the type of floor was classified according to the most representative material.



a) b)

Figure 2 Distribution of buildings collected by: a) period of construction; b) number of floors

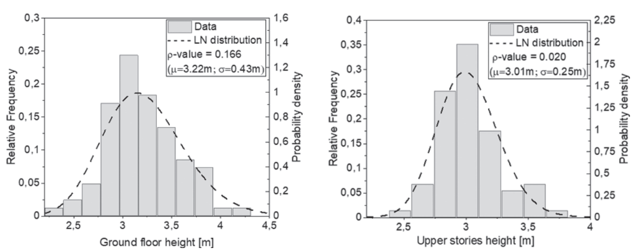
The range of the area in plan and the ratio between both directions is shown in Figure 3a and Figure 3b, respectively. The corresponding probability density for the fitted distributions is presented on the secondary y-axis.



a) b)

Figure 3 Plan dimensions of the buildings: a) area of implantation; b) relation Lx/Ly

The histogram for the ground floor and upper stories height is presented in Figure 4, 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.



a) b)

Figure 4 Building floors elevation: a) ground floor height; b) upper stories height

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 1. Figure 5 shows the openings ratio in the front and rear facade in the case of upper stories.

To define the distribution of interior walls, the respective density of walls and area of compartments were collected and shown in Figure 6.

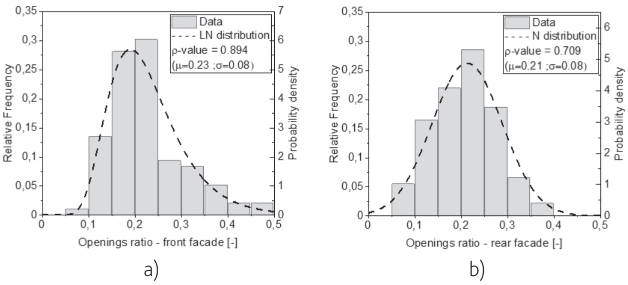


Figure 5 Opening ratio on upper stories: a) front facade; b) rear facade

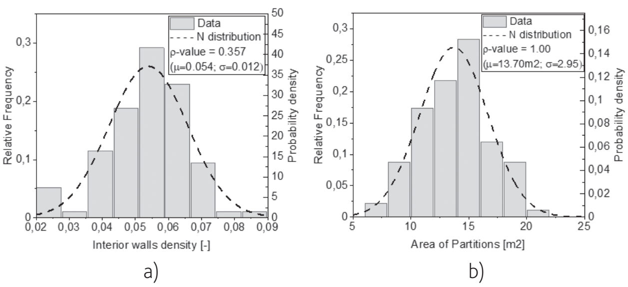


Figure 6 Interior walls characterization: a) walls density, b) area of partitions

Regarding walls, is presented in Figure 7 the histograms for the mean thickness of facades, lateral side walls, interior walls (staircases walls and between apartments), and partition walls that divide the compartments. The data set was statistically evaluated based on ANOVA tests to examine the influence of the number of floors, wherein the populations mean for the different number of floors was not significantly different for a significance level of 5%.

On the case of facade walls, the goodness-of-fit of the LogNormal distribution is rejected for a significance level of 5%. These results reflect the huge variability of the materials and constructive methods employed in the facade walls.

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

For the interior and partition walls, there is no significant variability in the total thickness. 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).

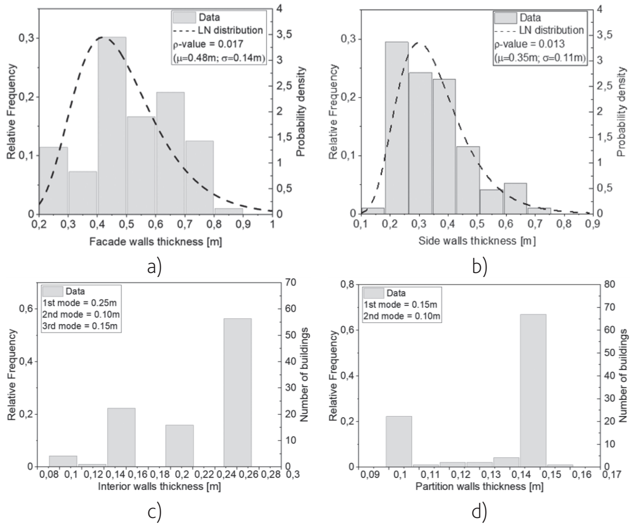


Figure 7 Walls thickness: a) facade; b) lateral side; c) interior; d) partition

The reduction of the wall thickness along the height (Figure 8a) was evident in approximately 30% of the buildings analyzed, wherein most of the cases correspond to the facade walls. The mean wall reduction per floor is around 0.10 m, independently of the building height.

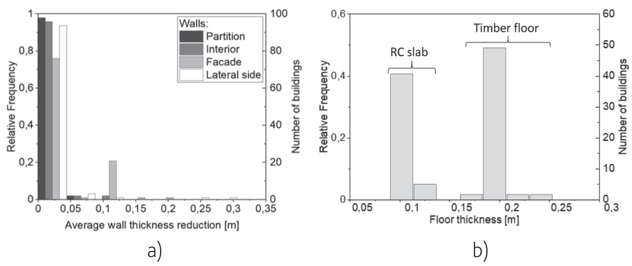


Figure 8 Average wall thickness reduction (left) and floor thickness (right)

Regarding the floor thickness (Figure 8b), depends on the type of floor: for RC floor the majority has 0.10 m and for timber floors the total thickness is around 0.20 m. 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.

Table 1 Statistical properties for the geometric parameters collected

Parameter	Unit	Distribution	Mean	C.O.V.	Mode	1st quartile	Median	3rd quartile
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
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	–	–	–

4 Conclusions

The main purpose of this work was to present and analyze the results of a survey study carried out to characterize the architectural geometric properties of the pre-code masonry buildings in Metropolitan Area of Lisbon (MAL), which is the region of Portugal with high seismic risk. 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.

A total of 100 pre-code masonry buildings up to five stories heigh were randomly selected and surveyed, which allow to characterize the following parameters: plan dimensions, elevation, stories height, number of partitions, hall dimensions, walls thickness, openings ratio, interior walls density type/thickness of floors. This information is essential to develop representative structural numerical models and to conduct seismic vulnerability analyses and more detailed seismic risk studies.

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