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Survey of the Facade Walls of Existing Adobe Buildings

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ABSTRACT
Adobe construction was very common in Aveiro district, Portugal, until the middle of the 20th century. At present, there are still many adobe buildings in use, a significant percentage of which have social, cultural, and architectural value. Many of these buildings, however, are in a poor state of conservation. The existing problems are partially the result of a lack of knowledge about the materials and building systems traditionally used. To contribute to this knowledge, a visual and dimensional inspection of the facade walls of twenty one adobe buildings located in Anadia, Murtosa, and Aveiro municipalities, in Aveiro district, was conducted. This article presents a description and analysis of the construction details, common defects, and state of conservation of the facade walls studied. This work aims to contribute with preliminary information that may help support the preservation and rehabilitation of existing adobe buildings.

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adobe; adobe facade walls; Aveiro; building defects; building systems; built heritage; earthen construction; Portugal; rehabilitation; traditional construction

1. Introduction

Earth is a construction material that was widely used in Portugal until the middle of the 20th century. In a large part of the Aveiro district, in particular, adobe was commonly used until the 1950s and 1960s, decades in which adobe construction was progressively replaced by reinforced concrete structures. At present, there are still many adobe buildings in use in this region. In fact, according to a recent survey, it is estimated that in the main area of Aveiro city (i.e., in the "Union of Parishes of Gloria and Vera Cruz"), approximately 40% of the existing buildings are made of adobe (Silveira et al. 2013). This percentage corresponds to 1330 adobe buildings, out of a total of 3388 existing buildings (considering the total number of buildings assessed in the 2011 census (INE 2011)). In the municipality of Murtosa, also according to a recent survey, it is estimated that approximately 25% of buildings are made of adobe (Silva 2012). This percentage corresponds to 1406 adobe buildings, out of a total of 5845 existing buildings (considering the total number of buildings provided by the 2011 census (INE 2011)).

Many of the existing adobe buildings have social, cultural, and architectural value, such as the numerous buildings influenced by the Art Nouveau style. However, a significant percentage of the existing buildings are in a poor state of conservation, displaying various structural and non-structural defects (Silva et al. 2010; Silveira et al. 2013). Adobe construction is particularly vulnerable to the action of weathering agents, especially to the action of water (Bonazza et al. 2009), and thus needs adequate protection and regular maintenance measures (USDOI 1978). In some cases, these measures have been neglected in the last decades. In other cases, buildings that were subject to maintenance and rehabilitation interventions have defects caused by the inadequacy of the materials and techniques used (Maia 2009; Tavares, Costa, and Varum 2012). Thus, the problems observed in the existing buildings result not only from neglect but also from a lack of knowledge about the characteristics and behavior of the materials and building systems used in this type of construction. It is thus essential to develop a thorough knowledge base that may support the preservation and rehabilitation of the existing built heritage.

2. State of the art

2.1. Research on adobe construction worldwide

The international scientific community has been developing work to document and preserve the existing earthen built heritage in different regions of the world and to promote good building practices in regions where this construction material is still used. The

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careful study of the material and building systems, defects, and vulnerabilities of existing earthen constructions has been deemed essential for their adequate preservation and rehabilitation. Various studies of adobe construction, in particular, have been conducted, focusing on regions of the world where this type of construction is especially abundant, namely:

- Latin America (e.g., Rivera and Muñoz (2005), Lardinois and Cancino (2012), Rolón and Rotondaro (2012), Jorquera (2013));
- Asia (e.g., Fodde (2009), Mecca and Dipasquale (2012), Pozzi (2012));
- Mediterranean Europe (e.g., Bosia (2009), Oikonomou and Bougiatioti (2011), Gil (2014)); and
- Africa (e.g., Abufayed (2005), Baglioni et al. (2013)).

Some of the studies carried out are focused only on the characterization of the material and building systems (e.g., Pozzi (2012), Baglioni et al. (2013)), while other studies also assess existing defects (e.g., Bosia (2009), Mecca and Dipasquale (2012)), seismic vulnerability (e.g., Lardinois and Cancino (2012), Jorquera (2013)), and hygrothermal behavior (e.g., Oikonomou and Bougiatioti (2011)). These studies generally focus on the existing construction in large geographical areas such as a country (e.g., Jorquera (2013)), province (e.g., Gil (2014)), or city (e.g., Abufayed (2005)), frequently including the analysis of a sample of representative buildings. Some of the studies address only adobe construction (e.g., Abufayed (2005)), while others also address other types of earthen construction (e.g., Gil (2014)). In some of the building typologies, adobe is combined with other building techniques, such as rammed earth, stone masonry, or wooden structures (e.g., Oikonomou and Bougiatioti (2011), Baglioni et al. (2013)). In some cases, methodologies for the assessment and rehabilitation of existing buildings have been proposed (e.g., Rivera and Muñoz (2005), Bosia (2009)).

2.2. Research on adobe construction in Portugal

Regarding the study of the building systems, defects, and vulnerabilities of existing adobe buildings in Portugal, there are a number of studies carried out with different objectives and focused on different geographical areas of the country. Some of the main studies are summarized below.

2.2.1. Aveiro municipality

The building systems and main structural defects of masonry buildings located in two distinct areas of Aveiro city—the great majority of which were made with adobe—were studied with the objective of assessing the seismic vulnerability of these urban areas (Ferreira 2008).

Another study of 120 adobe buildings located in Aveiro city was carried out. These buildings were subject to an expeditious visual inspection conducted mainly from the outside and the most important defects were recorded and analyzed (Martins 2009).

A survey of the existing adobe construction in the parish of Requeixo, in Aveiro municipality, was also conducted (Maia 2009). The research is focused on the study of the traditional production and construction processes and also on the characterization of the architecture, building systems, and main defects of selected buildings, including a brief suggestion of adequate rehabilitation measures.

2.2.2. Ílhavo municipality

A study of the adobe buildings in Ílhavo city, built in a phase of transition of the language of architecture, in the beginning of the Modernist movement, was carried out (Tavares 2009; Tavares, Costa, and Varum 2012). The study is focused on the architecture, building systems, and main defects of the existing adobe buildings and also on the influence of public and private agents in the transition process. It includes brief guidelines for the effective rehabilitation of the buildings studied.

2.2.3. Other regions

A study of the "*Gandaresa*" adobe house—a traditional rural housing typology—was conducted (Santiago 2007). The study is focused on the existing constructions in the coastal territory between the "*Vouga*" river and the "*Boa Viagem*" mountain range. It addresses the historical and geographical context of the "*Gandaresa*" house, the types of soil and processes used in the production of adobes, and the architecture, building systems, and main defects of this type of construction.

Finally, a study of the adobe building culture in Portugal was carried out (Fernandes 2013). This work includes a broad investigation of the adobe architecture, materials, and building methods in Portugal. It also includes a reflection on the importance of the conservation of the existing adobe buildings and on the possibility of future adobe production and construction in Portugal.

3. Motivation and objectives

Each region of the world has unique earth building materials and techniques that must be assessed independently. However, there are also common features and vulnerabilities among different building cultures that are relevant to the conservation of the earthen built heritage in general. The assessment of the existing built heritage is an ongoing process, and further attention by the international scientific community is necessary.

The research that has been conducted in Portugal, in particular, provides an important contribution to the knowledge base regarding the material and building systems of the existing adobe buildings. However, further work developed in a more systematic and comprehensive way is necessary to better characterize and understand this type of construction. This knowledge is essential to support the creation of solutions and guidelines for the preservation and rehabilitation of this built heritage. It is relevant for the conservation of the existing adobe construction not only in Portugal but also in other regions of the world.

To contribute to the existing knowledge base, a research group at the University of Aveiro, in collaboration with other institutions, has been carrying out a thorough survey of the existing adobe buildings in Aveiro district. The research is conducted using a methodology developed in three levels of increasing detail, described in the next section.

This article presents the analysis of part of the information gathered in "Level 3", namely the information resulting from the visual and dimensional inspection of the facade walls of 21 adobe buildings selected from 3 municipalities of Aveiro district. A detailed description and analysis of the construction details, common defects, and state of conservation of the facade walls is presented. Facade walls are key structural elements, responsible for the overall behavior and performance of adobe buildings. The good functioning of these elements is essential for the safety and comfort of the users of buildings. The present work aims to contribute with preliminary information that may help support the effective rehabilitation and functioning of these key structural elements.

It is important to note that a greater number of adobe buildings per municipality must be studied, in order for the results to be statistically representative. This first study is fundamental since it allowed to test and improve the survey strategy adopted, and the results obtained are relevant because this type of information did not exist for the areas under study. The results are, however, preliminary and must be expanded in future work.

4. Methodology

The strategy adopted in the survey of the existing adobe buildings in Aveiro district is developed in three levels of increasing detail.

In a first phase ("Level 1"), the city councils of all the municipalities of Aveiro district are contacted to obtain information regarding the distribution of adobe construction throughout the district. This information is obtained using a brief questionnaire completed by technicians working in the management of the existing built heritage. This first phase of the analysis is currently complete.

In a second phase ("Level 2"), a broad survey of the distribution, main characteristics, and global state of conservation of existing adobe buildings in selected parishes is conducted. The selection of these parishes is based on the information gathered in "Level 1". The survey method is expeditious and consists in the visual inspection of the outside of each building, accompanied by a brief photographic and written record of the main features of the building, making use of sheets specifically developed for this purpose. A survey focused on the former parishes of Gloria and Vera Cruz, in Aveiro Municipality (Silveira et al. 2013), and a survey focused on all the parishes of Murtosa municipality (Silva 2012; Silva et al. 2010) are currently complete.

The knowledge gained in the first two analyses ("Level 1" and "Level 2") allows the selection of buildings that are representative of the existing construction in Aveiro district for a more detailed survey of materials, building systems, and structural and non-structural defects ("Level 3"). This survey is carried out with the application of a set of sheets adapted specifically for adobe construction from Vicente (2008) (Neto 2008). The analysis of each building is conducted by a team of two persons (with appropriate training), during approximately one to two working days. The analysis consists of a visual inspection combined with basic measurements (carried out using a laser distance measurer, tape measure, and level) and a detailed photographic record. The information obtained is recorded in the aforementioned sheets.

This article presents the analysis of part of the information gathered in "Level 3". It focuses on the results of the inspection of the facade walls (including foundations and traditional masonry materials) of 21 selected adobe buildings. Part of the information about the identification of the buildings is also presented.

5. Identification of buildings

From 2007–2011, 21 adobe buildings in Aveiro district were subject to a thorough visual and dimensional inspection. The buildings are presented in Figure 1, with indication of the identification number assigned to each building. Table 1 displays the distribution of the buildings by municipality and parish. The type of setting (rural or urban) is also indicated. The buildings

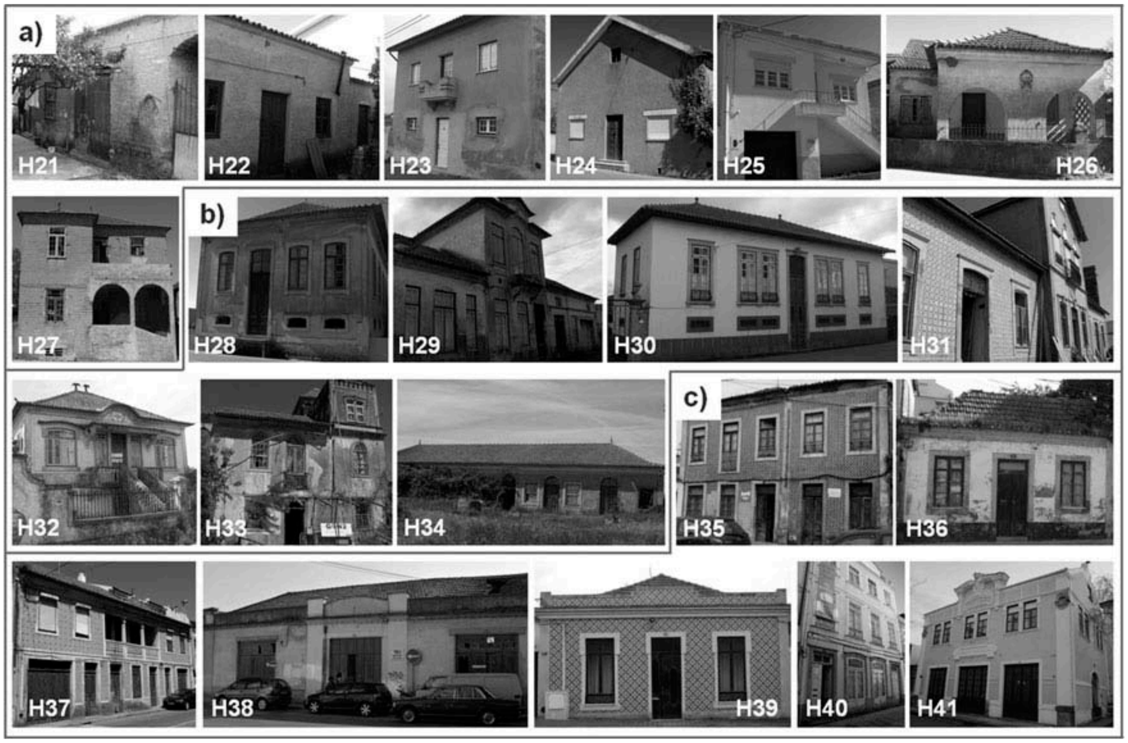


Figure 1. Adobe buildings analyzed in: (a) Anadia municipality; (b) Murtosa municipality; and (c) Aveiro municipality.

Table 1. Distribution of the buildings studied by municipality, parish, and type of setting.

Municipality	Parish	Setting	No. of buildings
Anadia	Sangalhos	Rural	7
		Total	7
Murtosa	Bunheiro	Rural	3
	Monte	Rural	1
	Murtosa	Rural	1
		Urban	2
		Total	7
Aveiro	(Former) Glória[a]	Urban	5
	(Former) Vera Cruz[a]	Urban	2
		Total	7

[a]The former parishes of Glória and Vera Cruz, officially united and named 'Union of Parishes of Gloria and Vera Cruz' in 2013, constitute the main area of Aveiro city.

were selected from three municipalities: Anadia (seven buildings); Murtosa (seven buildings); and Aveiro (seven buildings). The main reasons for the choice of these locations are as follows.

- Adobe construction is very common in these municipalities (as observed in "Level 1" of the study).
- There is diversity in the setting and location of the selected areas: Anadia and Murtosa municipalities are predominantly rural, and the selected parishes of Aveiro municipality are urban (corresponding to the main area of Aveiro city); Murtosa and Aveiro are coastal municipalities, located in the north of the district area where adobe construction is more common (as defined in "Level 1" of the study), and Anadia is an interior municipality, located in the south of that area.

Some of the main characteristics of the buildings studied are presented in Table 2. The majority of the buildings (57%) are detached. The second most common type of relative position is semi-detached or end-of-terrace (33%). In Anadia and Murtosa municipalities, the majority of the selected buildings are detached. This is consistent with the reality of these two municipalities, which, being mainly rural, have a greater percentage of detached buildings (e.g., approximately 60% in Murtosa municipality, according to Silva (2012)). Since Aveiro city is an urban setting, terraced, semi-detached, and end-of-terrace buildings are more common (approximately 75%, according to Silveira et al. (2013)). This was taken into account in the selection of the buildings in Aveiro city and, considering the existing buildings that were available for the performance of the inspections, the semi-detached and end-of-terrace positions prevail.

The function recorded for each building corresponds to its past function, in case it was vacant at the time of the inspection, or to its current function, in case it was in use. The great majority of the selected buildings are residences

Table 2. Relative position, function, and number of stories of the buildings studied.

		No. of buildings			
		Anadia	Murtosa	Aveiro	Total
Relative position	Detached	4	6	2	12 (57%)
	Terraced[a]	1	0	1	2 (10%)
	Semi-detached/ end-of-terrace	2	1	4	7 (33%)
Function	Residence	7	6	3	16 (76%)
	Residence and commerce/services[b]	0	0	2	2 (10%)
	Warehouse and commerce/services	0	0	1	1 (5%)
	Originally: residence; presently: municipal archives	0	1	0	1 (5%)
	Originally: fire station; presently: headquarters of the Federation of Fire-fighters	0	0	1	1 (5%)
No. of stories	1	4	1	2	7 (33%)
	2[c]	2	5	4	11 (52%)
	3[c]	1	0	1	2 (10%)
	4	0	1	0	1 (5%)

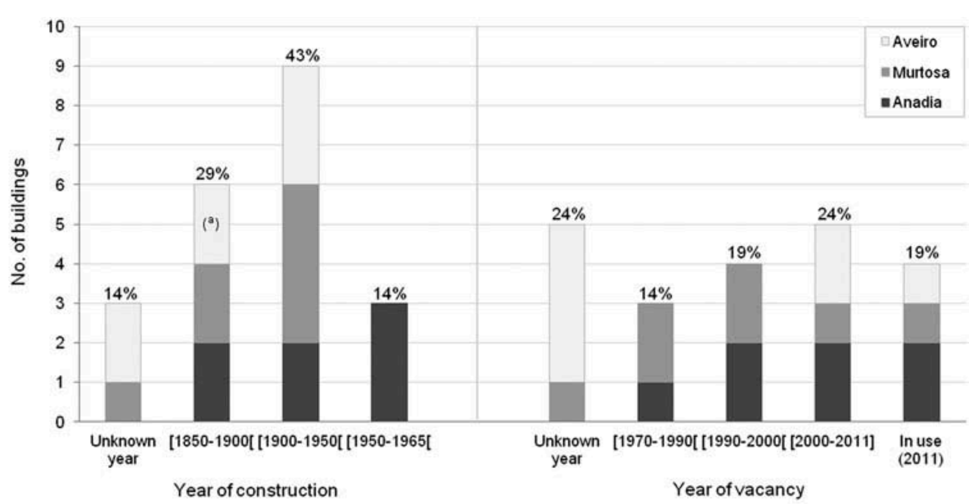
[a]"Terraced" is used to mean a building that is part of a row of buildings joined together (with at least one building attached to each side).
[b]The commerce/services section is located in part of the ground floor of the building.
[c]Two buildings with two stories ("H25", in Anadia municipality, and "H39", in Aveiro municipality) and one building with three stories ("H27", in Anadia municipality) have semi-basements, which are included in the total number of stories.

(76%), since this is the most common type of adobe building in Aveiro district—for example, approximately 90% of adobe buildings in Murtosa municipality and 70% in Aveiro city are residences, according to Silva (2012) and Silveira et al. (2013), respectively. The function of the adobe buildings in the selected parishes of Aveiro municipality is slightly more varied than in the rural areas of the district, and thus buildings with other uses were also chosen in these parishes.

The great majority of the selected buildings (86%) have one or two stories, which is representative of the reality of Aveiro district—for example, approximately 98% of adobe buildings in Murtosa municipality and 80% in Aveiro city have one or two stories, according to Silva (2012) and Silveira et al. (2013), respectively. Fewer buildings with three and four stories were analyzed, since adobe buildings with more than two stories are less common.

The distribution of buildings by interval of year of construction is presented in Figure 2. The majority of buildings (71%) were built between the late 19th century and the middle of the 20th century, with more buildings (43%) built in the first half of the 20th century. This distribution is representative of the construction dates of the existing adobe buildings in Aveiro district (Santiago 2007; Silva et al. 2010; Silveira et al. 2013). Anadia municipality has the only three buildings built after 1950, with the latest built in 1962. It was not possible to ascertain the year of construction of three buildings; however, given their characteristics, it is very likely that these buildings were also built in the late 19th century or early 20th century.

The distribution of buildings per interval of year of vacancy is also presented in Figure 2. Buildings were vacated since the 1970s until the last year of the inspections (i.e., until 2011), with an increase of abandonment in the last two decades. It was not possible to ascertain the year of vacancy of five buildings, but in all five cases vacancy has likely occurred within the time range identified for the other buildings (i.e., from 1970–2011). Four



a There is uncertainty about whether the two buildings in Aveiro were built in the late nineteenth century or early twentieth century.

Figure 2. Years of construction and vacancy of the buildings studied.

buildings were still in use at the time of the visits and analyses conducted.

6. Visual and dimensional characterization of facade walls

6.1. Structural system

6.1.1. Thickness of walls and masonry bonding

All the buildings under study have load-bearing adobe masonry facade walls. In one building ("H33"), adobe masonry is combined with schist masonry in the facade walls. Four buildings ("H24", "H25", "H37", and "H39") have rear additions. The exterior walls of these additions are made with reinforced concrete and ceramic hollow brick masonry and are not analyzed in this article.

The thickness of the adobe facade walls (including the thickness of wall coating) was measured and the results are summarized in Table 3 and Table 4. Considering all the studied buildings, the thickness of the facade walls varies between 0.30 m and 0.71 m. For a clear presentation of the results, the following three cases are distinguished.

- "Case 1" includes the buildings that have facade walls with constant thickness; this case can be divided in two sub-cases: facade walls with stretcher bond (mean thickness of 0.36 m) and facade walls with other types of bond (with greater thickness, varying from 0.43–0.63 m).
- "Case 2" includes the buildings that have facade walls with greater thickness at the semi-basement or ground floor (ranging from 0.45–0.65 m); this case can be divided in two sub-cases: facade walls with stretcher bond at the upper floors (mean thickness of 0.38 m), and facade walls with other types of bond at the upper floors (only one case, with thickness of 0.50 m).
- "Case 3" includes the buildings that have main facade walls with greater thickness (varying from 0.47–0.71 m) than the other facade walls.

Table 4. Thickness of facade walls ("Case 3").

	Thickness of adobe facade walls (m) – "Case 3": Main facade wall with greater thickness			
	Ground floor	First floor	Second floor	Attic
Building	Main facade/ other	Main facade/ other	Main facade/ other	Main facade/ other
'H35'	0.50/[a]	0.50/0.35	—	—
'H37'	0.71/0.48	0.53/0.36	—	–/0.32
'H40'	0.47/0.47	0.47/0.47	0.47/0.35	–/0.35
Mean:	0.56/0.48	0.50/0.39	0.47/0.35	–/0.34

[a]Impossible to measure.

The majority of the buildings analyzed in Anadia municipality (six out of a total of seven) are included in "Case 1", having facade walls with constant thickness and stretcher bond. The majority of the buildings in Murtosa municipality (five out of a total of seven) are also included in "Case 1", but have facade walls with greater thickness and other types of bond. Most of the buildings in Aveiro municipality (five out of a total of seven) have facade walls with variable thickness ("Case 2" and "Case 3"). In general, the buildings analyzed in Anadia municipality present the thinnest walls, while the buildings in Murtosa municipality have the thickest walls.

In most buildings, the thinner facade walls were built with stretcher bond (Figure 3a). The thickness of these walls corresponds to the width of an adobe brick plus the thickness of the coating layers. In the thicker facade

Table 3. Thickness of facade walls.

		Thickness of adobe facade walls (m)				
		"Case 1": Constant thickness		"Case 2": Walls with greater thickness at the semi-basement or ground floor		
		Stretcher bond	Other bonds	Ground floor[a]/upper floors (stretcher bond)	Ground floor a/upper floors (other bonds)	"Case 3": Main facade walls with greater thickness
Anadia	Mean:	0.35	—	0.45/0.35	—	—
	No. of buildings:	6	—	1	—	—
Murtosa	Mean:	0.37	0.53	0.65/0.45	—	—
	No. of buildings:	1	5	1	—	—
Aveiro	Mean:	—	0.47	0.50/0.35	0.60/0.50	[b]
	No. of buildings:	—	2	1	1	3
All municipalities	Mean:	0.36	0.51	0.53/0.38	0.60/0.50	[b]
	Min.:	0.30	0.43	0.45/0.35	—	
	Max.:	0.38	0.63	0.65/0.45	—	
	No. of buildings:	7 (33%)	7 (33%)	3 (14%)	1 (5%)	3 (14%)

[a]Or semi-basement.
[b]The thickness of the walls is presented in Table 4.

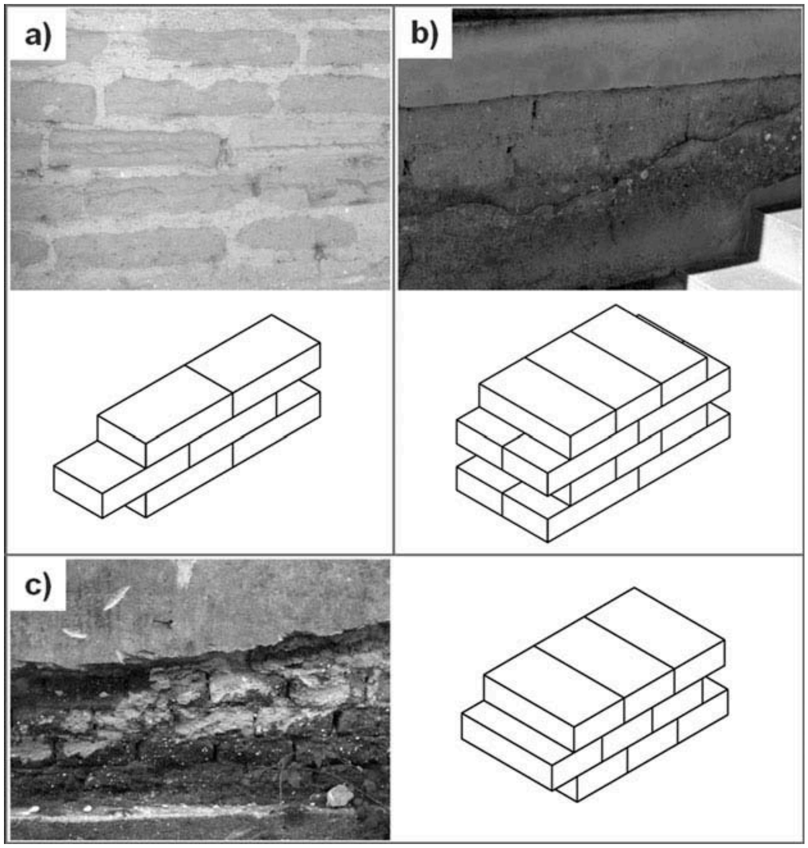


Figure 3. Types of adobe masonry bond: (a) stretcher bond; (b) English bond; and (c) header bond.

walls where observation was possible, two different types of bond were identified: English bond (Figure 3b) and header bond (Figure 3c). English bond appears to be the solution used in one building in Murtosa municipality, and header bond was used in four buildings of Aveiro municipality. In both cases, the thickness of walls corresponds to the length of an adobe brick plus the thickness of the coating layers. It is possible that other types of bond exist for the thicker facade walls. Some of these walls are possibly composed of a double leaf system, combining a stretcher bond leaf and a header bond leaf; however, it was not possible to confirm this hypothesis.

6.1.2. Wall openings

It was possible to observe the structure of the facade wall openings in 8 out of the total of 21 buildings (i.e., in 38% of the buildings). The common solution consists of a wooden lintel positioned above the opening with the ends embedded in the adobe masonry. In some cases, other reinforcing elements, such as small ceramic elements or stones, were added to the masonry adjacent to the sides of the openings. In two buildings, the wooden lintel is combined with other elements:

- In building “H24”, in Anadia municipality, two adobe bricks are positioned diagonally above the wooden lintel, forming a triangle.
- In building “H28”, in Murtosa municipality, an arch made with ceramic elements is located above the wooden lintel; in this building the wooden lintel extends along the perimeter of the building.

In buildings “H23” and “H27”, located in Anadia municipality, in place of the wooden lintel there is a reinforced concrete beam that runs along the perimeter of the building. In building “H27”, the openings are sometimes laterally reinforced with cement mortar.

Five buildings have a small number of wide openings built with arches. In four buildings the arches are made with adobe bricks (in one case, combined with a wooden lintel), and in one building the arch is made with small solid ceramic bricks.

6.1.3. Connection between walls

It was possible to observe the connection between facade walls in 13 out of the total of 21 buildings (i.e., in 62% of the buildings). In these buildings, the connection between facade walls is made with the interlocking of adobe bricks in the corners. In a few cases, small ceramic bricks or stones are sparsely distributed in the corners for additional reinforcement.

Five buildings, out of a total of nine where observation was possible, have bond beams (Table 5)—a bond beam is a structural element that runs continuously along the perimeter of the building, tying the facade walls together and contributing to the overall stability of the building. Three buildings in Anadia municipality and one building in Aveiro Municipality have thin reinforced concrete bond beams. In the ground floor (or semi-basement), the bond beams were observed at the level of the first floor structure (in buildings "H23", "H25", and "H39") or immediately above the openings, working as a lintel in these openings (in building "H27"). In buildings "H23" and "H27", in the first floor, the bond beams were observed above the openings (working also as a lintel in these openings). In buildings "H25" and "H39′" it was not possible to confirm the existence of a second bond beam at the top of the first floor. Building "H28", located in Murtosa municipality, has a wooden bond beam at the level of the first floor structure, which also works as a lintel in the openings of the ground floor, and a second wooden bond beam above the openings of the first floor, working also as a lintel in these openings. It was not possible to check the nature and quality of the connections of the wooden beams in the corners. These beams must be effectively interconnected in order to contribute to the overall stability of the building.

Table 5. Types of bond beam observed in the buildings studied.

		Bond beams			
		Wood	Reinforced concrete	Without bond beams	Not observed
No. of buildings	Anadia	0	3	3	1
	Murtosa	1	0	1	5
	Aveiro	0	1	0	6
	Total	1 (5%)	4 (19%)	4 (19%)	12 (57%)

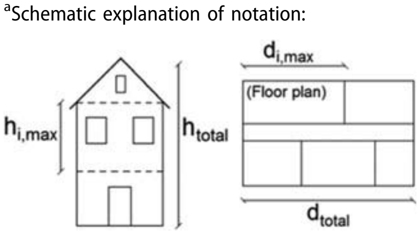
6.1.4. Dimensions and slenderness ratios of walls

The maximum total height of facade walls, inter-story height, total length of facade walls, and distance between lateral supports (i.e., transverse walls) are presented in Table 6. The maximum ratio between the inter-story height and the corresponding thickness of walls, and the maximum ratio between the distance between lateral supports and the corresponding thickness of walls are also presented. For the sake of simplicity, both ratios will be referred to as "slenderness ratios". The limits indicated in different technical standards for some of these parameters are also presented in Table 6.

Table 6. Dimensions and slenderness ratios of facade walls.

		Adobe facade walls					
		Maximum height (m)		Maximum length (m)		Maximum slenderness ratio	
		Total (h_{total}[a])	Inter-story ($h_{i,max}$[a])	Total (d_{total}[a])	Between transverse walls ($d_{i,max}$[a])	$(h_i/e)_{max}$[b]	$(d_i/e)_{max}$[b]
Anadia	Mean:	7.0	3.4	11.4	6.3	9.6	17.1
Murtosa	Mean:	7.9	3.9	17.0	9.5	8.1	19.5
Aveiro	Mean:	7.9	4.0	16.2	9.4	9.9	21.1
All municipalities	Mean:	7.6	3.8	14.9	8.4	9.2	19.2
	Min.:	3.5	2.8	8.5	3.9	7.0	10.3
	Max.:	12.1	4.8	32.3	13.8	14.8	28.0
	CV:	34%	15%	40%	37%	19%	27%
Standard limits	"NTE E.080" (SENCICO, 2006)	—	—	—	—	≤ 6[c]	≤ 12
	"NZS 4297" (SNZ 1998)	—	—	—	—	≤ 6[d]	—
	"IBC" (ICC 2009)	—	—	—	≤ 7.315	≤ 10	—
	"Eurocode 8" (CEN 2010)	—	—	—	≤ 7	—	—

[a]Schematic explanation of notation:



[b]"*e*": wall thickness.
[c]Considering the existence of a bond beam; if $(h_i/e)_{max} > 6$, additional reinforcement is required.
[d]Considering the earthquake zone factor for the areas of greater seismic hazard in New Zealand.

Both load-bearing interior walls (normally made with adobe) and non-load-bearing interior walls (normally "*tabique*" walls, made with a wooden structure filled and coated with lime mortar) were considered when determining the maximum distance between transverse walls. Even though "*tabique*" walls were generally built simply as partition walls, they have some load-bearing capacity and may improve the lateral restraint of facade walls. In the calculation of the slenderness ratios, it was assumed that the connections between perpendicular walls and between facade walls and floor and roof structures are effective. However, considering the observations carried out *in situ*, it can be concluded that these connections may not always be effective. Thus, in some cases, the real slenderness ratios of the facade walls are likely greater than the ratios calculated.

The maximum inter-story height of the buildings shows little variation (CV = 15%), with a mean value of 3.8 m. The maximum total height and total length of facade walls and the maximum distance between transverse walls exhibit greater variability, with coefficients of variation ranging up to 40%, and with mean values of 7.6 m, 14.9 m, and 8.4 m, respectively. The slenderness ratio calculated using the inter-story height presents a mean value of 9.2, with a coefficient of variation of 19%. The mean slenderness ratio calculated using the distance between lateral supports is 19.2, with a coefficient of variation of 27%.

In general, the buildings analyzed in Anadia municipality have facade walls with lower height and lower distances between lateral supports, when compared to those of other municipalities. However, given that the facade walls of the buildings are generally thinner, there is no great difference between the slenderness ratios calculated for the buildings of this municipality and those of other municipalities.

By comparing the results obtained with the limits indicated in different technical standards (Table 6), the following observations can be made.

- In general, the maximum distance between lateral supports of facade walls is greater than the maximum limits indicated in IBC (ICC 2009) and Eurocode 8 (CEN 2010).
- For all the buildings studied, the slenderness ratio calculated using the inter-story height is greater than the maximum limit indicated in NTE E.080 (SENCICO 2006) and NZS 4297 (SNZ 1998).
- All the buildings analyzed in Murtosa municipality, four buildings in Anadia municipality, and four buildings in Aveiro municipality have facade walls with slenderness ratios—$(h_i/e)_{max}$—that respect the limit indicated in IBC (ICC 2009);
- Only one building in each of the three municipalities respects the limit indicated in NTE E.080 (SENCICO 2006) for the slenderness ratio calculated using the distance between lateral supports.

It is thus concluded that, in general, the limits indicated in existing standards for the distance between the lateral supports and slenderness ratios of facade walls are not respected in the buildings under study. This may lead to instability of the walls, particularly when subjected to horizontal loads, such as seismic loads or loads imposed by the roof structure. It is important to note, however, that Aveiro district is located in an area of moderate seismic hazard (CEN 2010), while Peru and New Zealand, countries for which two of the standards used were created, are regions of high seismic hazard.

6.1.5. Foundation system

The buildings studied were built with strip foundations, both for the support of the facade walls and interior adobe walls. It was observed that in five buildings the foundation of the facade walls was made with stone masonry and in two buildings with adobe masonry (Table 7). In the majority of the buildings (67%), however, it was not possible to observe the type of material used in the foundation. It is important to note that, according to the existing literature, adobe masonry was more common than stone masonry in the foundations of adobe buildings (Maia 2009; Santiago 2007; Tavares 2009).

The stone foundations observed rise to a height above the ground level ranging approximately from 0.20–0.80 m. The stones are irregular, with varied sizes and shapes, and are generally bonded with an earth mortar (with or without lime). In buildings "H21", "H22", and "H25", in Anadia municipality, the foundations were made with limestone; in building "H33", in Murtosa municipality, schist was used; and in building "H34", in Murtosa municipality, a combination of schist and red sandstone ("*Eirol*" stone) was the chosen solution. Given that "mud adobes" degrade very easily in contact with water, buildings with facade walls made with "mud adobes" (described in Section 6.3),

Table 7. Types of masonry used in the foundation of facade walls.

		Foundations		
		Stone masonry	Adobe masonry	Not observed
No. of buildings	Anadia	3	1	3
	Murtosa	2	0	5
	Aveiro	0	1	6
	Total	5 (24%)	2 (10%)	14 (67%)

such as "H33" and "H34", in Murtosa municipality, required the use of stone or "lime adobe" foundations.

With the inspection carried out it was only possible to identify the type of material used and not the dimensions, defects, or state of conservation of the foundations. There are, however, defects observed in the facade walls that may be caused by differential foundation settlement, as is further discussed in Section 7.1.

6.2. Coating

The different types of coating observed in the outer surface of the facade walls are presented in Figure 4. The facade walls of the majority of the buildings (62%) are rendered with lime mortar. This was the solution traditionally used in the adobe buildings of Aveiro district. In some of these buildings, cement mortar was later applied in small areas of the wall to cover existing lime mortar deterioration. In 33% of the buildings studied, the facade walls are entirely coated with a recent layer of cement mortar, normally applied over the existing layer of lime mortar.

The facade walls of 38% of the studied buildings are finished with lime paint. Lime paint was the finishing solution traditionally used in the adobe buildings of Aveiro district. Other types of paint, which are now commonly used and generally have impermeable characteristics, were observed in 24% of the buildings. These other types of paint were added later, sometimes directly over the existing layers of lime paint.

Ceramic tiles were observed in the facade walls of two buildings located in Murtosa municipality and four buildings in Aveiro municipality (i.e., in 29% of the buildings studied). Tiles were generally applied in the facade walls that could be observed from the street. In the buildings from Aveiro municipality, in particular, ceramic tiles are only used in the main facades. In these buildings, the walls that are not finished with tiles are finished either with lime paint or with a more recent layer of a different type of paint.

Anadia municipality has the largest number of studied buildings that have been subject to recent interventions, and thus the facade walls of these buildings frequently have recent layers of cement render or paint with impermeable characteristics. In Murtosa and Aveiro municipalities, many of the buildings that were analyzed have facade walls that haven't been subject to any recent intervention, remaining with the original coating solution (i.e., lime render finished with lime paint or ceramic tiles).

6.3. Traditional masonry materials

The dimensions of the adobes and the thickness of the traditional mortars (i.e., the mortars made with lime and sand or with clayey soil) used in the facade walls of the buildings under study are presented in Table 8. The number of buildings where it was possible to perform measurements is also indicated. The dimensions of the adobes are relatively uniform throughout the different regions. Considering all municipalities, the mean dimensions of adobes are: $0.31 \times 0.11 \times 0.45\ m^3$. The thickness of render and plaster is far more variable, even for the same building. Considering all municipalities, the mean joint thickness is approximately 0.03 m, and the mean render and plaster thickness is approximately 0.02 m. There is a tendency for the render (applied on the outer surface of facade walls) to be

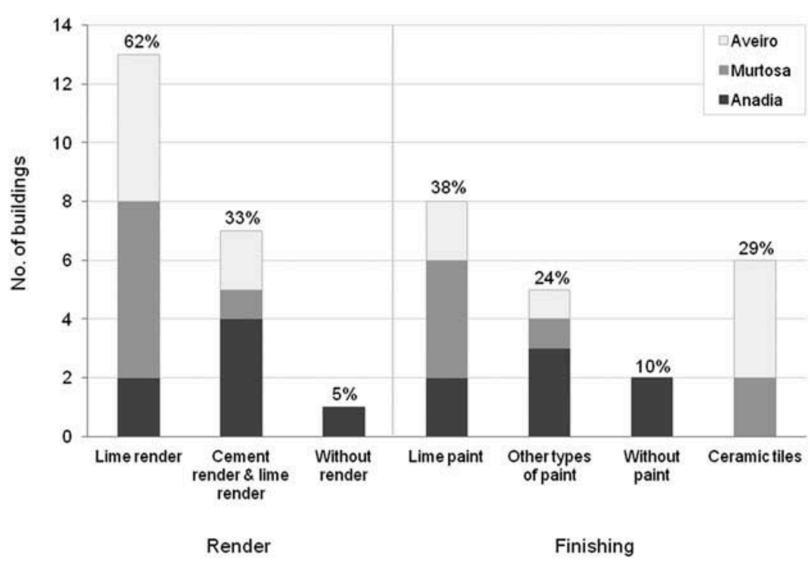


Figure 4. Coating of the outer surface of facade walls.

Table 8. Dimensions of adobes and thickness of joint, plaster, and render.

		Adobe dimensions (m)			Mortar thickness (m)		
		Width	Height	Length	Joint	Plaster (interior)	Render (exterior)
Anadia	Mean:	0.32	0.11	0.45	0.028	0.018	0.023
	n[a]:	5	6	6	6	5	4
Murtosa	Mean:	0.32	0.11	0.46	0.029	0.025	0.022
	n[a]:	4	5	5	5	4	4
Aveiro	Mean:	0.30	0.12	0.43	0.028	0.013	0.025
	n[a]:	4	5	4	5	3	1
All municipalities	Mean:	0.31	0.11	0.45	0.028	0.019	0.023
	Min.:	0.25	0.09	0.41	0.020	0.005	0.008
	Max.:	0.37	0.14	0.53	0.038	0.030	0.035
	CV:	11%	13%	7%	17%	47%	41%
	n[a]:	13	16	15	16	12	9

[a]Number of buildings where measurement was possible.

slightly thicker than the plaster (applied on the inner surface of facade walls).

The great majority of the buildings studied (18 out of a total of 21 buildings, i.e., 86%) have facade walls made with “lime adobes”. Two buildings (“H33” and “H34”) have facade walls made with “mud adobes”, and in one building (“H26”) a combination of both types of adobes was used. “Mud adobes” were used in Aveiro district in an early stage, and “lime adobes” were used in a later stage, from the 19th century to the middle of the 20th century. After a period of coexistence, “lime adobe” started to prevail until it became the solution normally used (Santiago 2007). “Mud adobes” were made with clayey soil, to which sometimes straw or other plant fibres were added (Oliveira and Galhano 1992; Santiago 2007). “Lime adobes” were made of arenaceous soil with a reduced silt-clay fraction (Santiago 2007) and air-lime in a percentage varying between 25% and 40% (Teixeira and Belém 1998). Local materials were used in both types of adobe.

The mortar used in the joints of the “mud adobe” facade walls analyzed in this study has a similar composition to that of the adobes (i.e., it is made with clayey soil). The traditional mortar used in renders and plasters, in this type of wall, is made with arenaceous soil and air-lime. The mortar used in the “lime adobe” walls—in joints, plasters, and renders—is also made with arenaceous soil and air-lime. In some buildings, the render consists of just one layer of mortar with composition similar to that of the lime adobes. In other buildings, it includes one or two additional thinner layers of mortar made with finer sand and a greater percentage of lime. In buildings “H33” and “H34”, both with “mud adobe” facade walls, small pieces of stone or ceramic material were also used in the joints, contributing to increase the strength of the walls and the adhesion of the render to the walls.

It is important to note that the study of the mechanical properties and behavior of the adobes

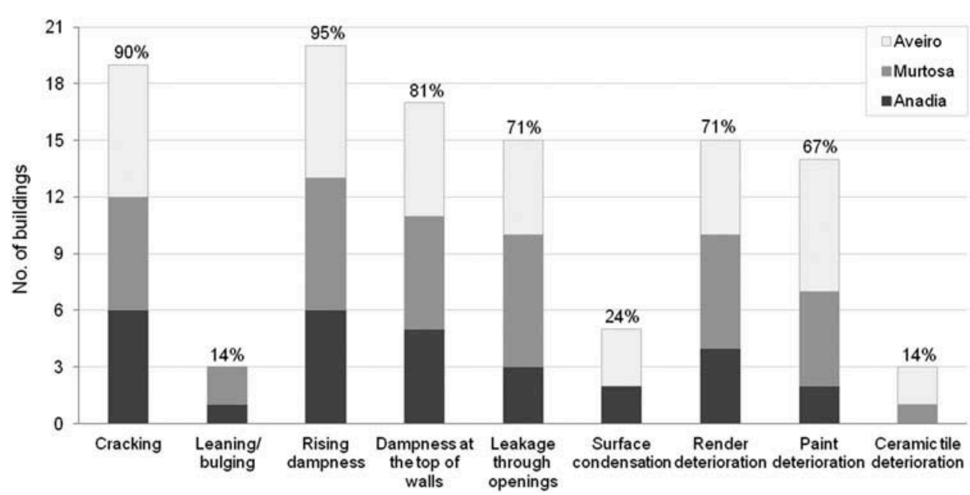


Figure 5. Common defects observed in facade walls.

and adobe masonry of Aveiro district has previously been carried and presented (e.g., Silveira et al. (2012), Silveira et al. (2015)), and thus it is not addressed in this article.

7. Defects in facade walls

The most common defects observed in the facade walls of the buildings studied are presented in Figure 5. The number and percentage of buildings, per municipality, that suffer from each defect are also indicated. The most common defects observed and their possible causes are described below.

7.1. Cracking and partial collapse

Cracking of facade walls was observed very frequently in the inspections conducted. In fact, 90% of the buildings studied have facade walls with superficial and structural cracks (Figure 5). The most relevant types of cracking observed are represented schematically in Figure 6. The number of buildings, per municipality, that suffer from each defect, is presented in Figure 7. For each type of cracking, the percentage of buildings, in relation to the total number of buildings studied, is also indicated. The different types of cracking observed and their possible causes are described below. A brief analysis of the damage that led to the partial collapse of two facade walls in building "H34" is also presented.

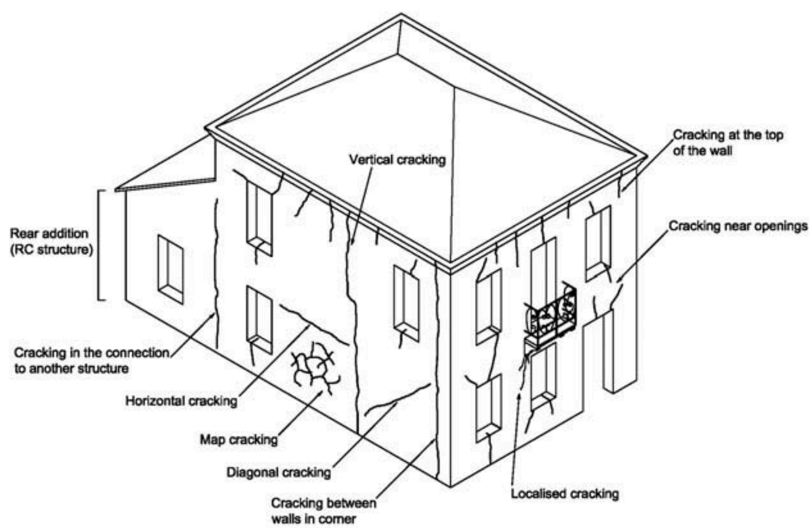


Figure 6. Schematic representation of the types of cracking observed in facade walls.

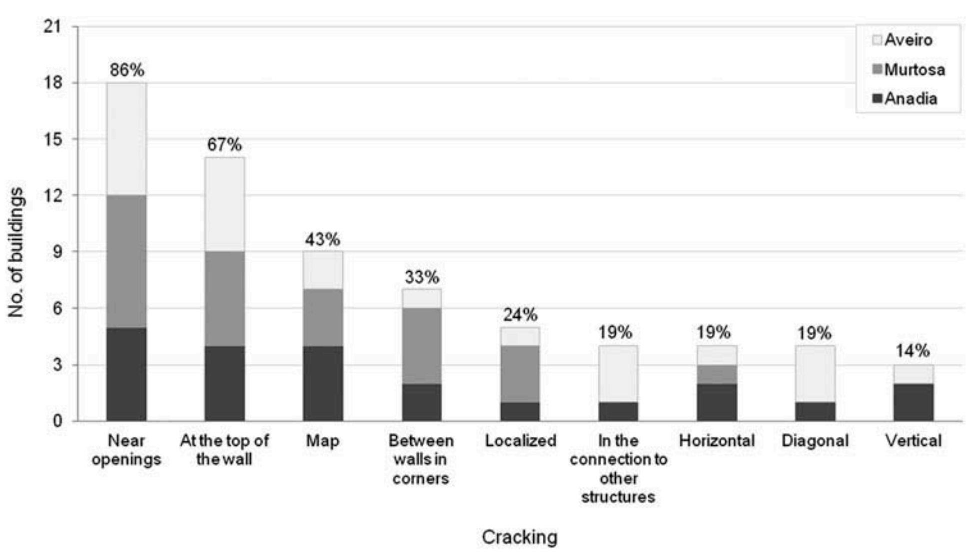


Figure 7. Types of cracking observed in facade walls.

7.1.1. Cracking near openings

The cracks near openings observed in the buildings studied are mainly located above or below the openings, frequently near the corners, and generally have vertical or diagonal orientation (Figure 6). In some cases, cracking is thin and superficial, affecting only the coating, but it is more frequently thick and deep, affecting also the support structure. In one building ("H21"), intense cracking led to the partial disintegration of masonry above two openings. Common causes for cracking near openings are: excessive load (Thomaz 2003), generally imposed by the roof or floor structures; insufficient support of the masonry above the openings; stress concentration in the corners; and excessive percentage of wall area with openings. In some of the cases, differential foundation settlement is also a possible cause for the existing cracking (Richardson 2001; Thomaz 2003).

7.1.2. Cracking at the top of the wall

The cracking observed at the top of the facade walls of the buildings studied is mainly vertical or diagonal (Figure 6). In some cases the cracks are light and superficial, but in other cases the cracks are thick and affect the support structure. This type of cracking is generally caused by excessive load or deformation imposed by the roof structure (Thomaz 2003).

7.1.3. Map cracking

Map cracking is a network of thin and superficial cracks, oriented in a random pattern (Figure 6). It generally occurs as the result of the drying shrinkage of mortar (Marshall et al. 2014). This type of cracking was mainly observed in cement render, but a few cases in lime render were also identified.

7.1.4. Cracking between perpendicular walls in corners

Structural cracking between perpendicular facade walls, in corners, was observed in some of the buildings under study (Figure 6). This type of cracking is generally vertical, following along the area of connection between walls. In some of the cases observed, vertical cracking is combined with diagonal or scattered cracking along the corner. Possible causes for this type of cracking are: deformation of the walls due to variations in temperature or moisture content (Thomaz 2003); differential foundation settlement (Pagaimo 2004); and horizontal thrust imposed by the roof which leads to the rotation of one or both perpendicular walls (Pagaimo 2004). These factors can lead to cracking or even separation between facade walls, especially when combined with a weak connection between walls.

7.1.5. Localized cracking

Localized cracking in the facade walls, due to stress concentration, was observed near the points of support of gutters, balconies (Figure 6), steel rods, and beams. This type of cracking is generally intense, affecting the support structure. The cracks are vertical or diagonal and sometimes are combined with crushing around the support points.

7.1.6. Cracking in the connection of buildings to other structures

Cracking was observed in the connection of buildings to adjacent land dividing walls and in the connection of the original buildings to rear additions (Figure 6). In these cases, cracks are generally vertical or diagonal, following along the connection surface. Possible causes for this type of cracking are the differential movement of the structures due to variations in temperature or moisture content (Richardson 2001) and differential foundation settlement (Thomaz 2003).

7.1.7. Horizontal cracking

Long horizontal cracking was observed in the facade walls of some of the buildings studied (Figure 6). In most cases, the cracks are thick and may affect the support structure. A possible cause for long horizontal cracking is excessive load imposed by the roof structure, causing flexion of the wall (Thomaz 2003). However, in the observed cases, the horizontal cracks may be the result of cracking that started in areas of structural fragility (such as near openings or near collapsed areas) and that extended horizontally along the bed joints. In one building ("H23"), horizontal cracking is located at the level of the first floor concrete bond beam and is likely the result of incompatibility between the behavior of the two materials (adobe masonry and concrete).

7.1.8. Diagonal cracking

Long diagonal cracking was also observed in the facade walls of some of the buildings studied (Figure 6). In all the cases, the cracks are thick and appear to affect the support structure. In building "H39", one diagonal crack is located near an opening, extending diagonally and downward towards a corner of the building, and seems to be caused by excessive load imposed by the roof structure. In the other cases where this type of cracking is observed, cracks appear to be caused by differential foundation settlement—in these cases, the diagonal cracks lean towards the point where the largest settlement occurred (Richardson 2001; Thomaz 2003). In building "H39", one diagonal crack of this type is particularly severe, compromising the structural stability of the building.

7.1.9. Vertical cracking in the central area of the wall

Vertical structural cracking in the central area of the facade walls was observed in a few of the buildings under study (Figure 6). The vertical cracks are long, sometimes extending from the bottom to the top of the walls. Possible causes for this type of cracking are (Thomaz 2003): deformation of the walls due to variations in temperature or moisture content; differential foundation settlement; and excessive concentrated load imposed by the roof structure.

7.1.10. Partial collapse

One of the buildings studied ("H34") has two facade walls where intense cracking led to the collapse of part of the walls. In the right side facade, the section of the wall above an arch made with adobe and with a large span (3.75 m) collapsed. In the rear facade, there was a section of wall with reduced thickness, made with ceramic bricks—covering a large niche, in a room that used to function as a chapel—that also collapsed.

7.1.11. Final comments

The main possible causes of the cracking observed in the facade walls studied are: deformation of the walls due to variations in temperature or moisture content; differential foundation settlement; and excessive load imposed by the roof structure. In some areas of Aveiro district, existing highly compressible and low strength soils (Bonito 2008) may contribute to the foundation settlement problems observed in the buildings studied. It is important to note that cracking of structural masonry is generally the result of a complex combination of factors, and thus it is often difficult to isolate specific causes.

Since excessive load imposed by the roof structure is one of the main possible causes of existing cracking, it is important to briefly describe the type of roof structure of the buildings studied. All the buildings, with the exception of building "H23", have wooden roof structures. Two types of structure were observed: with beams or with trusses as the main support elements. The majority of the buildings have roof structures made with king post trusses. These trusses are closed, i.e., have a horizontal beam (tie beam) that ties together the feet of the opposite rafters. In all the roofs, the ends of the main structural elements are embedded in the facade walls, normally without additional reinforcement of the areas of connection—which, in some cases, leads to cracking and crushing around these areas.

The possible causes identified, combined with the fact that adobe masonry is characterized by low tensile and shear strength and brittle behavior (Silveira et al. 2015), lead to significant cracking in the facade walls of the buildings studied. Walls made with "mud adobes", in particular, have very low strength values, and thus are more vulnerable to cracking and collapse. Indeed, the three buildings where "mud adobes" were used ("H26", "H33", and "H34") are among the buildings with the most severe cracking defects.

The cracking observed in the facade walls of the buildings under study can severely compromise their structural integrity. Cracking also creates areas of vulnerability to water seepage that can further degrade the adobe masonry. Effective measures to address and prevent cracking in the facade walls of existing adobe buildings are therefore fundamental.

7.2. Leaning or bulging of walls

Three out of the 21 buildings studied have leaning or bulging facade walls (Figure 5). These defects, however, are not very pronounced. Excessive vertical load imposed by the roof (USDOI 1978) or floor structures, expansion of the soil below the foundation, and horizontal thrust exerted by the roof structure (Pagaimo 2004), combined with excessive slenderness of walls and weak connection between walls and other structural elements, are possible causes for these defects.

7.3. Dampness

Dampness problems were observed in almost all the buildings studied (Figure 5). The different dampness problems identified and their main causes are presented below.

7.3.1. Rising dampness

Rising dampness is a very common defect (Figure 8a), observed both in the buildings with adobe foundations and in the buildings with stone foundations. The signs of rising dampness generally consist of damp patches, mold, moss, mortar detachment, and paint peeling located at the bottom of the facade walls. In some buildings, these signs are only visible on the outer surface of walls. In these cases, surface water may be the main cause of rising dampness (Freitas, Torres, and Guimarães 2008). In other buildings, the signs of rising dampness are also visible on the inner surface of walls and are of equal or even higher intensity in these surfaces. In these cases, groundwater may be the main cause of rising dampness (Freitas, Torres, and Guimarães 2008).

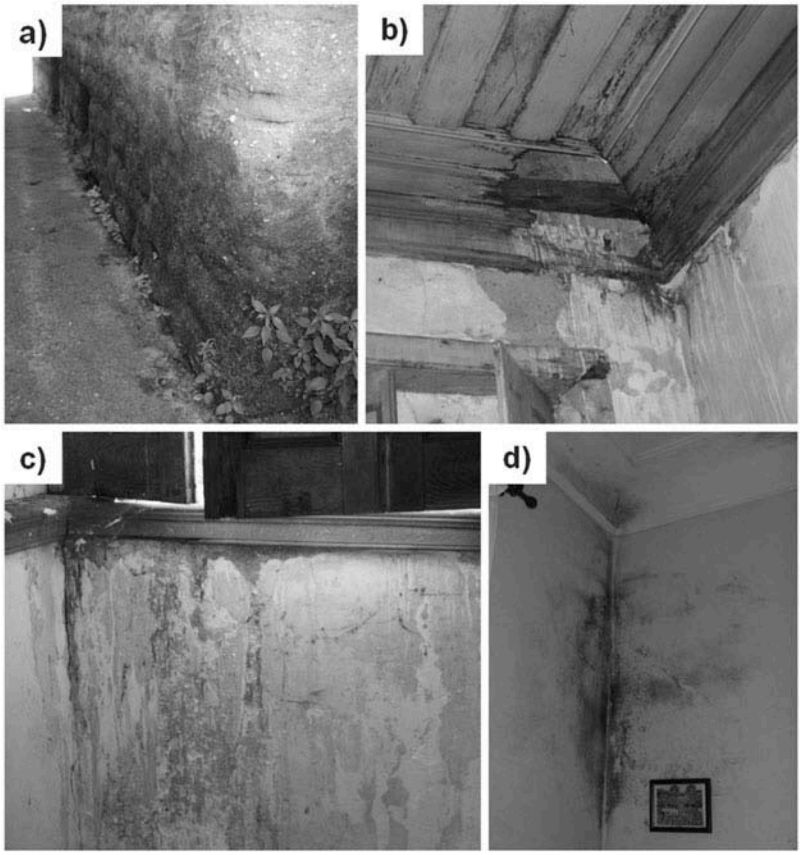


Figure 8. (a) Rising dampness; (b) dampness at the top of walls; (c) leakage through window openings; and (d) surface condensation.

Two main factors appear to contribute to the problem of rising dampness observed in the buildings studied: on the one hand, adobe is a material with high capillarity (Coroado et al. 2010; Martins 2009) and thus adobe walls are very susceptible to this phenomenon; on the other hand, many of the buildings studied don't have a rainwater drainage system or have a malfunctioning drainage system, which causes the accumulation of water near the base of the buildings.

7.3.2. Dampness at the top of walls

Dampness at the top of walls is usually the result of water leakage through the roof. This problem is generally observed on the inner surface (Figure 8b) and sometimes on the outer surface of walls. On the inner surface, damp patches, frequently combined with dripping water stains, are more intense at the top of the walls and often extend to the bottom. In some buildings, the formation of mold in these areas can be observed. On the outer surface of walls, the signs of dampness generally consist of mold and, in some cases, of peeling paint. In some buildings, the eaves have deficiencies (such as missing tiles or cracked tiles) that further contribute to this problem. The fact that most roofs have a lower slope at the base may lead to the accumulation of water in this area, which can contribute to the existing leakage problems. In addition, the formation of vegetation is this area, visible in many of the buildings studied, contributes to the accumulation of water and also to the damage of roof tiles.

Three buildings ("H38", "H39", and "H40", in Aveiro municipality) have roof parapets on the main facade walls. These facade walls have dampness problems, visible on the parapets and at the top of the walls in the interior of the buildings. In these cases, the roof parapet acts as a barrier to water drainage, leading to moisture problems in the roof and facade walls (Tavares, Costa, and Varum 2012).

In some cases, the wooden lintels above openings also have dampness problems caused by the rainwater that flows from the roof or hits the walls directly. Due to the prolonged presence of dampness, these elements suffer from biological deterioration, rotting, cracking, and fracture. The existing degradation in some cases may progress to a point where the lintel no longer fulfils its structural function.

Another type of defect observed in some buildings and included in this category is dampness on the outer surface of facade walls near the roof of contiguous lower-height building sections. Deficiencies in the drainage of rainwater from the adjacent roof lead to the accumulation of rainwater near the facade wall of the higher building section.

7.3.3. Leakage through window openings

Leakage through window openings is also a common cause of dampness in the facade walls of the buildings studied (Figure 8c). Rainwater seeps through the connection between window frames and facade walls or through gaps in the window frames. This problem is generally manifested by the presence of damp patches, dripping water stains, and peeling paint on the area below the openings.

7.3.4. Surface condensation

Another less common dampness problem that was identified is surface condensation. This type of defect occurs on the inner surface of the facade walls of some of the buildings studied and is manifested by the presence of mold (Figure 8d). This problem generally occurs in facade walls with northern orientation and in bathrooms. In some cases it is distributed along the wall, and in other cases it is concentrated at the top of the wall or is markedly more intense in this region. There is also a tendency for this problem to occur at the corners of walls.

7.3.5. Final comments

The main causes of the dampness problems observed in the facade walls of the buildings studied are the lack or malfunction of the ground and roof rainwater drainage systems and the existence of deficiencies in the roof and window openings that cause the water to leak. These deficiencies, combined with the fact that adobe is very vulnerable to the action of water, lead to defects that, if not timely and adequately addressed, compromise the habitability of buildings and may even jeopardise their structural integrity.

7.4. Coating deterioration

In addition to the cracking and dampness defects described above, a significant percentage of the facade walls studied suffer from other coating deterioration problems (Figure 5). These defects and their corresponding causes are described below.

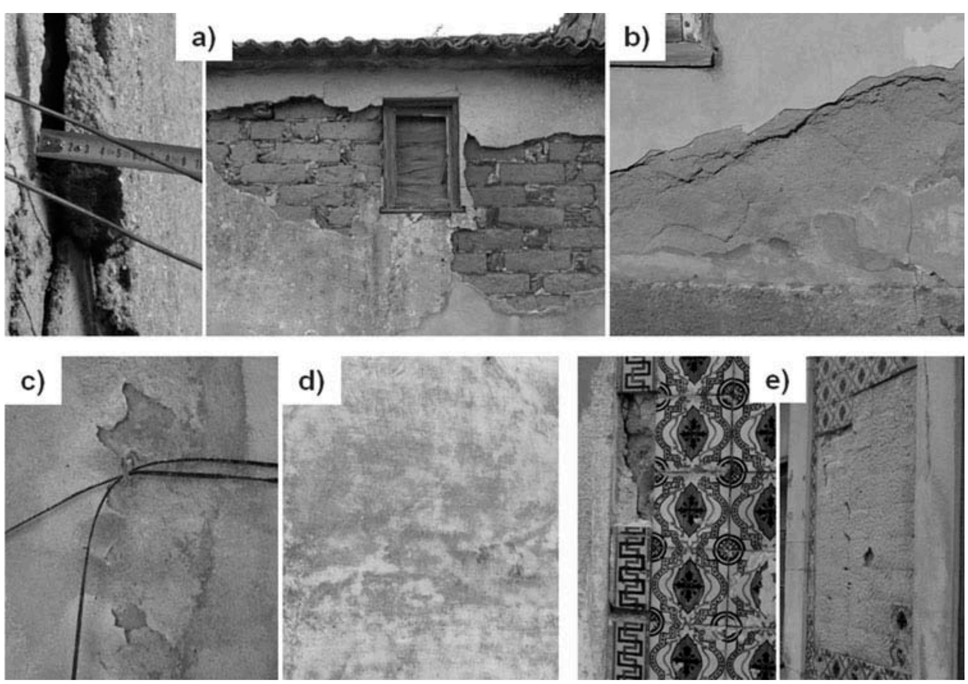


Figure 9. (a) Render detachment; (b) render erosion; (c) paint peeling; (d) paint erosion; and (e) ceramic tile deterioration.

7.4.1. Render deterioration

Render deterioration was observed in 71% of the buildings studied. Two main forms of render deterioration were identified: detachment and erosion.

Render detachment is the loss of adhesion between the mortar and the support masonry (Figure 9a). Possible causes for this defect are (Magalhães 2002; Rodrigues 2006): errors in mortar production and application; prolonged presence of excessive moisture on the wall (as pointed out previously); cryptoflorescences; deformation due to variations in temperature or moisture content; and support movements. In the facade walls studied, detachment has frequently led to the loss of the render layer (Figure 9a).

In some of the buildings where cement render was used, the render has cracking and detachment problems and the support adobes degradation problems. These defects are due to the incompatibility between the properties of cement mortars and adobe masonry (Rodrigues 2006). Cement mortar also hinders the exchange of water vapor, causing the retention of this vapor and the concentration of salts in the support structure—these elements, in turn, contribute to accelerate the degradation of the support structure (Rodrigues 2006).

Render erosion is the destruction or wear of the render (Figure 9b) with loss of material or only the alteration of the render surface (Magalhães 2002). It is caused by the direct action of weathering agents (particularly rain, temperature variations, and wind) or other mechanical agents that induce stresses in the material (Magalhães 2002). In a few of the walls observed where the erosion has been particularly intense, the adobes have become exposed. In one of the buildings studied ("H21"), the unprotected adobes are highly degraded.

7.4.2. Paint deterioration

Paint deterioration was observed in 67% of the buildings studied. Two types of deterioration were identified: peeling and erosion. The peeling effect was mainly observed in the layers of the impermeable types of paint (Figure 9c), which are not compatible with the support structure and often create a barrier to the passage of moisture (Rodrigues 2006; Tavares, Costa, and Varum 2012). The erosion effect was observed only in lime paint. In these cases, the paint has been partially eroded due to the action of weathering agents, and the support lime render has become visible (Figure 9d).

7.4.3 Ceramic tile deterioration

In half of the buildings that have facade walls with ceramic tiles, the tiles show mild superficial deterioration (Figure 9e). In one building ("H35"), there are small wall areas with missing tiles (Figure 9e). The main cause of tile deterioration is the action of weathering agents or other mechanical agents that induce stresses in the material.

7.4.4. Final comments

The main causes of deterioration of the external coating of the facade walls studied are the action of weathering agents and the incompatibility between the selected coating and the support structure. The external coating of facade walls is critical to protect them from the action of weathering and other degradation agents. The deterioration of this coating leads to the exposure of the support structure, which then becomes more vulnerable to degradation. The protection, regular maintenance, and repair of wall coatings and the use of compatible coating solutions are thus fundamental.

8. State of conservation of facade walls

The state of conservation of the facade walls of the buildings studied was assessed using a rating scale that varies between 1 and 5. For each building, one rating was assigned to the masonry structure and another to the coating of the facade walls. Each rating corresponds to a global evaluation of the facade walls of the building, taking into account the state of conservation of each wall.

The state of conservation of the masonry structure of each facade wall was evaluated as follows:

- 1 ("very poor"): the wall has severe defects that greatly affect its structural integrity; it may have suffered partial or complete collapse;
- 2 ("poor"): the wall has defects that affect its structural integrity;
- 3 ("reasonable"): the wall has defects that do not affect—or only slightly affect—its structural integrity; relatively simple rehabilitation measures would be sufficient to resolve the existing problems;
- 4 ("good"): the wall has few defects; the existing defects are of low to moderate intensity; and
- 5 ("very good"): the wall does not have significant defects.

The state of conservation of the coating of each facade wall was evaluated as follows:

- 1 ("very poor"): the wall coating has severe defects that significantly compromise its function;
- 2 ("poor"): the wall coating has defects that compromise its function;
- 3 ("reasonable"): the wall coating has defects that do not affect—or only slightly affect—its function;

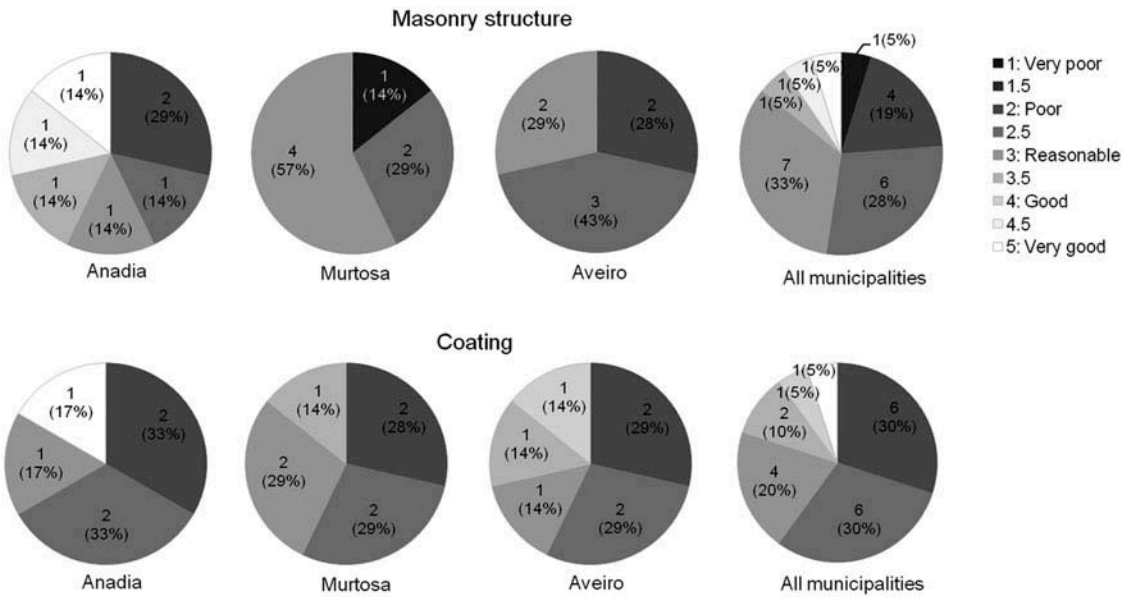


Figure 10. State of conservation of facade walls.

relatively simple rehabilitation measures would be sufficient to resolve the existing problems;

- 4 ("good"): the wall coating has few defects; the existing defects are of low to moderate intensity; and
- 5 ("very good"): the wall coating does not have significant defects.

In the evaluation of the state of conservation of the facade walls, where there was uncertainty between two consecutive ratings, the scale was refined using the mean of the two ratings (i.e., 1.5, 2.5, 3.5, or 4.5).

This rating system was used to enable a quick assessment of the state of conservation of the facade walls. With this simple system it is possible to acquire a general knowledge of the state of conservation of a significant number of buildings. For a more accurate evaluation and understanding of the state of conservation of a specific building, a more in-depth analysis is recommended.

The number and percentage of buildings per rating of state of conservation, for the masonry structure and coating of the facade walls, for each municipality, are presented in Figure 10. The same information, considering the three municipalities in conjunction, is also presented.

Considering all the municipalities studied, a wide interval of state of conservation ratings is observed. These ratings vary between 1 and 5, for the masonry structure, and between 2 and 5, for the coating. The facade walls of the buildings analyzed in Anadia municipality have the highest ratings of sate of conservation. This is mainly due to the fact that the three buildings of most recent construction (built after 1950), two of which ("H23" and "H25") have been subject to regular rehabilitation interventions, are located in this municipality. In general, mainly due to this fact, there is a slightly greater concentration of defects in the buildings studied in the other municipalities (Murtosa and Aveiro).

The masonry structure of the facade walls of 52% of the buildings studied is in a state of conservation rated below "reasonable". This percentage rises to 71% when the buildings of Aveiro municipality are considered separately. The state of conservation of the wall coating in 60% of the buildings was also rated below "reasonable". It can thus be concluded that the facade walls of many of the adobe buildings studied are in need of adequate rehabilitation measures.

9. Conclusions and final remarks

A visual and dimensional inspection of the facade walls of 21 adobe buildings selected from three municipalities of Aveiro district was carried out and the results obtained were presented in this article. This inspection allowed for the characterization of the construction details of the facade walls studied, including the identification of vulnerabilities that may contribute to the instability or poor functioning of these structural elements. This study also allowed to identify and analyze defects commonly observed in adobe facade walls and to identify likely causes for these defects. It was observed that many of the existing defects are linked to a lack of regular maintenance measures, to deficiencies in existing systems, and to the use of inappropriate materials in interventions.

Overall, it was concluded that the facade walls of a large percentage of buildings have defects and vulnerabilities that compromise their good functioning and, in some cases, the structural integrity of the buildings. The rehabilitation and strengthening of these key structural elements, addressing and correcting the root causes of existing defects, are fundamental. The performance of regular maintenance interventions is also essential for their adequate functioning. Despite the existing defects and vulnerabilities, many adobe buildings, including those that are currently vacant, if adequately rehabilitated and strengthened, can perform their function well.

The work developed and presented is intended to contribute to a better understanding of the building systems and defects of existing adobe building. This understanding is essential to support the development of rehabilitation and strengthening solutions and guidelines adapted to adobe construction. This work is also intended to contribute to enhance the awareness about the significance and potential of this type of construction. The results obtained, however, are preliminary and it is necessary to carry out an inspection of a larger number of adobe buildings in Aveiro district. In the future, efforts to develop technical guidelines and to implement activities to transfer the knowledge gained in existing studies to the individuals and entities that use and intervene in adobe buildings are also fundamental.

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