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Defects and moisture problems in buildings from historical city centres: a case study in Portugal

Paulo B. Lourenço[a,*], Eduarda Luso[b], Manuela G. Almeida[a]

[a]*University of Minho, Department of Civil Engineering, Azurém, P-4800-058 Guimarães, Portugal*
[b]*Polytechnic Institute of Bragança, P-5301-857 Bragança, Portugal*

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Abstract

Conservation of ancient buildings is a major issue for modern societies, both from economical and cultural viewpoints. Information about the ancient built heritage is vital to plan adequate remedial measures. Taking a historic centre in Portugal as a case study, this paper presents an extensive survey of building typology and materials, damage in the building envelope, indoor survey of damage, and measurements in indoor air temperature and relative humidity. Water-related problems can be confirmed as the single most important defect combined with inadequate sun exposure, ventilation and heating, and excessive moisture indoor production. Extremely low temperatures, high humidity and presence of mould therefore, compromise the indoor quality of life of the inhabitants; and make urgent repair at many levels necessary.

Keywords: Ancient buildings; Building damage; Traditional building techniques; Indoor moisture; Indoor temperature

1. Introduction

After the second World War many ancient buildings and historical centres needed major repairs and rehabilitation. Nevertheless, due to the low income after the war and because of the need for new materials such as reinforced concrete and steel, masonry buildings were in many cases abandoned to the population with less financial resources i.e. to those who could not afford the costs of adequate repair and restoration. Only during the last decades, the idea that ancient buildings could be restored and reused became appealing for the market. The present policy is not only to preserve but also to make buildings and the whole historic part of the cities came alive, functioning and appealing to the inhabitants and to the tourists. It is the unique atmosphere of narrow streets and historic squares that provide a meaning to the cultural heritage, which must be the everyday reality for the local population.

Due to the combined effects of environment (earthquakes, soil settlements, traffic vibrations, air pollution, microclimate, etc.) and lack of maintenance, now most of this heritage is damaged. The issue of structural safety is, of course, a primary requirement, particularly in seismic zones, see [1,2]. But the adoption of appropriate remedial measures and the elaboration of plans for the rehabilitation of historical centres call for comprehensive surveys of the existing built heritage, details of materials, prevalent damage, building typology, living conditions, etc.

Humidity is a major source of problems in buildings worldwide. Moisture can damage the building structure, the finishing and furnishing materials, [3,4] and can increase the heat transfer through the envelope and thus the overall building energy consumption [5]. Besides being a direct cause of human discomfort, high indoor humidity promotes mould growth, which can have

*Corresponding author. Tel.: +351 253 510 200; fax: +351 253 510 217.
E-mail addresses: pbl@civil.uminho.pt (P.B. Lourenço), eduarda@ipb.pt (E. Luso), malmeida@civil.uminho.pt (M.G. Almeida).

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adverse health impacts on the occupants [6,7]. Moisture-related problems are generally more severe in residential buildings due to the absence of air conditioning and presence of more intensive moisture sources. Moisture problems are also intensified when there is a deficient (or even lack of) insulation of the envelope and when no heating is provided on a regular basis, which is the case of the historical centre considered as case study.

The present paper addresses both the issues of detailed characterizations of the urban composition of a Portuguese historical centre and hygrothermal indoor conditions. Damage survey in the building envelope and indoor is addressed, and, for a selected sample, measurements of the room temperature and relative humidity were made during the most grievous season (winter). An accurate characterization of the indoor building environment and of the construction characteristics of the building components, such as done here, are an essential step for the preservation of the built heritage and for the selection of adequate remedial measures.

2. Materials and methods

The investigation was carried out sequentially in consecutive steps and using three levels of refinement. The consecutive steps were: (a) building typology (Section 3.1), (b) building materials (Section 3.2), (c) damage survey in the building envelope (Section 3.3), (d) indoor survey of hygrothermal conditions and damage (Section 3.4).

The first level of refinement was the entire classified historical centre area, and the objective was to address the building typology (Section 3.1) and the building materials (Section 3.2). The investigation was carried out using the general plan of the area, available from the Municipality, and visual observation from the exterior. The historical centre possesses two clearly different distinguishable areas (inside and outside the walls) and the building typology and materials have been addressed independently for each area.

A second level of refinement had to be used for the subsequent step of damage survey in the building envelope (Section 3.3), due to the relatively large size of historical centre and the available resources. In this case, the complete area inside the walls and two main streets have been selected for further analysis in the building envelope. Again, only visual inspection from the exterior was carried out, using a classification of damage rooted in the literature and the defects found in the first level survey, previously carried out.

Finally, a third level of sample refinement was considered, aiming at analysing the indoor conditions of the building stock (Section 3.4). For this purpose, around 25% of the houses inside the walls have been selected with the aim of a deeper characterization, with a special focus on damage manifestation, sources of damage and hygrothermal measurements. A special form has been prepared and filled for this sample of sixteen houses, which required indoor observation and an interview with the inhabitants. The measurements of temperature and relative air humidity were carried out for three consecutive days during the coldest period (December to March, 2001), separately in the kitchens, living rooms and bedrooms. The equipment used is produced by Testo (Testostor 175-2) and includes an internal sensor to measure air temperature and air relative humidity, internal memory and a battery. The readings can be afterwards downloaded to a PC. The precision of the equipment is $\pm 0.5\,^{\circ}\mathrm{C}$ for the air temperature and $\pm 3.0\%$ for the relative humidity. The readings have been registered every hour and the equipment has been always placed 1.0 m above the floor level, so that the different results can be compared.

2.1. Characterization of the historic centre of Bragança

The city of Bragança is located in the North-East of Portugal and old documents refer that Bragança was already inhabited in the first century BC, even though the first walls of the Castle date from the 12th century [8]. Being located far away from the large cities and the Atlantic coast, with difficult access through a mountainous region, the city was never wealthy and powerful. This fact resulted in ancient buildings being mostly simple and modest, even though some monumental buildings exist.

The classified historical centre area is a total of $0.33\,\mathrm{km}^2$, 724 houses and 1087 inhabitants, see Fig. 1. Two areas are clearly distinguishable: one inside the walls (Citadel) and another outside the walls. The Citadel is the oldest part of the city, which later grew outside of the walls with more spacious and wealthier houses.

The climatic conditions are rather harsh with considerable rain (an annual average of 800 mm, mainly between October and May) and cold temperatures in the winter (the number of degrees-day, on a $20\,^{\circ}\mathrm{C}$ base, is 2850 and the heating season duration is of eight months), see also Fig. 2.

3. Results and discussion

3.1. Building typology

Housing is always the result of a multiplicity of several interrelated constraints, reflecting natural and historical conditions, building techniques, economical and social structure, profession, family requirements, aesthetics and feelings, especially group feelings of the people that built the house and live there. These

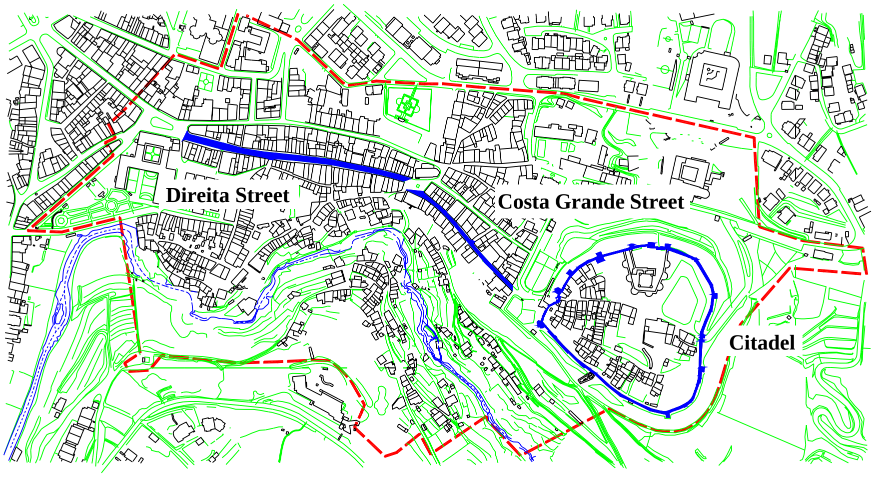


Fig. 1. Map of the historical centre, with the definition of the protected area (inside dashed line), two major streets (Direita and Costa Grande) and Citadel (inside walls).

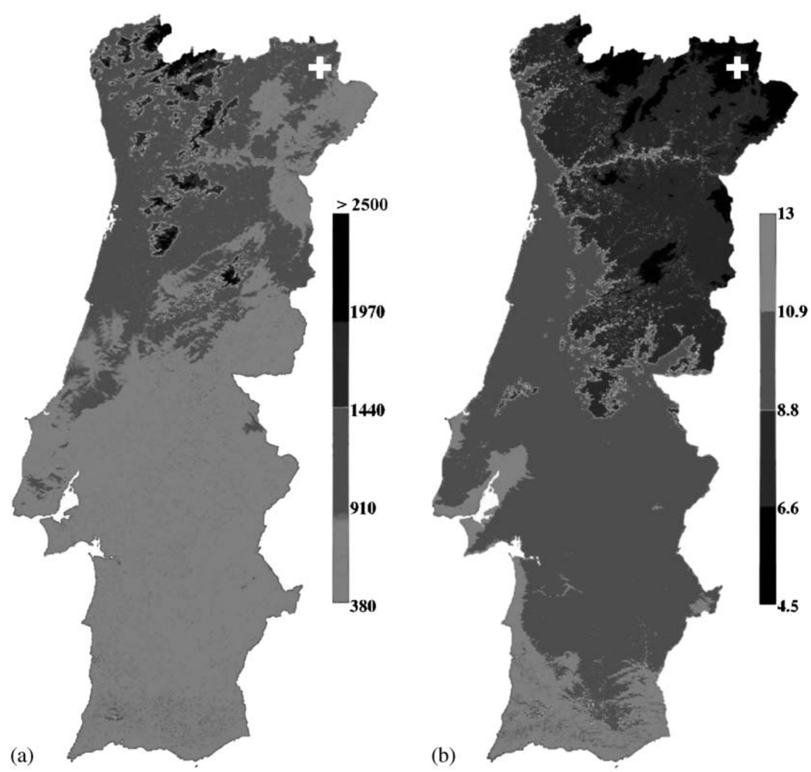


Fig. 2. Rain and temperature average annual maps for Portugal [9], with the location of Braganca (+): (a) total rain (mm); (b) average minimum daily temperature (°C).

constraints mean that it is rather difficult to define building typologies for a given compound.

Nevertheless, in the case of Bragança, it is possible to clearly distinguish different building typologies inside and outside the walls. The houses of the Citadel (inside walls) are predominantly detached or semi-detached with one or two floors, plane façades and double sloping roof, and simple construction, see Fig. 3. The average in plan size of the houses is only 54 m^2 (minimum of about 20 m^2). An internal floor is also common, dividing the single-floor house partially in two and taking advantage of the sloping of the roof. Even if a fireplace is usually present for heating, for food preparation and for food preservation (smoked meat), these houses do not have chimneys. A ceiling is also usually not present, and the timber truss and the roof tiles are visible from inside. In some houses, a couple of tiles in the roof are removed to facilitate the expulsion of the smoke.


(a)


(b)

Fig. 3. Examples of typical houses in the Citadel (inside walls): (a) one floor; (b) two floors.


(a)


(b)

Fig. 4. Examples of buildings outside the walls: (a) commerce and housing building; (b) noble house.

Outside the walls, the city grew in the background of a wealthier population occupied in trade and small industry. Historically, it was possible to avoid paying city taxes here, which promoted the development of the city outside the walls. These buildings diverge from the intra-walls typology and it becomes difficult to find similarities among the different buildings, see Fig. 4. The average in plan size of the houses varies from 120 to 630 m^2 and a more sophisticated architecture can be observed. Bourgeois and noblemen houses can be found with a large scatter in size, openings, type of balconies and ornamental elements of the facades. Nevertheless, semi-detached houses with two or three floors exist, with front aligned facades and building width around 15 m. The first floor was usually used for commerce and the upper floors were used for housing.

Only a few examples exist of very slender houses, which proves that earning space by adding extra floors was hardly necessary because there was no pressure for additional housing. The few of such houses are located in the Direita Street, which was rather commercially active in the 18th century [8], with shoemakers, tailors, potters and other craftsmen.

3.2. Building materials

Masonry and timber are the oldest building materials that still find wide use in today's building industry. Naturally, innumerable variations of these materials, techniques and applications occurred during the course of time. The influencing factors were mainly the local culture and wealth, the knowledge of materials and tools, the availability of material and architectural reasons [10]. For vernacular architecture, traditional building materials are almost exclusively local materials, usually used without much processing or with a minor improvement using elementary tools.

The external walls of the ancient buildings in the historical centre of Bragança are made of irregular masonry, see Fig. 5. The stones, in granite and schist, are of variable size, sometimes with stone slabs used as an external ornament. Small stones and brick fragments

Fig. 5. Typical examples of masonry for external walls.

are used to fill larger voids, with joints made of clay or clay–lime mortar. Walls are, usually, rendered with lime mortar and painted with limewash, creating flat and white façades. Timber (or, rarely, stone) lintels strengthen window and door openings. The timber beams that sustain the floors and roofs are supported directly in cavities in the external masonry walls.

The internal walls can be built with two different techniques. One of the techniques, usually called bulkhead, consists in the construction of a structure with wood boards, placed vertically, with a second set of boards nailed diagonally. On top, horizontal wood laths, with a cross section of about $2 \times 2\,cm^2$, are nailed with an interval of about 4 or 5 cm, see Fig. 6a. Then, the surface is plastered and painted with limewash. Although, this building technique is more frequent in internal walls, it is also sometimes applied in external walls. A second technique consists in the construction of a rectangular frame of timber beams, with the empty space filled with a second material, usually mud and straw, see Fig. 6b.

It is noted that the noble houses are practically the only ones using granite in the external walls, because granite is not readily locally available.

3.3. Damage survey in the building envelope

In order to characterize the existing damage in the building stock, eight groups of damage were considered in the envelop of the buildings, see Fig. 7: (a) collapsed structures, (b) bulging walls, (c) stains on walls at soil level, (d) detachment of rendering and painting, (e) cracks, (f) mould, fungus and vegetation, (g) roof deterioration, and (h) timber deterioration in openings frames or balconies. A more comprehensive

(a) (b)

Fig. 6. Example of internal walls: (a) wooden lath walls and (b) "fachwerk" type.

classification of defects can be found elsewhere [4]. The results of the survey are merely qualitative, as a detailed quantitative evaluation of the building stock is outside the scope of the present work.

Three different areas from the historical centre were selected for analysis, namely the complete Citadel (inside walls), and two streets outside walls (Costa Grande Street and Direita Street), see Fig. 1. The results from the survey are given in Fig. 8. It can be observed that significant damage is present in the sample, in almost all non-structural items. This means that the presence of the different types of damage occurs simultaneously as a result of lack of maintenance. It is possible to see that in about 40% of the cases, cracking, deterioration of wood and deterioration of rendering, are present. In the structural items (collapse and bulging of walls), the situation is not severe, with the exception of out-of-plumb walls in the Citadel.

The damage in the Citadel is almost always larger than the damage outside the walls. This occurs due to the fact that the buildings in the Citadel are older, are of poorer construction and are more abandoned, meaning that maintenance is less effective here. The sole exception is cracking damage, which is higher in buildings located outside the walls, due to the usage of new cement-based renderings. This is confirmed by the fact that the rendering and painting damage in the Citadel is similar to the walls outside; as this is not expected, it seems clear that incompatible materials are being adopted for the rendering and painting.

In the Citadel, 52% of the houses present wall strains at soil level, caused by rising humidity and rainwater splashing. It is stressed that 43% of the building do not exhibit gutters and 13% of the buildings have an incomplete downpipe [11], see also Fig. 9. The bulging damage of the walls occurs essentially in buildings with at least two floors, and the 25% value found indicates that detailed structural inspection and diagnostic of the Citadel is needed. It is also stressed that cracks with large width were found in the Citadel, confirming the presence of structural damage. Adequate recommendations for methodology and remedial measures in these cases have been recently published by ICOMOS [12].

Fig. 7. Example of damage: (a) collapsed structures, (b) bulging walls, (c) stains in walls at soil level, (d) detachment of rendering and painting, (e) cracks, (f) mould, fungus and vegetation, (g) roof deterioration, (h) timber deterioration in openings frames or balconies.

Fig. 7. (*Continued*)

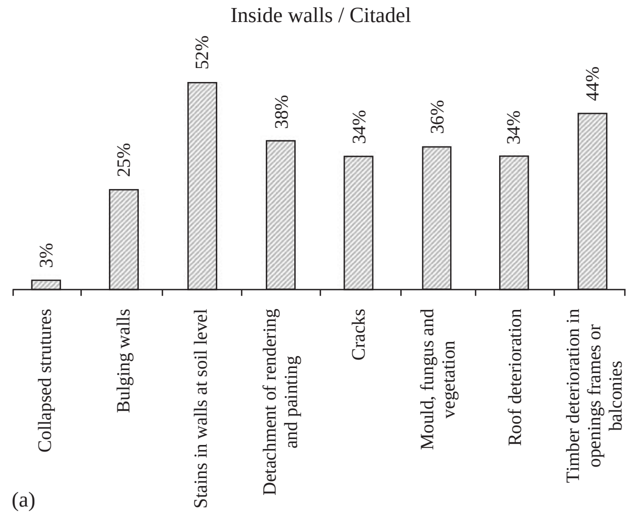
In conclusion, the water-related problems in the building envelope can be confirmed as the single most important defect. In the facades, it is possible to observe the existence of damage originated essentially by humidity, which appears in several forms, namely humidity caused by rain, by infiltration from the roof, by leaking connections and from rising damp. Humidity is both responsible for deterioration of the materials, namely rendering, painting, metal and wood, and for damage of the structure due to larger thrusts of the deteriorated timber elements and increased deformation of masonry elements.

3.4. Indoor survey of the Citadel

In order to better understand the living conditions of the occupants and further study the water-related problems, a sample of 16 houses located in the Citadel was selected for further study, see Fig. 10. The sample represents 25% of the total inhabited buildings in the Citadel and 15% of the entire stock (it is stressed that despite the damage detailed in the previous Section, 61% of the houses in the Citadel are still occupied). The selection of the Citadel as a smaller case study was due to the fact that defects are in larger quantity there and the building stock is of moderate size.

In the smaller sample, the following data was gathered for each house in a specially developed form, see Fig. 11: (a) plan location in the Citadel, (b) orientation of the facade, (c) characteristics of the sun exposure, (d) number of occupants, (e) presence of water, sewage and rainwater systems, (f) characteristics of the ventilation systems, mainly in compartments with larger production of moisture, (g) type of heating system, (h) presence and type of toilets, (i) type and thickness of walls, (j) type and conservation state of the roof, (k) details on previous repairs, (l) other remarks.

Inside each building, damage was characterized with respect to the presence of humidity stains and efflorescence in the wall (dimension and location) and the development of mould. In addition, hourly measurements of the room temperature and relative humidity of the air were carried out, in three consecutive days during the winter period. As an example, Fig. 12 illustrates the results for a house without bathroom, with kitchen and two small bedrooms. Fig. 13 shows photos of damage



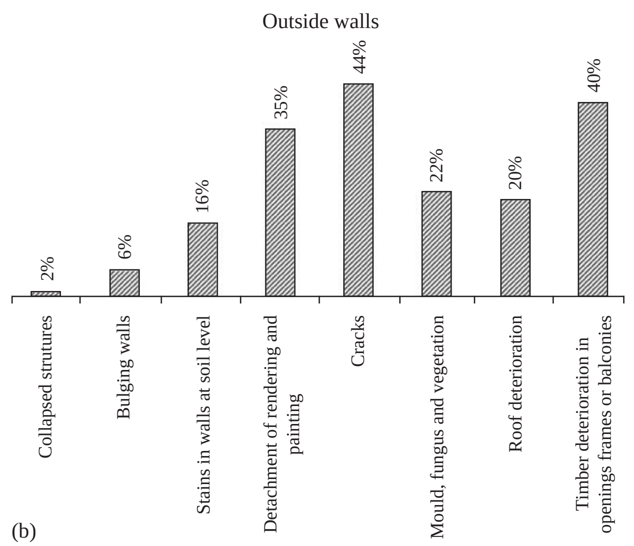


Fig. 8. Damage survey for the historical centre of Bragança: (a) inside walls and (b) outside walls.

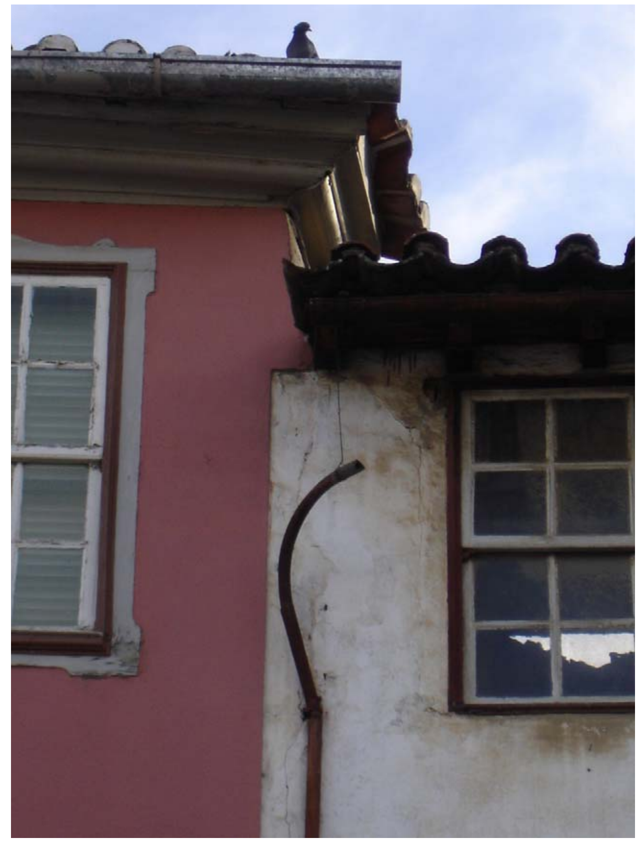


Fig. 9. Typical example of a defect in a downpipe.

observed indoors: (a) biologic activity, (b) stains due to humidity, (c) timber and roof deterioration, (d) detachment of rendering and painting.

3.4.1. Global analysis of the results

The analysis of the data from the 16 houses in the sample allowed pointing out the following aspects:

- The occupation of buildings is rare. Only 151 inhabitants live in the Citadel, which represents an average of three people per house. Twenty-one of the inhabitants live alone (15 female and 6 male), which represents 14% of the total. Therefore, overpopulation is not a cause for water condensation.
- There is an evident lack of ventilation with 87% of the houses having at least one internal compartment without any ventilation system. Usually, ventilation resorts to occasional opening of windows and, often, there is no mechanical exhaust system even in the kitchen.
- Solar gains are very low. Most houses have an East–West orientation but narrow streets induce shading and prevent sun exposure.
- Heating systems are low tech and not continuously functioning, which is common in Portugal. Heating occurs exclusively in the compartments under use and only when the occupants are there.
- Gas heating system is mostly used (50% of the cases), often combined with wood and electricity systems. This causes an increase of the water vapour in the air.
- During the winter, air drying of clothes occurs inside the houses, which is a major source of moisture [13,14]. Bathrooms are not present in 21% of the houses.
- The area of the compartments is usually very low. As an example, the bedroom area is, on average, only 8 m^2. In many cases, the kitchen and the living room are parts of the same compartment.
- Roofs are very deteriorated, with broken tiles and severely damaged timber elements. Frequently, downpipes do not exist and, if present, they are normally obstructed, severely damaged or incomplete. In some cases, the windows and doors frames are also very deteriorated.

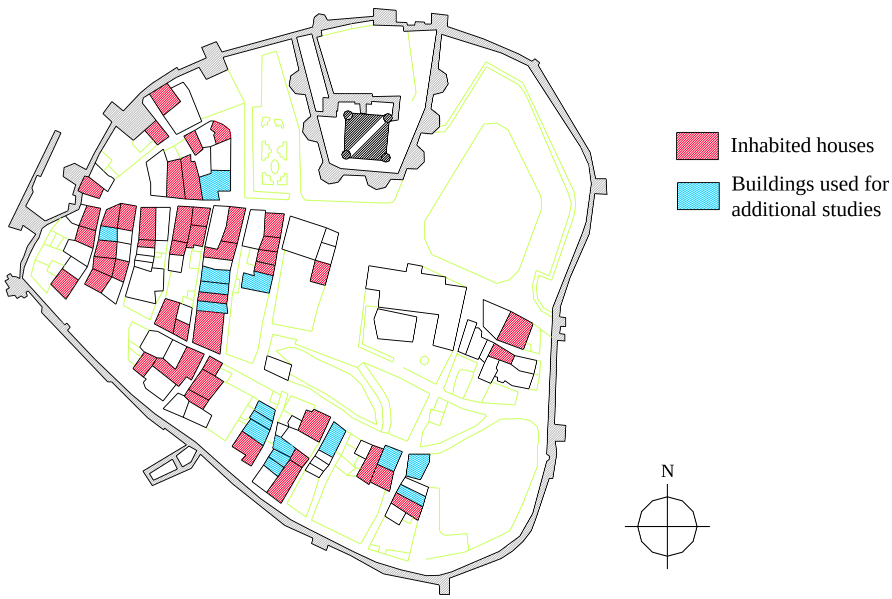


Fig. 10. Location of buildings for additional studies, in the Citadel.

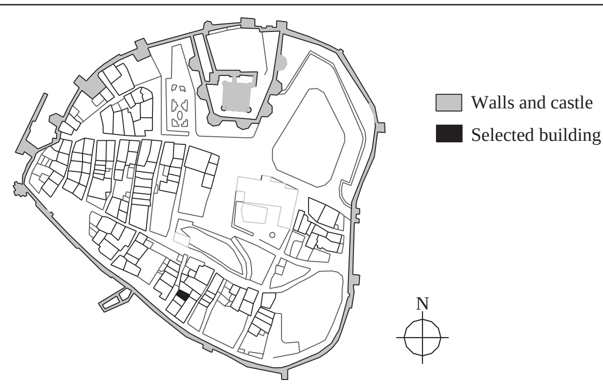
Location:	
Orientation of the façade:	Northwest
Sun exposure:	Bad
Number of occupants:	1
Systems:	Water, sewage and rainwater
Ventilation:	Two internal rooms without ventilation
Heating System:	Gas
Toilets:	Only a water closet, nearby the entrance door
Walls:	Externally: stone masonry (schist/granite); 60 cm thickness Internally: bulkhead; 15 cm thickness
Roof:	Ceramic tiles, reasonable condition
Previous repairs:	The only window of the house was replaced by aluminium frame; zinc foil was added under the tiles to prevent rainwater fall
Remarks:	The building is in bad conditions, with respect to comfort and maintenance; Extensive mould is present, with characteristic smell; no ceiling is present

Fig. 11. Typical form for detailed survey of building in the Citadel.

- The attempts to obtain better housing conditions occur without appropriate technical support, using remedial measures such as aluminium window frames and placement of water-vapour-proof linings in the roof, which, in most of the cases, aggravates the already deplorable conditions of these residential units.

3.4.2. *Analysis of hygrothermal measurements*

The three-day temperature and humidity records from the 16 houses in the sample allowed pointing out the following aspects, see also Table 1.

- Very low temperatures were recorded in the winter, particularly in rooms seldom used. The heating system

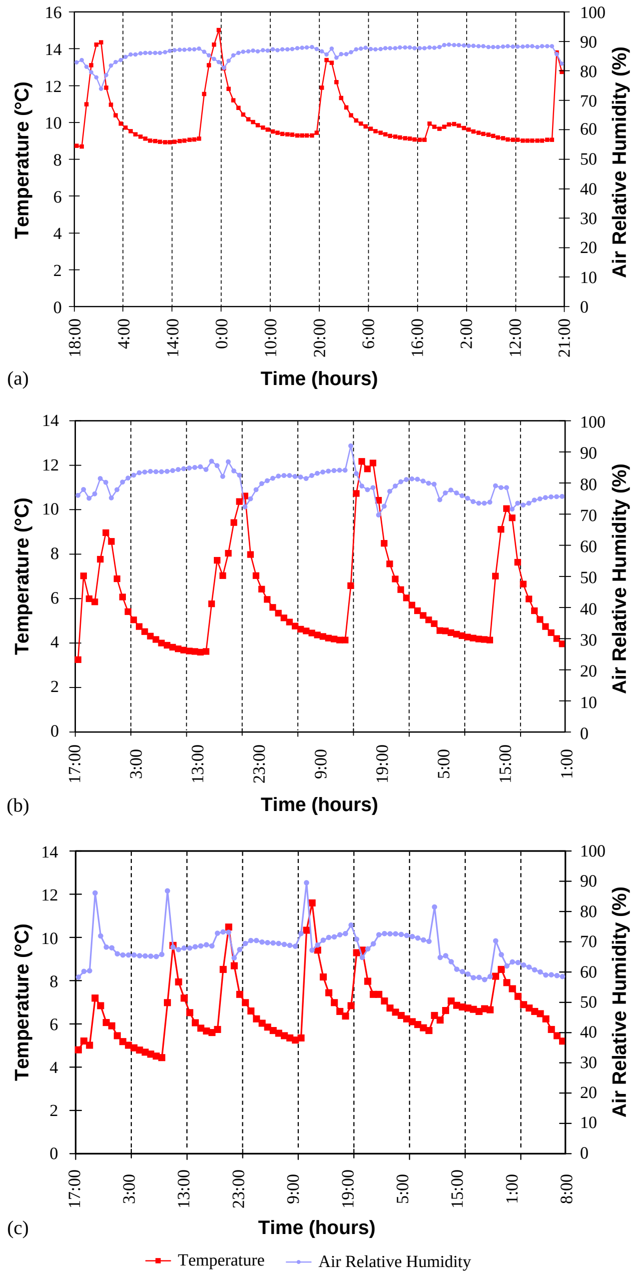


Fig. 12. Examples of graphs recorded in the sample buildings: (a) living room, (b) bed room, and (c) kitchen.

is localized and is used only in the space where the occupant is, and only during his presence. Internal temperatures around 3 °C were observed in empty compartments, for a global average of 6.7 °C. The temperature is higher in the compartments used during the day, namely kitchens and living rooms, although still very low (about 9–10 °C). The external temperatures in this period were around −5 °C (minimum) and 6 °C (maximum).

- The relative humidity is inversely proportional to the temperature, being higher in the coldest spaces and lower in places where the temperature is higher. The relative humidity of the air in the houses assumes, in general, values above 75%. In the houses where the fireplace is used as a heating system, the relative humidity values were lower.
- The indoor temperatures are, frequently, very close to the exteriors ones, which is also a consequence of the poor quality of the building envelope, being considerably below the minimum acceptable temperatures of comfort.

3.4.3. Damage manifestations

According to the survey, the most frequent defect is the emergence of pathological manifestations in the upper part of the walls that are in contact with the exterior or with a contiguous building. These moisture manifestations include stains, sometimes accompanied by mould. This type of biological colonization appears nearby the windows and doors frames, also corners or roofs, accompanied often by a strong odour.

Defects and deterioration of the roof is the major cause for water leakage and building pathology. Mould is usually associated with compartments with large production of water vapour, such as kitchens and toilets, but it occurs also in bedrooms and living rooms in the present case study. Condensations are also visible in coldest zones and non-ventilated places. In underground walls, deteriorated paintings, detachment of rendering and formation of efflorescence with high presence of salts were found.

4. Conclusions

The present study adopts a historical centre in Northern Portugal as a case study. For the building stock, the study presents a survey of defects in the envelope, a survey of indoor defects and comprehensive measurements in indoor air temperature and relative humidity. The results indicate extensive damage in the envelope mostly due to cracking, deterioration of wood and deterioration of renderings. Water-related problems can be confirmed as the single most important defect, which are combined with inadequate sun exposure, ventilation and heating, and excessive moisture indoor production. Therefore, the indoor quality of life of the inhabitants is compromised by extremely low temperatures, high humidity and presence of mould. The present situation is typical of historical city centres in Northern Portugal, characterized by considerable rain and cold temperatures.

In the specific case of buildings in the Citadel of Bragança (oldest part), urgent repair is needed at many levels, with a special focus on: (a) construction of toilets, when absent, (b) repair or substitution of roofs, (c) conservation or substitution of renderings. Most of the existent pathological manifestations are caused by infiltrations of water through the roof or the facade and

Fig. 13. Examples of the damages observed inside the houses: (a) biologic activity, (b) stains due to humidity, (c) timber and roof deterioration, (d) detachment of rendering and painting and efflorescence with high presence of salts.

Table 1
Summary of temperature and air relative humidity values, sorted by compartment type

	Building	$T_{\min}$ (°C)	$T_{\max}$ (°C)	T_{average} (°C)	$Rh_{\min}$ (%)	$Rh_{\max}$ (%)	Rh_{average} (%)
Bed room	E86	8.0	9.7	8.9	68.9	78.9	73.6
	E74	6.0	7.6	7.0	61.6	77.3	72.1
	E68	3.7	9.9	4.7	41.6	72.3	65.5
	E42	2.7	4.8	4.0	58.3	88.9	79.3
	E87	3.3	12.2	6.0	69.7	91.9	79.7
	E92A	4.0	10.1	6.2	57.2	84.4	75.9
	E92B	1.8	9.9	5.4	58.9	87.8	78.5
Average bed rooms		—	—	6.7	—	—	71.3
Living room	E74	1.8	7.2	5.3	72.9	85.7	79.7
	E68	4.8	9.2	5.9	38.3	61.9	55.5
	E40	9.5	12.1	10.7	75.4	87.6	81.6
	E78	4.4	10.0	6.2	58.0	85.7	76.4
	E51	8.7	15.0	10.1	73.9	88.9	86.4
	E39	9.8	11.5	10.7	72.3	86.6	75.8
	E73	9.3	13.6	10.3	71.9	84.3	80.4
	E71	8.0	14.2	10.3	72.5	83.5	77.8
Average living rooms		—	—	9.3	—	—	75.0
Kitchen	E86	9.3	10.2	9.8	68.5	72.8	71.3
	E74	2.2	6.9	4.8	72.1	78.2	76.7
	E68	11.9	18.8	15.7	31.0	42.7	38.0
	E91	6.5	9.4	8.1	80.9	90.1	84.7
	E40	11.9	15.6	13.5	67.0	90.4	75.3
	E88	4.4	11.6	6.6	57.7	89.5	67.7
	E11	11.9	13.2	12.6	72.4	85.5	76.8
Average kitchens		—	—	10.3	—	—	71.3

by condensation phenomenon, creating unhealthy conditions for the occupants. The water infiltration can be avoided by the above remedial measures. The condensation phenomenon is related with the occupants' habits (punctual heating using gas equipments and drying clothes inside the house in the winter, which produces enormous quantities of vapour) and with the characteristics and poor quality of the envelope (lack of ventilation, reduced fenestration, reduced or inexistent solar gains and no thermal insulation). Repair measures must, therefore, also provide ventilation, thermal insulation and proper heating systems.

Finally, it is noted that the modern approach towards the conservation of cultural heritage buildings, made using old materials and old construction techniques, require low invasive and, mostly reversible, techniques. An appropriate knowledge and a good coordination between all agents involved in the rehabilitation of historical city centres is a key aspect to reach adequate and effective solutions.

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