

576: Embedded Stone Wall Construction in Lisbon

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Most of central Lisbon has been built over the last 200 years, after a massive earthquake and tsunami destroyed its medieval city centre in the eighteenth century. Rebuilding from 1755 took as a model a prefabricated four-storey building of wooden structure encased by external walls of embedded stone. An analysis of 500 of these structures has shown that there have been few changes or modifications to the basic construction, the model clearly withstanding the passage of time. This paper focuses on the potential of existing environmental features for passive solar retrofitting design measures in these buildings. The paper is structured in six parts: the first part contains the introduction, followed by the historical context, the third describes the existing study model, the fourth explains its construction characteristics, the fifth examines the existing environmental features and the sixth includes design measures for environmental retrofitting of these buildings.

Keywords: solar passive design, comfort

1. Introduction

The content of this paper is part of a PhD research study based on the analysis of 500 buildings with unique construction characteristics built over 200 year ago in the centre of Lisbon along a 5km route, Fig. 1. The research focuses on the potential of existing environmental features for passive solar renovation design in these buildings. The findings will then serve as a basis for the development of a methodology/strategy to improve, modernise and/or preserve these structures where they are valuable, taking current needs into account and making use of new and innovative technologies available in the market today. The basic model was also built by Portuguese master builders around the world (Brazil, Angola, etc.) and the formulation of a global environmental methodology could prove to be an invaluable tool for the upkeep of these buildings worldwide

The study area is the perimeter of the area affected by the earthquake on 1 November 1775 in the city of Lisbon. This is estimated to have been at scale IX (of XII) of the Mercalli scale or 9 (of 9) magnitude of the Richter scale and was felt as far as Rabat, Meknés, Fez, Larache and Arzila.

The starting point for the chosen perimeter is the Tagus river to the south of the city centre (known as the *Baixa* – downtown) along the western line of the old city walls to the old north city market before reaching the eastern slope below the St Jorge Castle and ending at the main city square by the river. The route height above sea levels fluctuates from 4m to 65m giving a variety of locations with different orientations and climate conditions to study.

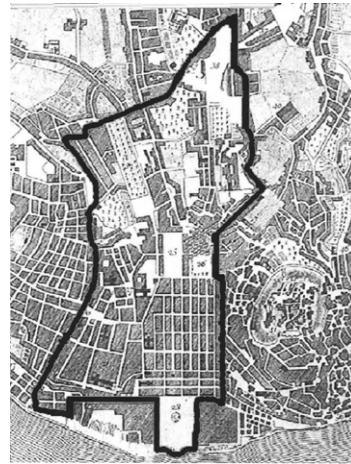


Fig 1. The route mapped out on an 18th Century map of Lisbon. Map extracted from source [1]

Due to Lisbon's 7-hill location, many of these buildings had to adapt to the terrain and abandon the flat *Baixa* style, thus creating a variety of off-shoot styles, some with no basement, others with one or more, some with façades exposed to the sun's rays, others with the back built into slopes. This 5km perimeter route with 545 buildings is punctuated by 7 key points – some open squares, some closed in ones, some with gardens, some paved in, some in the valley, some at hill tops and some by the river, Fig. 2. They stand approximately half a kilometre apart and together they form 10kms of façades to be studied. These are being analysed in terms of original and increased heights, original and new construction, external finishes to walling and roofing, number and type of openings at wall and roof level, overall conservation and demolished plots.

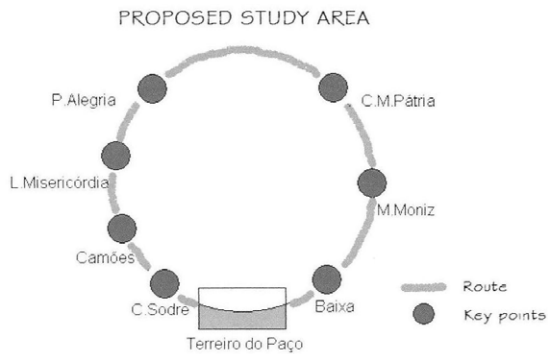


Fig 2. Key points along the study route

2. Historical Context

The buildings studied in this paper have a construction technique very much of their own, first developed in Lisbon for the reconstruction of the medieval city centre devastated by an earthquake and tsunami in the mid-18th century, which killed ten thousand of its quarter of a million inhabitants. The model developed and tested on the public square before King José I was conceived by Manuel da Maia to be applied to his 1758 new city plan [2]. Maia had been the master architect for three consecutive reigns and had been teaching the art of fortifications building techniques for 30 years and was also an expert at river bed hydraulic construction. Along with three of his best students, he devised an anti-seismic wooden four-storey cage made of timber pre-fabricated elements for both structure and foundations, creating a flexible building able to react and adapt easily to earth tremors. This was to be the base model for the buildings and the first large scale European exercise in city planning.

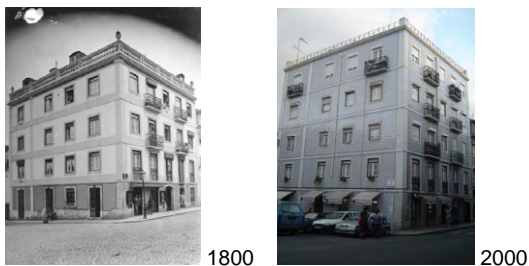


Fig 3 The same building – new height and awnings. Source [3]

The plan in Fig. 4 shows the interlocking relationships of a clearly defined urban fabric. Original buildings stand beside some that have been extended, others that have been given new uses, and empty plots where new structures will be slotted in. The route used for this study provided enough buildings to gauge the evolution of the original model and it is very clear how well it has withstood the passage of time.

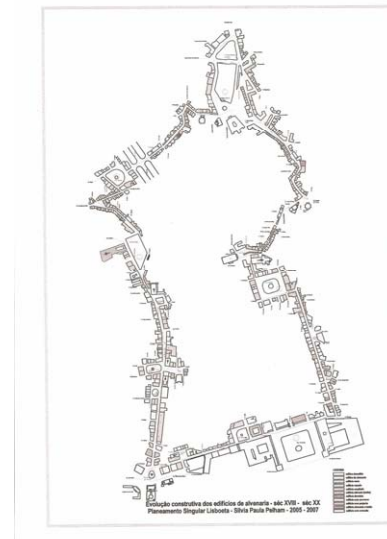


Fig 4. Variation to the model over 200 years

3. The Original Model

The design of the façades and the building volume established allowed for generous floor-to-ceiling heights and were set at the start by the architects, Fig. 5 and 6. The master builders had the freedom to design the non-loadbearing internal partitions at will and as was convenient to their future users.

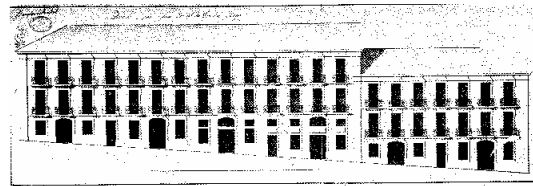


Fig 5. Typical 18th century façades. Source [3]

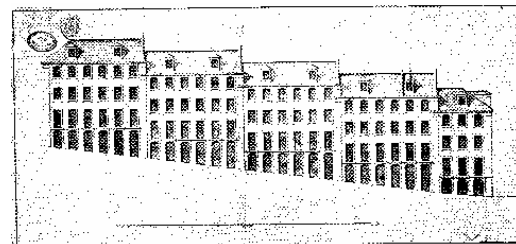


Fig 6. Façades adapted to the city slopes. Source [3]

Three main types of façades were designed with 22 variations, 52 types of windows, 34 types of doors, 4 types of *Mansard* openings and 13 types of roof openings.

The plan measurements varied too and were chosen according to their location: on major thoroughfares (with vehicle and pedestrian circulation – the latter protected by arcades), on secondary roads, outside the controlled city centre planning layout, at the centre of a city block or at the corner of a block.

Plan A, 11.8x11.8 with 4 windows increased to 12.8x12.8 if it turned the corner and automatically had a right to its own patio; B, 17.4x11.8 had six windows whereas C, 20.8x12.8 had 7 and

enough depth to turn a corner with 4 more windows and patio; D, 23.8x12.8 had 8 windows and did the same and finally D, the odd one out, 12.8x6.8, 4 front windows and 2 side ones, although it turned the corner could not fit a patio, but appeared quite often as a filler to the various block designs.

This allowed the city to develop a uniform and harmonious town planning system, set within controlled design parameters and allowed master builders to initiate, develop and complete their buildings quickly and without further control, thus speeding up the whole reconstruction procedure.

This construction method, called the *Pombalino* (in reference to the Planning Minister at the time the Marquis de Pombal), was used throughout the city until 1830. From that date onwards it started to be simplified both in terms of the quality of the wood employed (and as the construction moved away from the river's influence) and its connections, with a new style emerging, the *Gaioleiro* (a depreciative term from the original *Pombalino* cage style the *Gaiola*). This model also spread to the rest of Portugal and was taken by master builders to the countries where the Portuguese arrived over the years to inhabit and trade. Apart from Europe we can find them in Africa, South America and as far away as Macao in China. But by the mid-20th century, as the memory of the earthquake and tsunami grew fainter and economic pressures set in, the anti-seismic structure designed to withstand an earthquake of the greatest magnitude, by simply shaking and detaching itself from its envelope and internal walling structure, leaving it standing alone, pristine and intact, was abandoned.

The ubiquitous concrete structure arrived and prevailed ever since.

4. The Construction

4.1 Infrastructure

The decision makers had to act fast at the time of crisis. They decided to demolish all the still standing structures and use the rubble to alter the topography of the town, raising its bed by nearly 10 metres and placing the new town 4m above sea level. They also decided to use wood pile foundations not to take the load of the new buildings but to make sure there were no land slides or side movement below the rubble. These piles, 150/200mm in diameter and placed at 400mm/500mm centres, were cut from young pines still full of sap, which turned impervious to damp and went down from 9m to 23m, by the river bank to the middle of the valley, depending on the position of the bed rock, Fig.7.

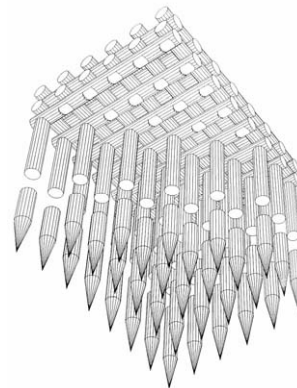


Fig 7 Rafting and pile foundations. Source [4]

Once the piles were in position, a massive 5-tier wooden raft made of 200/300mm *Pinus pinaster* trunks was built across the whole site, acting as a continuous foundation stabilising the base for the re-birth of the new town. Cut-stone pillars sprung from the raft below to take the structural walls and the buildings started to take shape.

4.2 Superstructure

This ranges from one to six stories although the original module had four.

The wooden cage was developed using the artistry and long experience of naval carpenters of this seafaring nation which were transferred from the shipyards to the building site. The initial wood was all autochthonous, *Quercus pedunculata*, *Quercus suber*, *Quercus ilex* (oaks) and *Castanea sativa* (chestnut) for the 130x150mm columns and the 100x130mm beams (approx. measurements) but as work progressed wood was needed from all over Europe, especially *Larix decidua* (European Larch) and the Nordic *Pinus sylvestris* (wild fir from northern Europe). The final structure formed a single interwoven wooden cage holding the wooden floors and roofs, Fig. 8.



Fig 8 The wooden structure

Lioz, the local lime stone, surrounded windows and doors, structured the corners of all buildings as well as vertically separating façades at the limits of building plots.

4.3 Walls

Walls continued to use rubble from the demolished buildings as the foundations had. As such they were mixed with lime and red sandy clay in 200/300mm layers. Fig.9. They started at 900mm-1000mm at the lower levels and diminished in thickness as the building rose, carrying less weight, to finish at 300/400mm at roof edge, with parapet under the windows switching to ordinary solid brickwork infill. Internal partitions vary little as the model progresses through time. Those on the structural grid are built of embedded stone of smaller calibre or turn simply to solid bricks. These can also be found in the kitchen area, supporting marble slabs for stoves and sinks or at loft level separating two adjacent buildings or at roof level acting as fire stops.

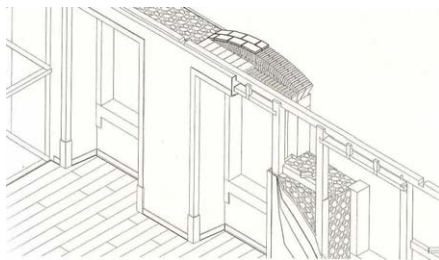


Fig 9 Section showing external embedded stone wall and wooden cage. Source [5]

4.4 Roofs

These are very simple and can have habitable lofts and their shape depends on the age of the building. The original model had a pitched roof with a reasonable height due to the depth of the building and the inclination needed to shed rain water but Mansard (a French engineer working in Lisbon) lifted the original structure even further by doubling the single pitch, allowing doors and balconies to be inserted to the perimeter of the roof. This allowed developers to entice prospective buyers to climb up four stories in search of a desirable view over the city.

5. Existing Environmental Features

5.1 Ventilation and Heat Control

5.1.1 External Layout

As urban planning goes, climbing and descending slopes with different orientations mean that the buildings can easily create external spaces between them and along the contours. These patios or terraces act either as ventilation shafts or as air stabilizers, enhancing or minimizing air temperature differences in cross ventilation systems throughout the year. Side entrances usually mean a passage through to a back yard and are increasingly being opened to allow air intake to the otherwise stuffy and unventilated block interiors.

5.1.2 Internal layout

Most buildings have a central entrance with individual dwellings to either side, with access

staircase with front and back openings and clearstory roofing for ventilation. If the plot is long and thin, internal rooms occupying its hub will have no windows to the exterior. Ventilation will be borrowed from adjacent rooms either by opening sashes above the doors or a high level opening on the dividing wall. If the plot is short and wide, ventilation will be provided through a central opening, the "saguão", Fig 9. This opening was usually small and deep and was designed to provide light and ventilation into adjacent rooms, and was part of the innovative sewage system as well.

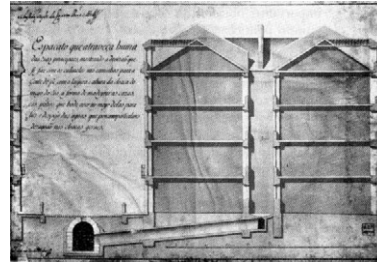


Fig 10 Section showing "saguão" and sewage system 18th century. Source [6]

5.1.3 External walls

External wall width in the original 18th century model diminished to half its size by the mid-20th, reducing its thermal inertia. Air temperature differences are acceptable in summer but uncomfortable in winter. Parapet walling under windows with reduced wall thickness offers even less protection from the exterior and on upper levels air temperature is uncomfortable both summer and in winter.

5.1.4 Lower floors

Most ground floors for commercial purposes and those built into slopes or with basements are usually made of solid *Lioz* slabs over *abobadilhas* (interlinking stone arching spanning between brick tiling filled with rubble over loadbearing walls). These are usually well above street level, allowing unilateral ventilation into basements as well as keeping a constant temperature throughout the year. Habitable ground floors are made of wood and are well above road level, reached by three to ten or more steps, depending on topography and width of plot. This change in level places in effect the building on an air-bed cross-ventilated platform, from street to back garden or yard, allowing the structure to breathe and stay healthy.

5.1.5 Upper floors

The upper floors are punctuated by rows of windows, the richer ones coming down to a stone based veranda protected by open latticed founded iron balustrades for older models and wrought iron ones for modern ones. The balconies' depth allows for some pot planting with potential to bring down air temperature locally through plant evaporation. The projection also helps to change air pressure before and after the opening and promote the flow into the building.

These two levels are the most comfortable to be in the summer – the *piano nobile* and floor above. As far as air temperature goes in winter, since they are trapped between the roof space and the lower ground floor, they seem to still be the most comfortable of all.

Many of these balconies have been enclosed over the years, trapping the sun in the summer and heating excessively the interior of the building. In most cases, air conditioning installations followed, to provide better comfort conditions in the summer.

5.1.6 Roofs

Roofs are heavily built with ceramic tiling singly placed on wood rafters. They have little ventilation through roof tiles and usually there is no insulation on the loft floor.

This turns this space and adjacent floors into an extremely uncomfortable area both during summer and winter.

Openings, such as dormers, can be very small and with or without parapets. They were typical in the older models of the servants' floors, and provide little or no ventilation.

The *Mansard* model allows for adequate cross-ventilation through its large side doors to the whole loft space.

Openings above stairwells only perform satisfactorily if placed on perforated or grilled upstands which can be left open most months of the year, providing a let-out for stagnant and/or hot air trapped in the interior of the building.

5.2 Daylight and Shading

5.2.1 Lower floors

Doors and windows are evenly distributed along the façades and are normally of solid wood with glazed lanterns to allow lighting into the entrance staircase. If they have no lanterns, a circular or oval opening is punched through the wall for the same purpose. Glazed doors are only found as part of shop fronts and are protected by awnings from direct sunlight. Raised ground floors also allow direct daylight into the basement areas.

5.2.2 Upper floors

Upper floors get more daylight as they rise and are freer of obstructions. Shading is usually provided in the older model by internal wooden shutter doors which can have incorporated a movable opening sash. Newer shading devices include external PVC roller blinds and aluminium shutter doors. Balcony projections also help shade the opening directly below it. It should be noted though that if a patio is not provided in the design and the plot is deep, middle rooms at all levels will be without windows and direct sunlight.

5.2.3 Roofs

These are the better lit areas especially if the roof shape allows for windows and doors. The amount of daylight varies greatly with the orientation of the building but as these spaces are kept as open plan areas, it is relatively easy to keep them well lit throughout the year.

Shading devices are usually in the form of internal awnings and curtains to roof windows.

5.3 Finishings and Colour

5.3.1 External

External walls are sometimes clad in cut stone at ground level, at corners and to separate adjacent buildings. The rest is usually rendered and painted. Stone finish allows damp-proof protection at ground level and lets the wall breathe above it, helping also to prevent condensation. The buildings put up from the middle to the end of the 19th century were clad in *azulejos* (typical Portuguese wall tiles) which were used as a common and inexpensive maintenance technique applied to structures which were already a century old or more. Their reflective characteristics help to bring down the air temperature on the wall surface in the summer, thus reducing the passage of heat into the interior. In winter they protect the surface from rainwater infiltration and helps prevent the appearance of fungus in the interior. A palette of accepted pastel colours was proposed by the local town council to be used at first on buildings on historical quarters but has now become the norm throughout the city. This helps in the summer to reflect the sunlight and bring down the temperatures at the wall surface and also lasts longer. Darker colours fade more quickly and painting is necessary more often.

5.3.2 Internal

All walls are finished internally in the same manner, whether they are external or internal, and the same system is applied to ceilings. Horizontal 40x20mm battening used to support roof tiles is applied throughout the interior surfaces to take stucco and paint. This provides not only good sound insulation but as both walls and ceilings are painted white it also helps to reflect as much light as possible into the dark interiors.

5.4. Services

All services are placed at the rear of the building. Kitchens and chimneys line up with the back wall and either a new extension was built or back verandas enclosed to fit a bathroom in. All domestic drainage flows to the back yards and is directed back to the roads under the building, Fig.9. Only richer buildings have fireplaces. Ordinary buildings do not have any heating devices at all.

6 Measures for Environmental Retrofitting

6.1 The Envelope

6.1.1 External walls

These need to be insulated, especially at higher levels as well as roofs, in order to control air temperature differences between external and internal conditions, both in summer and winter. This can either be done externally or internally, altering existing materials and providing new ways to capture sunlight or heat, maintaining it by accumulation and redistributing it effectively.

6.1.2 Patios and terraces

There should be a way to bring in air and light through the patios, vertical shafts and the external façades into the middle rooms to make them habitable. This could be achieved in many ways from reflective surfaces applied to the underside of existing ceilings to the use of fibre optics for natural daylight and by creating internal vertical ducting with lower and upper openings for ventilation.

6.1.3 Roofs

The roofs are the areas where most alterations need to be done. As has been seen, the structure can take a whole new floor easily, so adapting the roof structure to new uses should be relatively simple and safe. There is no need to lift the structure for there is enough floor-to-ceiling height to fix new internal and external surfaces to the existing wood cage.

6.1.4 Openings

These need to be totally revised. If the wooden structure is to be kept for windows and glazed doors then new glazing methods need to be found to allow for better insulation at this level. Old sashes which were criss-crossed by wood pinnacles and gave some sun protection have been replaced by large single-glazed panes which allow for excessive sunlight and heat to come into the building. Double glazing is a simple, effective but still expensive way to deal with this and practically impossible to place if the original window frame is kept. Other protective ways need to be found both externally and internally which can perform just as well and not alter excessively the design of the façade. The use of insulated shutters, for instance, could be a good solution for insulating during the winter and the cold nights when temperature drops, while allowing daylighting and solar radiation penetration during the day.

6.2 The Interior

6.2.1 Internal walls

Internal walls at the centre of the building need to be revised to allow for natural daylight and ventilation to come into these areas. This can be done either by altering the structure and changing solid materials to see-through ones, opening new passageways by re-organising the circulation areas or simply knocking them down. Most of these walls are built over the floorboards with a simple post and beam structure closed in on both sides by solid vertical or diagonal wooden planks and are very easy to remove. This would also allow heating elements to be placed, new services to run and better comfort conditions all round.

6.2.2 Floors

These should be kept as designed as the basic framework but new finishes need be thought of especially for the central unlit rooms. If the layout is to be kept, these interior rooms could become bathrooms and new drainage systems would

have to be devised. This would alter the finished level of the floors and solutions would have to be found to prevent alterations to common staircase access levels.

Sound and heat insulation should also be thought of in terms of both floor and ceiling new finishes.

6.2.3 Stairwells

These will have to adapt to new fire regulations. One of the requirements is to allow at least one metre square of the glazed stairwell roofing to be operable from the inside and open to the outside. This implies modifications to the stairwell structure and alterations to the top floors connections. With the introduction of natural gas, new ventilation shafts are being placed in this area as well as other common services, reducing the circulation space available. These are just some of the emerging problems with the rehabilitation of these buildings.

7. Conclusions

These structures of embedded stone construction in Lisbon now also represent part of an important cultural world heritage, so preservation is extremely important.

The study demonstrated that it is clear that these structures offer great potential for retrofitting to new uses with relatively easy and inexpensive measures able to modernise the interior while improving environmental performance.

The buildings show valuable design features with potential for environmental improvements for both the summer and the winter periods. In the summer these are mainly due to the structure's thermal inertia and potential for cross-ventilation, but also for the integration of solar control measures, such as the use of shutters and awnings. In the winter the existing structure together with well oriented existing large glazed openings offer potential to help raising internal air temperature to a comfortable level. In addition, the existing model offers various opportunities for exploring solutions for daylighting.

8. Acknowledgements

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