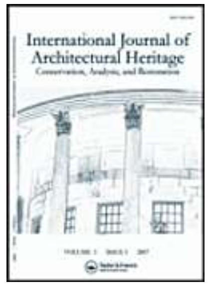

Gaiola vs Borbone system: a comparison between 18th C anti-seismic case studies

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Keywords:	timber structure, earthquake resistant structures, gaiola pombalina, casa baraccata, architectural heritage

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Abstract

A deep understanding of the architectural heritage in all its aspects is essential in order to evaluate a correct conservation and rehabilitation approach.
The heritage rehabilitation requires a careful analysis of the available techniques for structural improvement, seeking a weighted compromise between the paradigms of contemporary use and the cultural value of the historical building.
This paper briefly discusses the seismic-resistant heritage of the 18th C, circumscribed in Lisbon's *Baixa Pombalina* (post 1755) and *case baraccate* of southern Italy (post 1783).
A comparison of these anti-seismic systems is discussed through the architectural principles and the mechanical behaviour. It is shown that, despite the wide diversity of cases and the different geo-historical conditioning, both systems arise from an intuition of the compound seismic efficiency, Enlightenment pragmatism and an interpretation of the classic composition code.
Two specific case studies, a private building in *Baixa Pombalina* (Lisbon) and the Bishop's Palace of Mileto (Calabria region) are compared. We briefly analyze: i) configuration and structural principles; ii) characteristics of the materials; iii) seismic behaviour.
A standardized spatial morphology closely linked to traditional construction techniques positively determines the seismic response and it is one of the key common factors in this heritage to be preserved.

Keywords: timber structure, earthquake resistant structures, *gaiola pombalina*, *casa baraccata*, architectural heritage.

Research aims

The aim is to establish analogies and differences between composite structures in the Mediterranean area to perform a critical analysis for the safeguard of the architectural heritage, dated from the late 18thC. This work contributes to multidisciplinary knowledge of the traditional techniques that influence the spatial configuration and represent an identifying cultural element.
We want to deepen the knowledge related to the impact of the original architectural and technical solutions in the seismic response of the building, through the analysis of the two models in the light of their geometrical and structural characteristics.
The comparison of the anti-seismic heritage, in Italy and in Portugal, should help to clarify a current methodological approach to the heritage safeguard. From a state of art that integrates areas generally addressed separately, this paper focuses on two specific cases, analysed from a typological starting-point. The selection of these two specific cases depended also on the actual possibility to observe directly the structure, alongside the historical and experimental research. Differences arise in the two cases related to the development of density of occupancy, the walls structure and the mechanical behaviour.

1. Introduction

As a result of the catastrophic earthquakes in Portugal (1755) and Southern Italy (1783), official military engineers promoted radical reforms for urban and architectural planning.
Since the last decade of the 18th century a heterogeneous and vast heritage was established based on mixed systems: the compact urban grid in Lisbon and the reconstruction of dispersed urban centers in southern Calabria.
The *Borbone* system and to a greater extent the *Pombalino* system owe their wide spreading to two key factors: i) high-efficiency of the construction model based on timber and masonry; ii) cost-effectiveness, thanks to the reuse of local (or existing) materials.
Due to the extraordinary technical and formal quality and the remarkable consistency of this anti-seismic heritage, an extensive literature covering various fields of research may be found.

Regarding the Portuguese case, França [França 1983] and Rossa [Rossa 1998] deepen and contextualise the socio-cultural environment, whereas Mascarenhas [Mascarenhas 2004] reports the typological evolution and characterization through several examples of *Baixa Pombalina* buildings (1755/1880).

In the Italian case, detailed studies have mapped out the groundwork to a recognition of the value of *case baraccate*, namely Maretto [Maretto 1975] analysing the urban setting and building typological features in some Calabrian centres, Principe [Principe 1976] with incidence on urban, historic and political aspects. Furthermore, it is relevant to mention Tobriner [Tobriner 1997] highlighting the strength of the constructive principles and Barucci [Barucci 1990] focusing on a diachronic study and the extraordinary variety of Italian treatises during the 19th C. Significant and recent contributions to knowledge concerning historical, constructive and experimental aspects f the system are carried by the second author et al.[Ruggieri 2013; Ruggieri et Tampone et Zinno 2013; Galassi et al. 2014].

Comparative studies and research covering seismically active regions worldwide, as India, Turkey, Central America and the United States also assimilating the Portuguese and Italian cases were carried out by Langenbach [Langenbach 2007].

With regard to studies on the materials characterization and the efficiency of the structural system, it can be said that scientific literature on historic timber frames is fairly recent, particularly in the Italian case.

In the context of experimental campaigns, initially researchers from the Portuguese National Laboratory for Civil Engineering (LNEC) and more recently from the University of Minho have investigated various aspects of the performance of the *gaiola*. In particular, numerous cyclical tests were carried out in order to clarify: i) the contribution of the internal timber-masonry wall and of each components, namely timber and masonry, to the global seismic resistance of the structure; ii) the influence of the wall filling material and of the joints in the mechanical behaviour; iii) reinforcement techniques [Lourenço et al. 2014].

In the case of Santos's experimental campaign the cyclical tests were performed in real wall sections removed from buildings [Santos 1997, Silva 2002], as well as in scale models characterized by a replica of the original geometry and traditional joints [Meireles et al. 2012]. The latter assessed strengthening techniques namely steel plates with different configurations and steel flat bars inserted with the Near Surface Mounted (NSM) technique [Vasconcelos et al. 2014].

A model of the *borbone* wall was reproduced in September 2013 at the CNR/Ivalsa Laboratory in Trento to be subjected to cyclic actions based on UNI 12512 loading protocol [Galassi et al. 2013, Ruggieri 2014, Ruggieri et Zinno 2015].

However, a systematic comparison of architectural principles and construction techniques was never tackled, especially from a multidisciplinary perspective. Detailed studies on experimental research relating to the strengthening interventions, the systematic inventory of the several types and the principles for safeguard the *casa baraccata* are still lacking.

2. Architectural and structural principles

2.1 General principles

Due to reasons related to a contingent pragmatism and the specific historical period, these anti-seismic models take over classical canons, as sagacity construction (*fabrili subtilitate*) is achieved through modularity and accuracy (*officinatoris exactio*) in the detail.

Four principles in earthquake-resistant systems may be outlined: i) a regularity of the plan and elevation development; ii) the behaviour of the building as a whole unit; iii) the joints and overall ductility; iv) the reduction of the mass compared to an ordinary masonry building.

These principles are now analyzed in more detail.

The composition of the buildings of the late 18th century, both in Portugal and Italy is characterized by a clear layout with the repetition of proportional order systems. This feature is evident in the representations included in the *Cartulário Pombalino* [AA.VV. 2006] and the ones drawn by Eng. Ferraresi in Vivenzio's treatise [Vivenzio 1783]. The regularity of the layout both in vertical and horizontal sections induces regularity in the distribution of mass and stiffness.

In both cases the design and execution were based on a metric module where the whole and each part were commensurable. This commensurability was achieved through the fixed module (palms) in elevation and plan, to economize the constructive process.
This control measure differs from previous medieval architecture. During reconstruction this measure was based on human dimensions, as an abstract quantity applied indiscriminately to all the artifacts and had some variations depending on the location of construction.
Greater importance was given to the elevation, in the rigid logic of the alignments of the openings and the constant rate between 'empty' and 'full' parts of the surface.
The difference of the two cases in density of occupancy (higher in the Portuguese case) lies in the historical-geographical setting. Both cases seek the relation between the construction technology, typology and urban planning.
Specifically in Portugal, the facades composition should be inspired from neo-classic canons, namely from Serlio studies [Duarte 2004] and reflected the streets hierarchy. The buildings are grouped in rectangular and homogenous blocks (70x25m^2) with a narrow central yard (45x2m^2) [Ramos et Lourenço 2004]. Typically, four floors were built including the ground floor with a commercial use and the attic with a renting apartment.
It respected the same height of the urban complex, so as to facilitate similar dynamics and a better seismic performance, through *"row"* behaviour in which every building benefits from the presence of the confinement assured by the contiguous one.
The layout is quite simple and is repeated in height, comprising two apartments per floor with a central staircase ("*right-left"* plan) or one apartment per floor ("*singular"* plan), a functional solution to a rental use. The so-called "*right-left"* plan has a bi-axial symmetry distribution and accounts for 54% of the *Pombalino* heritage [Mascarenhas 2004].
In the Italian case instead a modest type of townhouse prevails, also with biaxial symmetry and with one or two floors.
The second principle, the behaviour of the building as a whole unit, is achieved through the connection of the structural elements in the three dimensions of the fabric, thus reaching an overall balance.
According to this principle both systems have the structural strength of a three-dimensional behaviour because of the good compatibility and the combined work of the orthogonal walls. The box-like effect that is achieved through the solidarity between the structural elements results in a lower vulnerability of the entire compound. In fact, during an earthquake, the shear wall avoids or reduces the possibility of collapse, acting in the parallel direction to the imposed action with stiffness greater than the perpendicular one.
In the *Pombalino* building (1755-1870) the principle of vertical continuity of timber walls was peremptorily respected along the whole height. The connection of all the structural components was carefully executed and assures that the structure is one single unit reacting in a flexible way to the stresses acting during an earthquake.
The third principle – overall ductility – is the basis for the good performance of the system under earthquake strain. Under seismic actions an ordinary masonry, as well as timber structures, have a predominant brittle behaviour. In the case of wood, the ultimate limit state and/or the collapse is reached predominantly under the linear field.
With these composite structures the excessive flexibility of the wood is limited by the presence of the filling materials; on the other hand the elasticity of the timber frame manage to bring the wall to its original position, at least for moderate displacements. Furthermore, the system is suitable to dissipate seismic energy thanks to the presence of the timber structure nodes that are not rigid enough to result in brittle fractures. Moreover, ductility is enhanced by the friction generated between the elements of the walls, as well as at the interface between wood frame and masonry filling. The energy dissipation also takes place thought cracks in the mortar joints and stones expulsion.
Finally, the fourth principle is a result of the specific strength of the system. Due to the lowest specific weight and high strength (in comparison with a structure entirely in masonry), the seismic forces produce a moderate acceleration in the framed structure, lower than most of other kinds of structure, such as reinforced concrete or unreinforced masonry. Moreover, considering the timber structures redundancy, there is an effective solidarity in case of failure of a structural element and

other force-carrying elements compensate and prevent a collapse of the entire system.

2.2 Timber framed system: *Frontal Vs Borbone* wall

The aforementioned systems are based on the use of collaborating materials, masonry and wood, whose influence determines the overall behaviour of the building under cyclic loading.
A unique set of construction principles prevail in Lisbon (with innumerable alterations over the centuries), as opposed to Calabria region, where many structural variants are spread over that territory. The heterogeneity of the Calabrian heritage is possibly explained by the nature of the Italian code (*Istruzioni Reali*, 1784), without precise information and dimensional drawings, but only qualitative descriptions of the system to be adopted.
Another important distinction should be highlighted: in Portugal, it may be said that these buildings are *wooden architecture*, given the predominance of this material in terms of quantity and performance; in the many Calabrian variants, however, it is still *stone architecture*.
Therefore the Portuguese wall seems to depart from the Roman model, *Casa Graticcio*, in Herculaneum [Geremia 2014], to a greater extent than that of Calabria. In Lisbon, the timber execution is the starting point and center phase of the entire constructive process and not simply, as in the Vitruvian case, to stiffen the wall or optimize the execution time.
The *"gaiola"* is a cage formed by an orthogonal grid of vertical panels ("*frontais"*) and timber floors. Each panel consists of a set of triangles (a non-deformable shape): improving the shear strength of the wooden elements vertically, as well as under the horizontal loads. An almost perfect system was achieved by the solidarity among different structural elements (also multiple of the palm) to form St. Andrew's crosses, where the connection is essential for the general bracing of the structure.
With regard to the plan spatial configuration, *Pombalino* buildings present the wooden cage as a three-dimensional structure stiffening the load-bearing walls, assuring solidarity between every structural element and with "*tabiques"* (internal partition walls made of wood and mortar).
Regarding the materials characterization, the system is constituted by a several wooden members filled with heterogeneous material. In the same building various types of wood species and genus may be found, often *Castanea sativa, Quercus ilex, Pinus silvestris, Pinus palustris, English Oak, Quercus suber, Quercus Iex*. The filling is made of irregular blocks of limestone and/or clay bricks, gravel and small ceramic elements and mortar. A particular type of mortar was prepared on site with clayish sand and quicklime with the addition of small portions of tallow. The result was a remarkably waterproof mortar [Santos 1994].
The *Borbone* system, instead, is based on timber wood wrapped up in masonry. The local wood, *Calabrian Chestnut,* is the most frequently adopted. However, the reduced availability of timber and the long return period characterizing the southern earthquakes were the causes for a progressive simplification. Unlike the Portuguese case, where the filling masonry was completely irregular, in *Borbone* wall, rectangular blocks, roughly squared in different dimensions, were adopted. The external walls of the *case baraccate* were built with the wood framing, while the inner, less thick (25 cm) were wood and uncoated masonry, or sometimes with simple frame filled with brick-like *gaiola*, however without connections to the floor.
To sum up, the Portuguese system may be designated by *timber frame walls*: a framework of timber infilled with masonry, while the Italian system may be designated by *masonry reinforced with timber frames*: stone and bricks walls with a wooden skeleton [Ruggieri 2014].
The function of the timber elements is substantially different. In the half-timbered model of Lisbon, the bearing system works under static field and dynamic loads. Conversely, in the *casa baraccata*, the wooden frame does not take part, or only in a limited way, in static field; under dynamic action, the wooden skeleton provides to the masonry an additional tensile strength. The energy dissipation capacity is derived from the connections of the wooden structures and the filling, characterized by ruptures and expulsion of stones. The greater amount of energy dissipation takes place by means of friction generated between the stone elements of the filling and at the frame-masonry boundary. Even joints contribute, albeit to a lesser extent, to the seismic energy dissipation [Ruggieri 2014; Galassi et al. 2013; Ruggieri et Zinno 2015].

Another significant difference arises in the ground floor construction. In *Pombalino* building, the wood frame was not executed in the ground floor where masonry arches are the structural element that carries loads to this level masonry walls. This principle is generally respected in order to avoid fire destruction and wood degradation due to humid environments, as well as conferring stiffness to the system on the base. In Calabria, the wooden framework was applied in the walls on all floors (two) to a maximum height of 28 palms, and the arches and stone vaults were, on the contrary, prohibited.

3. Case studies: *Pombalino* building *Vs* Bishop's Palace of Mileto

3.1 Brief historical analysis

The Portuguese reconstruction was developed *in situ* as one major option from the authorities. On the contrary, at Mileto (as in twenty other centers of Calabria, out of 53) the decision was taken to rebuild in an area located 20 km apart from the original urban core [Centro Servizi Culturali Vibo Valentia 1982].

The two cases, however, have in common the technicality operating in solving public problems, such as the widening of streets, the height and geometry of the buildings, the system of collecting water. Moreover both reconstructions were articulated with the aim of overcoming the structural limits of the building before the earthquakes of the eighteenth century. In Portugal these limits are a consequence of salient elements in the façade, global weight, disproportion between height of the building and street width and geometric irregularity. In Italy the limits are predominantly conditioned by a poor construction practice.

Analyzing the two specific cases the main difference is that the Portuguese case is part of an urban block and the Italian case is an isolated block.

The four-storey building is localized on a lot of the *Baixa Pombalina*, bordered by a medieval area. It's a so-called *singular* plan, with a stair on the side of the property and with a small rear patio (2.00X2.90m^2). The distributive organization of the whole building is articulated with a sequence of four internal walls, parallel to the street. There are no corridors and internal circulation is assured from room to room.

This case study is an example of a *Pombalino* building that has been altered, as the presence of the continuous balcony was not part of original design [Fig.1]. However as noted for the typology layout and the material characterization it fully respects the set of *Pombalino* rules.

The facade is severe, defined on either side by an order of pilasters that are interrupted on the fourth floor by a balcony. The façade composition, along its surface, is characterized by: the alignment of the ashlars around the openings; an'empty' to 'full' ratio of one and the inequality of height in relation to the adjacent buildings, due to the addition of extra floors. The exceptions to this composition are the ground and the mezzanine floors.

The Calabrian case is a complex intended to the Bishop's house and a seminary. It dates back to 1784, a year after the macro earthquake that struck Mileto and other cities of the Tyrrhenian coast.

The building has an east-west orientation and is characterized by an elongated shape that fits in the regular town plan designed by Eng. Francesco La Vega and Arch. Ferraresi [Fig.2].

The architectural design is neoclassical mannered built in two stages. Despite substantial changes, like volumes added on the back south side, infill panels and wide openings on the east elevation of the ground floor, the original layout is still legible.

The wide front wing of the building has two levels, the ground floor and a mezzanine level. It is characterized by an alternation of openings, with an'empty' to 'full' ratio of approximately 4/11. Every window is framed by a side order of pilasters and by triangular or curved-shape brick gables alternating on top.

The front is asymmetrical: the main entrance is not centrally placed and the first three divisions are separated by an order of a pilaster, while in the subsequent this division is based on a double order of pilasters. As can be deduced from some fragments, the pilasters were originally characterized by thick grooves [Fig.3].

The basement, in bossage, reaches the windowsill of the ground floor's windows. The doorway is enhanced by the stretched transom with curved sides on the keystone and at the base of the pilasters with a floral motif. The staircase with three flights connects with a central corridor parallel to the longitudinal front. The roof is a wood truss and the eaves height is approximately 6,50m.

3.2 Survey and characterisation

In both cases, a very thick lime plaster and mortar normally hides the timber structure, making it difficult to identify the structure condition.

In the Portuguese case study, the wall and ceiling finishing layers (mortar and plaster) were completely removed to control the different structural materials and their degradation condition within the scope of an ongoing rehabilitation project; in the Italian case, the external walls are only partially visible.

In the *Pombalino* building, three main types of walls were detected: i) external wood framed masonry walls; ii) rubble stone masonry walls (partition of the lot); iii) internal timber-masonry structural walls [Fig.5].

These interior walls are divided into three vertical modules of Saint Andrew's crosses in all floors but the mezzanine floor, with two modules [Fig.6]. This conformation is the antithesis of the initial rule defined after the earthquake, which involved three of these vertical modules in the first floor and two modules in every other upper [Mascarenhas 2004].

The vertical wood elements, (so-called *"prumos"*) reach a height of more than one floor and have a variable section (approximately 15X30cm in mezzanine, 10x16cm in upper floors). This structural continuity allows a greater mechanical strength of the structure. In some cases, as in the mezzanine level, the horizontal elements are longer than the dimension of the module, supporting the diagonal and vertical elements [Fig.7].

The straight and rounded edges solid wooden beams were placed progressively with smaller section, from the mezzanine to the upper floors. The filling of the triangular voids was carried out with bricks and irregular stones and lime mortar [Fig.7]. In some cases, the bricks are arranged in diagonal position, while the stones are horizontally arranged.

The carpenters fabricated the wooden skeleton continuously over the height of the building, properly shored, before the filling of the frames. There is a hierarchy in the structural response; the wood structure has the greatest burden, both under static and horizontal actions; in the latter case the masonry filling cooperates providing additional stiffening [Fig.8].

The timber elements are notched or connected by rounded head nails or iron ties. A half lap joint is one of the frequently used, adapted *in situ,* improving the connection and then the stiffness [Fig.9]. The timber joints are carried out with more caution and effectiveness on the lower floors. To avoid inlays (that would reduce the mechanical strength and would require more processing), diagonals uprights are often not coplanar [Fig.6].

Differences arise in the characterization of Calabrian walls, which have more regular composition than the Portuguese case. The construction technique is a mixed masonry with brick and granite splitters, combined by a fairly stiff mortar. Almost rectangular blocks roughly squared in different dimensions prevail. It should be inferred that the only processing performed in the quarry is the cutting to obtain two smooth and parallel faces. In-situ laying was performed filling joints using bricks, probably from collapsed buildings after the earthquake. As in the Portuguese case, the bricks are horizontally arranged and the mortar stands out for a good cohesive capacity [Fig.10].

In both cases, on the top of the internal wall, a summit wooden beam support the timber beams, bound by the half wood joints. [Fig.6, Fig.10]. The beam allows a distribution of the concentrated load on a larger surface area and mainly improves the solidarity between orthogonal walls.

Regarding the exterior walls, on the top a wooden beam guarantees adherence only by friction.

Regarding the *Pombalino* case, two aspects about the floor structure are outlined. First: a reduced spacing between wood beams, probably to achieve a greater stiffness since there is a more efficient distribution of the earthquake actions to shear walls moreover, this low spacing also supports in preventing possible risks of tilting in the case of horizontal actions perpendicular to the plane. Secondly, transversal wooden elements are included between main wood beams, to assure a bi-directional structural performance.

In the mezzanine level, the arches characterized by a low profile, whose pushing action is contained by principal walls, are parallel to the front facade, on one side and on the other by *gaiola*, that support longitudinally the staircase. The floors are continuous and perpendicular to the main façade, with the exception of the ground floor. The floors should be considered as flexible diaphragms, confining the relative out-of-plan displacements of parallel masonry walls [Cardoso et al. 2005].

Conclusions

This article attempts to underline a critic lecture of the local anti-seismic culture of the 18th C, in Italy and Portugal, outlining strengths and weaknesses in *Pombalino* and *Borbone* heritage. The common principles highlighted could be considered innovative and particularly efficient to achieve a better seismic resistance.
Through two examples illustrated with a detailed survey, it is shown how the structural effectiveness is based on the coherence between architectural composition, technique and structure.
The aim of this paper is to underline the importance of the "authenticity" of these structures. The rehabilitation of this seismic-resistant heritage should preserve its historical value, principally based on this coherence, with the aim of improving its resistance and not to make the building "adequate"[Giuffrè 1992].
The art.7 of the *"Carta Italiana del Restauro"* (1931) has defined the preference for the conservation of the original techniques, distributional layout and constructive scheme is highly recommended, where reasonably feasible. Every conservation charter published afterwards confirmed this procedure.
Due to a recent significant increase in the number of interventions on this heritage (especially in Lisbon), it is necessary to highlight that its historical value embrace the whole building and not just isolated elements (façade or stairs), as determined in ICOMOS guidelines [ICOMOS 2001].
Despite the actual structure of ownership the systemic view is essential in order to associate the overall intervention. It is important to assess and make a choice on the distributive character and the spatial distribution of stiffness, avoiding substantial changes.

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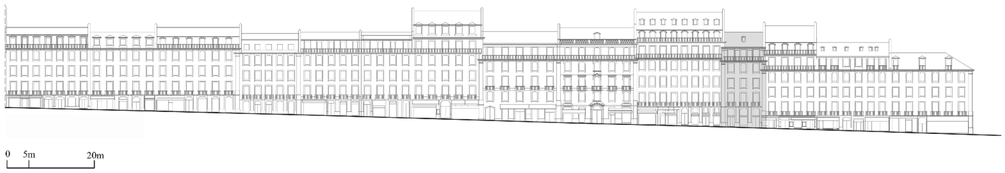

Fig.1- Pombalino case study: building in Rua Fanqueiros, n.110A-114 (Lisbon drawing based on data from Lisbon Municipality)
458x78mm (300 x 300 DPI)

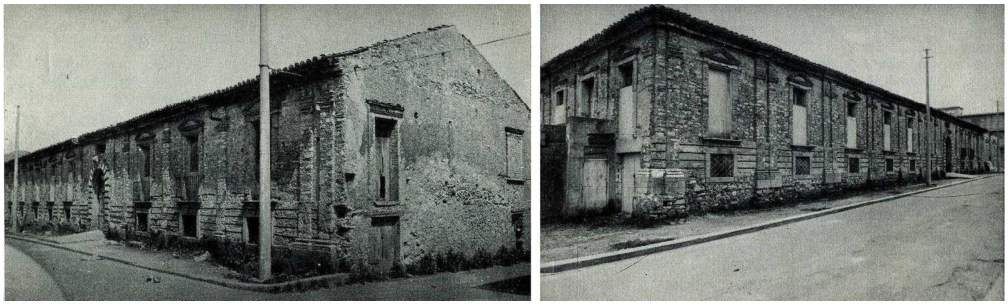

Fig. 2- Borbone case study: Bishop's Palace of Mileto [Centro Servizi Culturali Vibo Valentia 1982]
185x55mm (300 x 300 DPI)

Fig.3- Borbone case study: Bishop's Palace of Mileto, basement detail
131x45mm (150 x 150 DPI)

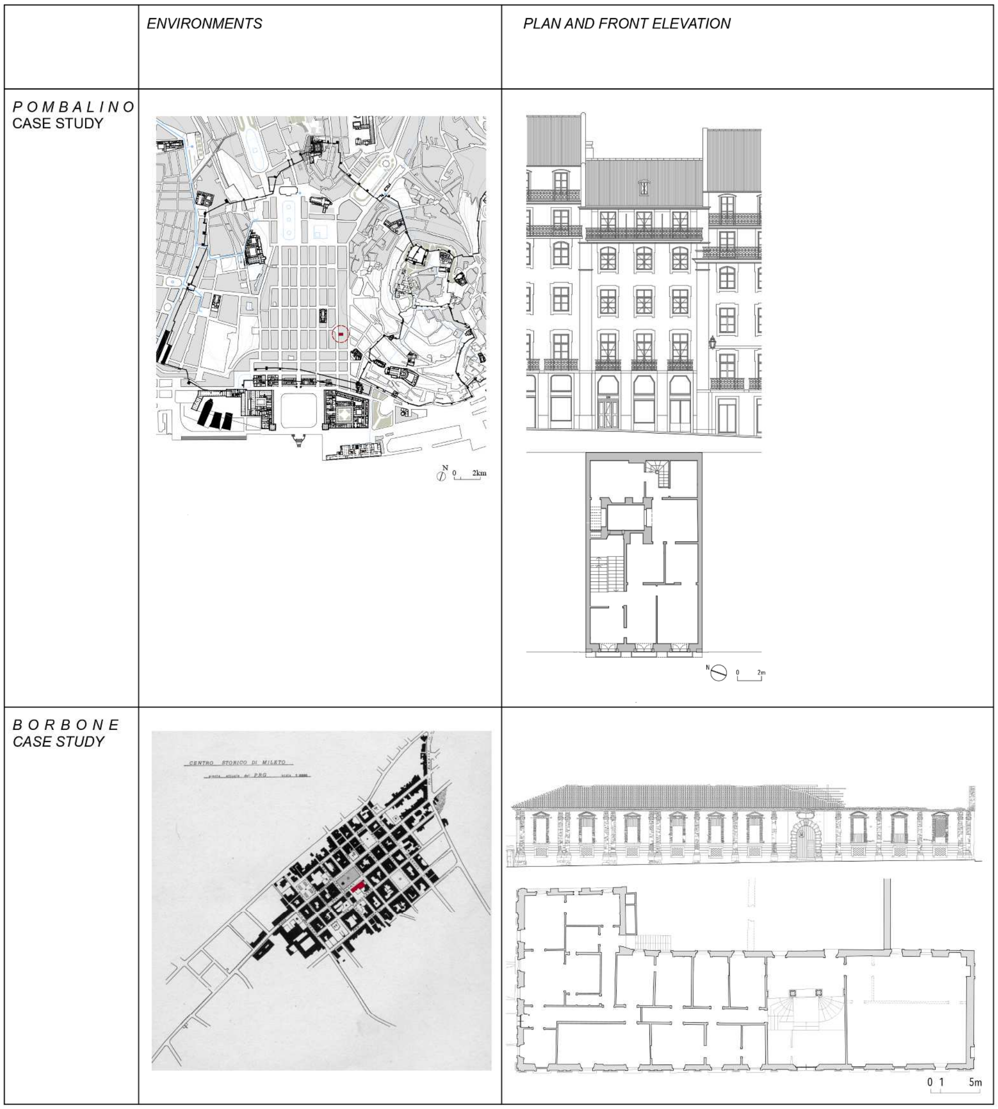

Fig. 4- Pombalino case study Vs Borbone case study (drawing relating to the Pombalino building from survey carried out from Santa Rita arquitects; Mileto's map from [Centro Servizi Culturali Vibo Valentia 1982] and drawing relating to the Borbone building from survey carried out by Prof. Andrea Lonetti)
218x244mm (300 x 300 DPI)

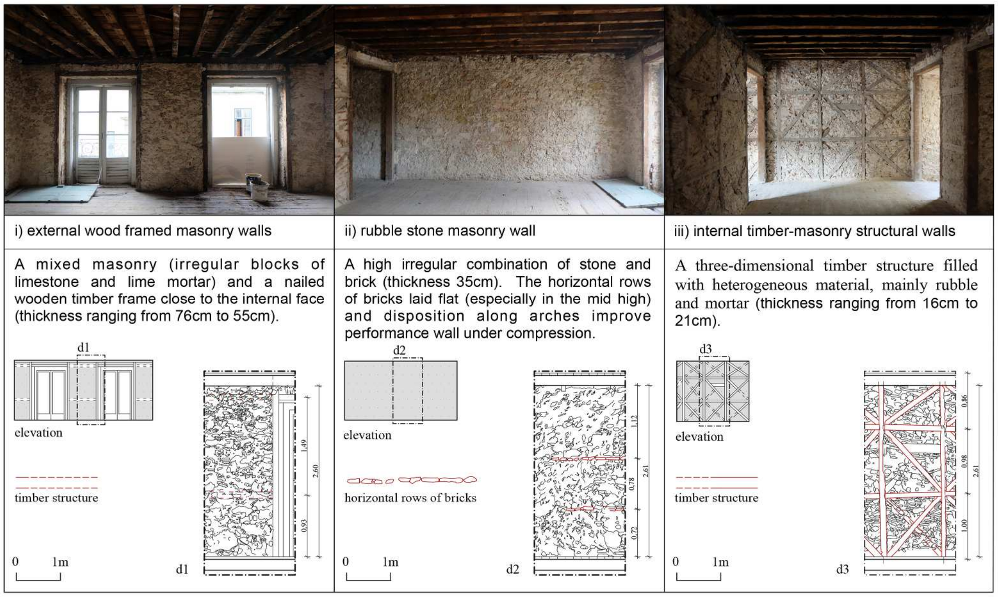

Fig. 5- Pombalino case study: i) external wood framed masonry walls; ii) rubble stone masonry wall; iii) internal timber-masonry structural walls
249x149mm (300 x 300 DPI)

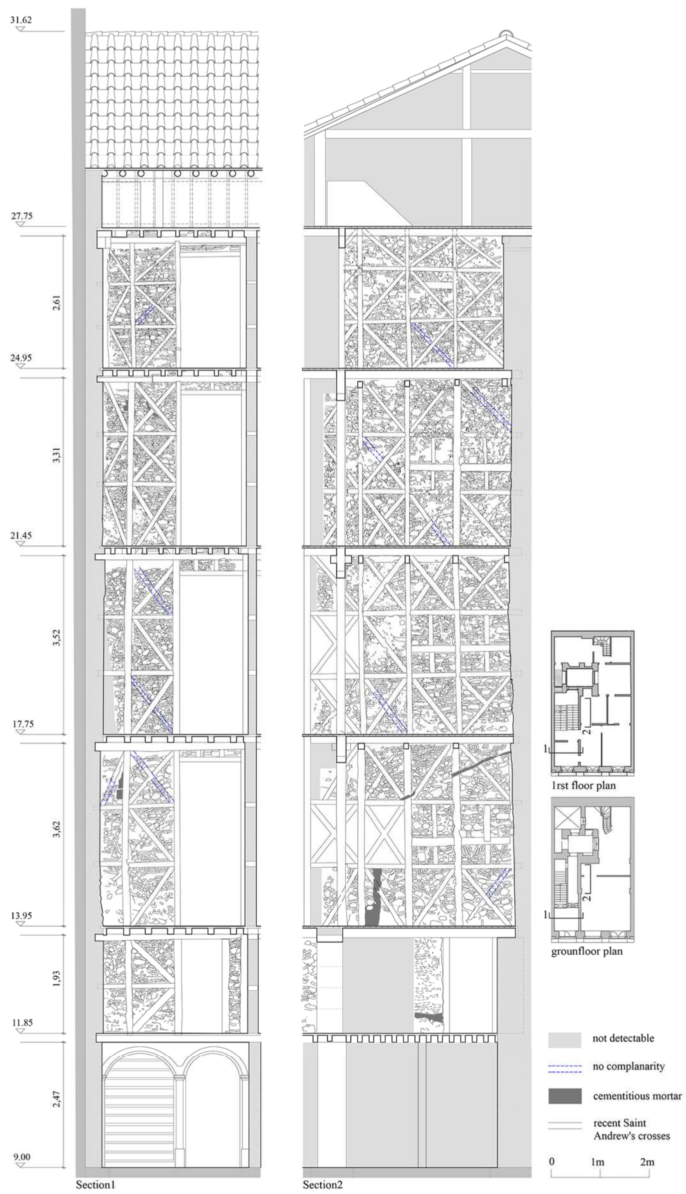

Fig. 6- Pombalino case study: partial sections and plans
113x199mm (300 x 300 DPI)

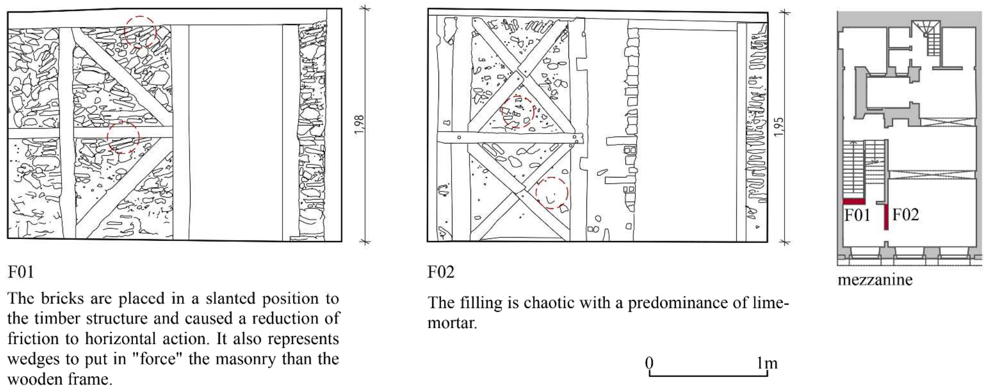

Fig.7- Pombalino case study: comparison of two walls (type iii) located in the mezzanine floor
307x130mm (300 x 300 DPI)

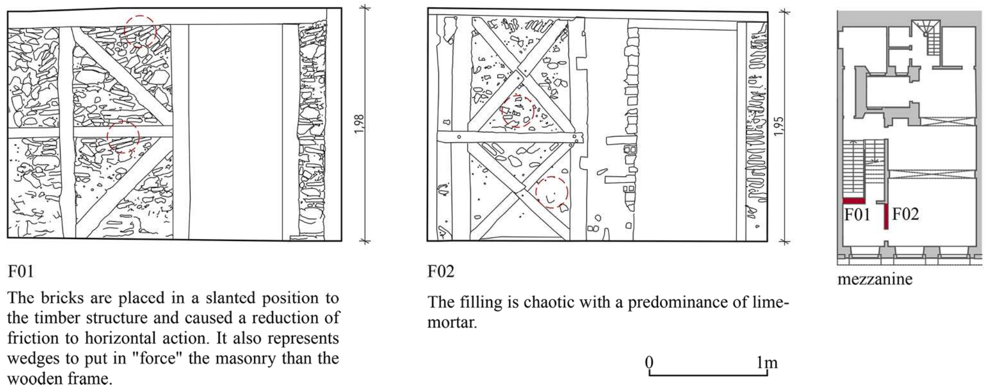

Fig. 8- Pombalino case study: internal view
189x80mm (300 x 300 DPI)

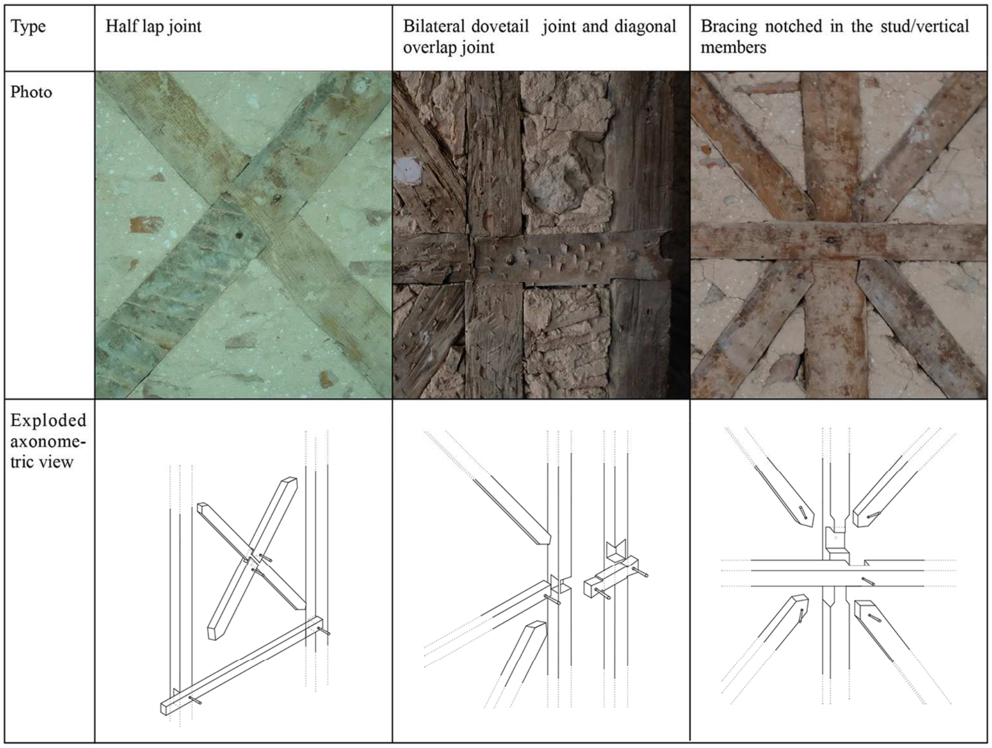

Fig. 9- Pombalino case study: details of timber connection
133x100mm (300 x 300 DPI)

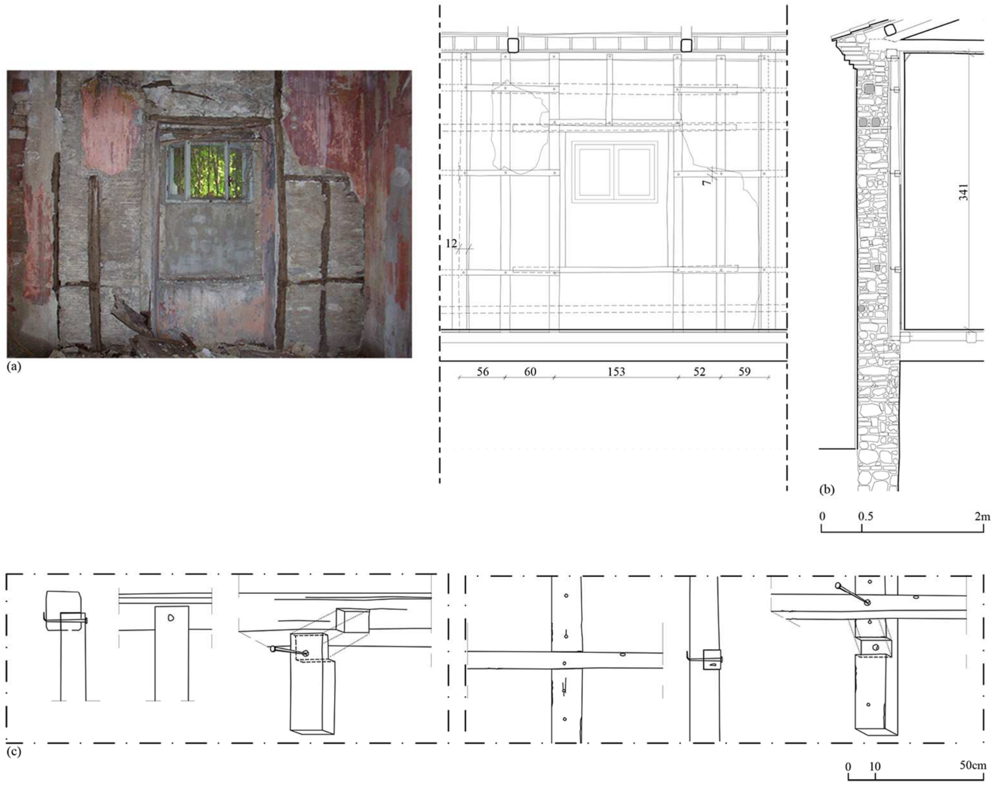

Fig. 10- Borbone case study: (a) photo and survey of the partial elevation (interior face); (b) section; (c) detail of timber connection
132x104mm (300 x 300 DPI)