Comparison between Two Traditional Earthquake-Proof Solutions: Borbone and Lefkada Timber-Frame Systems

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Abstract: On the basis of a critical analysis of damage produced by earthquakes, over time, traditional construction techniques have developed effective solutions for earthquake-resistant buildings. Meaningful examples of this can be found within the vernacular tradition of the Mediterranean area, which is characterized by frequently recurring seismic events. Specifically, in southern Italy and in the Greek Ionian Islands, two interesting construction types still survive and merit special attention in relation to the structural solutions adopted, which are consistent with modern views of earthquake-resistant design. In both cases, the mixed use of timber and masonry is present, although with different modalities and purposes; indeed, in the Italian case, timber elements are present over the building's entire height as an additional bracing system, whereas in the Greek one, timber is used at the second and third stories to reduce the structural mass. In this work, two selected case studies are presented, through which the distinctive construction details of each tradition are commented on.

Introduction

The search for earthquake-resistant construction techniques has characterized building traditions since early times, well before the scientific approach to the problem began and earthquake engineering methods were introduced. For a long time, earthquake-proof solutions were developed empirically, learning from the behavior of buildings, as highlighted by postearthquake damage surveys. Among others, remarkable cases of refined solutions are offered by the traditional building system that is still in use in Lefkada, one of the Greek islands in the Ionian Sea, and by the so-called Borbone system in southern Italy. Such examples refer to construction techniques that have been constantly improved over time under the influence of recurring earthquakes and still prove effective, sparking interesting considerations in relation to new designs.

Both cases belong to the Mediterranean area, which has always obliged builders to cope with strong seismic activity, thus becoming an effective vantage point for the aforementioned issue of empirical building skills. From the beginning, builders and local populations were prompted to make a careful analysis of the earthquake phenomenon, their experience being fed by critical observation. Within the context of seismic vulnerability, therefore, important historical-social implications can be recognized: over time, local commun-ities, subject to recurrent heavy earthquakes, adopted special con-struction methods, choosing to stay rather than to relocate.

Both the Lefkada and Borbone systems are based on the traditional wooden architecture developed in the geographical areas to which they belong. They closely recall the Gaiola or Pombalino constructive system, which represents a well-known Portuguese tradition, commonly considered to be at the origin of this particular building typology. This system, initially developed inside the vernacular tradition, became renowned due to the positive performance it provided during the 1755 Lisbon earthquake; it was therefore improved and systematically adopted in the reconstruction, consti-tuting one of the first examples of a seismic-resistant building solution (Stellacci et al. 2016).

The level of sophistication reached by such systems merits special consideration because it represents the best of the seismic design criteria in use in the 18th and 19th centuries, in addition to anticipating some prominent concepts in modern building codes. Examples of this are the interlocking details of orthogonal walls, which reflect an awareness of box behavior; regularity in plan and elevation; and the reduction of dead loads.

In the present work, the two earthquake-resistant systems belonging to the Mediterranean area are compared, emphasizing the most meaningful aspects of the relative construction technologies, which are plainly in line with modern seismic design concepts.

These aspects deserve special attention because they might provide inspiration for new construction strategies that, in line with current sustainability requirements, would prove both effective and environmentally compatible.

Meaningful Traditions from the Mediterranean Area

The two examples of traditional earthquake-resistant solutions discussed here have been highlighted by important studies that have demonstrated their ability to resist seismic action (Touliatos 2001; Vintzileou and Touliatos 2004; Tsakanika 2008; Ruggieri et al. 2013; Tonna et al. 2014; Ruggieri et al. 2015; Kazantzidou-Firtinidou et al. 2016).

Although similar, the Pombalino system, which represents a rich and sophisticated example within the timber-frame building tradition, exhibits important differences. This system is constituted by a wooden cage composed of two orders of frames, including both vertical and horizontal members, braced by wooden diagonals and masonry infill. The entire structure is delimited by masonry walls, which provide protection against fire propagation. The Pombalino

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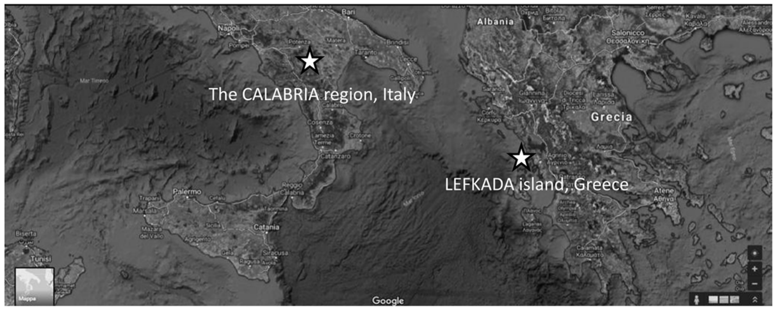
(a)

(b)



(c)

Fig. 1. Representative views of (a) Cropani (CZ); (b) Lefkada Bay; and (c) map of the Calabria region, where the Borbone system was developed, and Lefkada Ionian Island. [Images (a) and (b) by Sandra Tonna; map data (c) © 2018 Google.]

structure has a different structural behavior, with an independent historical genesis and development (Ruggieri 2013), than the two timber-frame systems analyzed in this article.

The Pombalino system can be referred to as a half-timbered wall, where timber elements play a fundamental role in resisting both gravitational and seismic loads. The Italian Borbone constructive system, conversely, can be defined as masonry reinforced by wooden framing, in which masonry supports static loads, and timber elements develop resistance in tension under the effect of seismic actions. A third typology is represented by the Lefkada system; here the ground floor is constituted by masonry with a supplementary timber structure, the upper level being characterized by half-timbered walls.

It is believed that the two Mediterranean cases deserve to be pre-sented and investigated because, even if they look less sophisticated and as though belonging to a less refined context, they have repeatedly exhibited good seismic performance during major seismic events.

A comparative analysis of the two architectural systems is useful to better characterize the peculiarities of each. They belong to ho-mogeneous seismic areas, marked by frequent earthquakes with magnitude values of 5 or more. From the architectural point of view, the two systems were developed in close regions, probably connected by the main commercial routes. Nevertheless, although similar in appearance, they developed different peculiarities to better conform to local needs. It is difficult to define to which extent seismic experience interacted with the sequence of different dominations in the definition of building typologies; what is relevant nowadays is the recognition of two earthquake-resilient systems, which are little known despite the long tradition they represent.

The Italian Borbone type, developed in southern Italy following the 1783 earthquake (Fig. 1), demonstrated effective seismic performance during the Calabria earthquakes of 1905 and 1908.

The Lefkada system (Fig. 1) was improved and systematically applied after the severe earthquake that occurred in 1825 during the British administration; the major seismic event that occurred in Greece in 2003 provided clear evidence of the system's ability to resist seismic action.

(a)

(b)

Fig. 2. (a) Borbone structural type. The damage caused by the 1908 earthquake was due to the stone structure and poor material properties, which favored the wall overturning; the timber frame suffered limited damage (reprinted from Commissione Genio Civile 1909); and (b) the traditional Lefkada type, with stone masonry at ground level and a timber frame at the first story (image by Sandra Tonna).

At first glance, the two systems appear very similar; however, although they are both based on the use of a combined masonry–timber structure, the Italian case is a clear example of a frame house, whereas the Greek one features a more atypical solution.

In the Borbone system [Fig. 2(a)], the timber frame extends over the building's entire height. This is a major difference in comparison to the Greek case, which presents, on the contrary, a timber-frame solution at the upper levels only [Fig. 2(b)].

Consequently, resistance to earthquake-induced lateral loads is developed in diverse ways within the two structural solutions. At the lower level, indeed, where the global seismic action must be transferred to the ground, the in-plane shear resistance of the walls is founded on different mechanisms: in the Italian case, it is mainly provided by the filling material inserted within the frames and by the wooden bracing (if any), whereas in the Lefkada system, it is developed by the stone masonry.

Going into more detail, it should be observed that the Borbone earthquake-resistant system is characterized by a double timber frame, an arrangement typical of public buildings that, in many recurrent cases, can also be single, located at different depths inside the wall's thickness; evidence of this comes from both 18th-century technical literature and from observation of actual cases. Different situations may occur in relation to the way the in-plane stiffness is generated. Specifically, the frame's deformability can be reduced by means of timber Saint Andrew's crosses or, in other cases, through the masonry infill. An alternative scheme is also possible, simply consisting of timber struts braced with masonry, where hori-zontal members are not present; therefore, this is not a real frame system. This last configuration, although introducing the advantage of a global mass reduction due to the replacement of masonry portions with wooden elements, has not proved suitable to develop adequate resistance to horizontal cyclic actions. In general, it has been adopted in sporadic cases, also in consideration of the reduced resistance to out-of-plane seismic loads, resulting in the overturning of masonry walls; with this specific arrangement of timber elements, indeed, the resistance increase is limited, and the masonry continuity is interrupted.

As already mentioned, a different criterion inspired the Lefkada system [Fig. 2(b)], consisting of a multistory building with masonry walls at ground level and a timber-frame structure on the upper lev-els. With reference to studies developed at the National Technical University of Athens (Touliatos 2001; Vintzileou and Touliatos 2004; Tsakanika 2008), it is possible to briefly summarize the main characteristics of a typical Lefkada traditional building (Fig. 3).

Such a system is normally characterized by one to three stories in addition to the ground floor; the latter presents a purely stone ma-sonry structure, whereas a frame solution is adopted at the upper levels, based on the mixed use of timber and clay bricks. At ground level, the interstory height never exceeds 3 m; the walls are constituted by limestone masonry, with a thickness in the range of 60–100 cm. The wall's external leaf is normally characterized by roughly shaped elements, whereas those used in the corners are regularly shaped; stones on the internal leaf are plastered. The inner layer, separating the outer leaves, is filled with mortar and small pieces of brick and stones. Openings are arranged symmetrically in the plan.

A peculiar aspect, which is noticed exclusively in this building tradition, can be observed inside the house on the ground floor, where timber columns are present, adjacent to the external masonry walls at a distance of 2–3 m from each other [see Fig. 3(b)]; these constitute a secondary load-bearing system, which provides additional support for the first-floor slab and the wooden frames of the upper structure.

Due to the reduced horizontal stiffness, this secondary structural system does not contribute to seismic resistance, which is totally developed by the masonry walls [see typical diagonal cracking in Fig. 3(a)]; however, being fully connected to the upper structure, it does play a fundamental supporting role in case of the partial or total collapse of the masonry walls, ensuring continuity in the propagation of vertical loads, and avoiding the collapse of the upper floor. Fig. 3(b) shows a case of total absence of the external masonry wall, with the upper floor fully supported by timber columns.

It therefore provides a passive protection system, which comes into play in case of damage to the masonry, the primary resistance sys-tem; in addition, it allows partial or even total removal of the masonry walls during repair interventions (Vintzileou and Touliatos 2004).

(a) (b)

Fig. 3. Damage observed in buildings belonging to the traditional Lefkada type after the seismic event of November 17, 2015: (a) diagonal cracks between the openings at the ground floor; and (b) the upper part is still standing, even though the masonry at the first level has totally collapsed. (Images by Sandra Tonna.)

Fig. 4. Bishop's Palace at Mileto. (Image by Nicola Ruggieri.)

Interestingly, such a special system has been implemented in both vernacular and monumental constructions, with the adoption of different-quality materials, although always following the same compositional design. Therefore, this structural concept follows well-defined rules, inspired by a clear view of organizing the structural elements into a specific hierarchy.

Two Significant Case Studies

To better characterize the building traditions examined, still-surviving examples of both have been selected and are discussed herein; these are the Bishop's Palace (*Palazzo Vescovile*) in the city of Mileto (Figs. 4 and 5) and the British Ambassador's House in Lefkada city (Fig. 6).

The Bishop's Palace in Mileto was erected in the 18th century using a specific building code ("Instructions for the Reconstruction of Destroyed Villages in the Calabria Region," *Istruzioni per la ric-ostruzione dei paesi diruti della Calabria*), issued following the 1783 earthquake (Ruggieri 2017); it constitutes an outstanding example of the Borbone system.

This palace is characterized by several technical solutions, specifically conceived to reduce seismic vulnerability. The single-story building, raised over a basement, is characterized by a load-bearing structure constituted by 60-cm-thick masonry walls, reinforced by uniformly spaced timber frames, located inside the wall thickness, adjacent to the wall's internal side. Other horizontal members are present inside the walls, randomly organized, with no apparent order. Looking at the different timber elements, a dimensional hierarchy can be recognized: the plate beams running at the top of walls

Fig. 5. Timber-frame structure of the Bishop's Palace at Mileto. (Image by Nicola Ruggieri.)

Fig. 6. British Ambassador's house in Lefkada city. (Image by Sandra Tonna.)

are approximately 30×20 cm, and the sizes of the posts and horizontal elements are approximately 12×10 cm and 7×7 cm, respectively. Some wooden vertical members extend below ground level through the entire basement. The half-lap joint, strengthened by special metal nails, is used to provide a connection between structural elements. The internal partition walls present a reduced thickness of approximately 25 cm; the masonry cross section, therefore, is almost entirely occupied by the timber frames. In such masonry units, struts are juxtaposed to the orthogonal walls; at the intersection, the relative constraint is represented by the top horizontal member, which, through a notch, connects the two perpendicular panels. Where wooden diagonals are lacking, in-plane stiffness is provided by masonry, normally arranged in a haphazard pattern; the provenance rock can be classified as calcilutite, a type of limestone also known as cementstone. However, a certain regularity is given by the presence of variable-size pseudoashlars, with the addition of bricks, most likely coming from other buildings destroyed by earthquakes.

The joint mortar bed, about 2–3 cm thick, is composed of lime and quartz–granitic aggregates with dimensions between 2 and 5 mm. The assembly of posts and ring beams, connected by nails, presents details clearly aimed at opposing the possible rotation of wall panels around the base, with the collapse either inward or (more easily) outward of the building. Indeed, notches are regularly alternated on the opposite sides of timber elements, indicating a clear understanding of the classic collapse mechanism consisting of a wall overturning.

As for the Lefkada system, a classic example can be found in the British Ambassador's house, which, due to its particular shape and central location, is still considered a monumental version of the classic vernacular building (Fig. 6).

Although abandoned for a long time, the building has conserved its original features, despite a total lack of maintenance and the repeated occurrence of earthquakes. This inspires a first consideration of the high construction quality, clearly pursued in relation to local criticalities.

The two-story building presents regularity in its plan, with a rectangular shape and a symmetrical organization of the rooms, which is also reflected on the external façades. Openings are arranged on the two main fronts only (east and west) and are aligned along vertical axes. They look well proportioned in relation to the wall extension and are of relatively small dimensions. The same applies to the gateway, surmounted by an arch, which is fairly small, in spite of the building's prestigious role. This, indeed, is not in line with the trend, common at construction time, to make extensive use of decorations in embassy buildings. This is a sober-looking edifice, well proportioned and relatively simple both in its structural organization and its façade [Fig. 7(b)].

(a) (b)

Fig. 7. (a) Masonry ground floor realized with two different stone types; and (b) external sober-looking façade. (Images by Sandra Tonna.)

The reason for this must be recognized in both the local building tradition, refined by the constant observation of earthquake effects, and in the English administration, capable of recognizing its virtues without imposing its own style. During the British administration, an earthquake occurred in 1825; due to a careful analysis of the most affected buildings and of the construction materials, well-defined rules were imposed for new construction and repair works (Tonna and Chesi 2015).

From the ground to the top, the building description follows the main characteristics of the prototype building representing the typical Lefkada construction system.

The masonry walls at the ground floor have a thickness of approximately 60 cm and are made of well-squared sandstone blocks. At the corners, bigger limestone pieces are used, as for the gateway frame, the upper arch, and in general, all the openings at the first story [Fig. 7(a)].

In the upper part, a mixed structure is present, consisting of a timber frame with brick masonry infill. The frame includes vertical, horizontal, and diagonal elements; the diagonal elements, which are

(a) (b)

Fig. 8. Internal views of timber-frame organization on the first floor: (a) the horizontal, vertical and diagonal elements distribution in the vicinity of a corner; and (b) the panel organization near an opening. (Images by Sandra Tonna.)

Fig. 9. Timber columns along the external wall. Details of the two curved reinforcing elements at both corners are shown. (Images by Sandra Tonna.)

(a) (b)

Fig. 10. (a) Timber-frame structure (image courtesy A. Trimboli); and (b) detail of the timber strut braced by masonry (image by Nicola Ruggieri).

responsible for the bracing effect, are laid in different patterns, arranged symmetrically within the façade. Such a structural pattern cannot be seen from outside, being covered by a layer of timber planks that protects the structure from dampness. At some locations, however, it could be observed on the inside during a building inspection (Fig. 8).

The connection between the lower stone masonry walls and the upper timber frame is given by the timber slab, supported by a wooden curb resting on the masonry and anchored to the wooden columns through timber angles. The slab timber beams provide a connection between the columns and masonry walls.

Timber floors play a double role, resisting both vertical loads coming from upper levels and those directly acting on them; such loads are transferred not only to the perimeter walls but to the secondary timber structure as well. All the connections in the timber structure are extremely accurate and well detailed (Tonna and Chesi 2016c).

Lightweight, thin, internal partition walls, with a thickness of approximately 10 cm, were used, consisting of a simple wooden structure coated with a layer of small rods and plaster.

Again, thanks to the investigation inside, the presence of wooden columns parallel to the walls was noticed, both on the ground and first floors, clearly aligned on the same vertical axis. These, as previously described, serve the role of a secondary slab support system. A constant feature in this building, rarely observed in humbler homes, is the presence of reinforcing corner elements at the column ends (Fig. 9).

Peculiarities in the Structural Configurations

As previously described, these structural systems are difficult to classify, mainly due to the mixed use of materials. According to the European Macro-Seismic Scale (EMS-98) for the evaluation of seismic intensity, the vulnerability of this construction type could be considered as medium to high (from A to C, depending on the maintenance level); however, on the basis of onsite analyses (for the Greek case, surveys were performed after the two recent earthquakes that occurred in 2003 and 2015, respectively), the real vulnerability looks to be lower.

Onsite inspections performed after the 2003 and 2015 earthquake events (Tonna and Chesi 2016a; Kazantzidou-Firtinidou et al. 2016), besides revealing the real capabilities of the timber-frame system, also highlighted the potential building life guaranteed by the repair possibilities, clearly conceived in the design phase. Such a concept applies to both the Italian and Greek systems, even if they differ in the solution adopted for the timber frame at the ground floor.

An exception may be the reduced Borbone system, less frequently adopted and considered a poorer solution (Tonna and Chesi 2016b). This system, used only in the 19th century, is characterized by the adoption of unreinforced masonry at the ground floor and *half-timbered walls* at the upper levels—a solution allowing for construction economy derived from the consideration that in several cases, the earthquake damage had been observed at the upper levels of the building only.

In general, in the Greek case, the timber frame is mainly conceived to reduce the building's mass with height (Fig. 8), whereas in the Italian one, it comes from the necessity to optimize the use of local materials (rarely imported and almost exclusively found in the area), making the entire structure stronger and, at the same time, lighter (Fig. 10).

This construction criterion is based on the presence of structural elements that play different roles, yet all collaborate during an earthquake; this is only made possible by the outstanding quality of the workmanship, which is typical of these preengineered buildings.

By now, due to lack of maintenance, these structures are characterized by high vulnerability; at the same time, however, they can

Fig. 11. Internal view of a building belonging to the traditional Lefkada type. (Image by Sandra Tonna.)

still prove the performance and effectiveness of this construction type. As already mentioned, an important aspect, typical of this structural typology, is the relative ease of intervention for restoration purposes: it has often happened that, with the main structure being almost sound, an easy substitution of the collapsed elements was perfectly feasible; in addition, only crack repair was required.

Clear evidence of this was given by an experimental campaign carried out at the Ivalsa Laboratory [Italian National Research Council (CNR)] (Ruggieri 2015) on a full-scale specimen of the Borbone system. Under the effect of cyclic loads, cracks were recorded only in the masonry infill, with the timber frame totally undamaged. The building seismic capacity was also confirmed by numerical analyses (Galassi et al. 2015) based on the use of a specific methodology (Pugi and Galassi 2013), according to which the specimen is represented through a discrete model, where the structure, both timber members and masonry infill, is subdivided into rigid blocks, connected by three different types of joints: masonry to masonry, wood to wood, and wood to masonry.

Therefore, effective structural behavior can be recognized for both structural types, based on the good performance of the horizontal and vertical elements, stiffened by diagonal members, and in the Greek case, further reinforced by curved corner elements [Fig. 3(b)].

In Lefkada, the particular building solution may also have been influenced by the soft soil conditions; the city, indeed, lies on an ar-tificial soil, resulting from reclamation works performed during the 18th century under the Venetian dominion. Experimental testing has shown high deformability properties for this soil (Tonna and Chesi 2016a).

It can be assumed that for maximum effectiveness, the system requires that the columns (Fig. 11) rest on a stable supporting surface, not allowing for differential settlements; this normally happens on natural rocky soil or may be obtained through a well-connected compact foundation system.

Foundation System

A high level of soil deformability is a typical feature of the Lefkada urban area, and this might also affect the behavior of the sophisti-cated structural system conceived to resist earthquakes. In the ab-sence of a rigid base, indeed, the passive secondary system might well lose effectiveness due to relative settlement and a consequent modification in the load propagation through the structure.

From the analysis of the literature, it appears that the Lefkada foundation system has only been investigated to a limited extent. However, thanks to a recent study (Tonna et al. 2014), it is now possible to formulate certain considerations regarding this system, assuming that a couple of different solutions were systematically adopted, depending on the availability of time and economic resources.

Due to the possibility of a shallow water-table level, local build-ers were forced to develop techniques that enabled mortar to set in the presence of water or air, whatever the situation; two different solutions, therefore, were generated. Where the use of pozzolan or volcanic materials was permitted, a hydraulic mortar was used for the foundation walls, which could then come directly into contact with the water-saturated soil. Where, instead, the use of such materials could not be afforded, a timber grid was used, constituted by two or more layers, providing a flat surface for the erection of the walls; contact between masonry and water was thus avoided.

The grid extended homogeneously beneath the entire house perimeter; in the case of a higher water-table level, additional timber layers were inserted, normal to each other.

In the Italian case, no special solution was developed for the foundation system. It should be considered, indeed, that a better soil quality was normally present, with no special problems in relation to the water-table level; in addition, the significant difference in the structural mass in comparison to the Greek case should also be considered. Moreover, it is worth highlighting that the Italian construction system, although derived from local experience developed in relation to timber structures in the Calabria region, was subsequently imposed by the Borbone Building Code; the latter provided general guidelines, with no reference to specific ground conditions.

In the Borbone system, the foundations in use correspond to a couple of basic types: shallow or deep. For the latter case, a classical building manual (Vivenzio 1783) recommends that wooden piles be driven approximately 3 m deep into the ground. In the same years, an alternative pioneering solution was formulated by Milizia (1781), who suggested to isolate the load-bearing structure from the underneath soil to improve the seismic capacity of the building.

In the atlas annexed to a famous treatise written in the 18th century (Sarconi 1783), an interesting drawing can be found, documenting the foundation details. This drawing refers to the reconstruction works for the town of Polistena, in southern Italy, which had been destroyed by the 1783 earthquake. The table, which is almost didactic, shows a building with timber framing already erected in the foreground, near the pile foundation; the supply of the timber elements is also described (Fig. 12).

In a treatise by Christian Wolff (1738), which was well known in southern Italy during the 18th century, cooperation among the structural elements was considered a basic requirement for a building's positive performance during earthquakes. The German scientist devoted a chapter of his treatise to the description of a wooden frame for the foundation stones, aimed at opposing the loss of cohesion of various parts during earthquakes and, consequently, increasing overall stability.

Such a foundation system, consisting of a stone base, also includes two sets of orthogonal timber elements connected by dove-tail joints. In Wolff's work, the clear intention to recommend an effective interconnected system is evident, both in the text and the figures (Fig. 13); he suggests the adoption of a wooden grid, with members connected by dovetail joints, so that tensile forces can be exchanged among the elements; a full collaboration of the foundation elements is considered the premise for homogeneous load propagation throughout the above structure during seismic events.

This specific solution presents clear similarities with the one adopted in Lefkada; it must be considered, however, that they correspond to different design criteria: in the Italian case, the grid plays the role of a compact, stiff base for the upper structure, whereas in the Greek one, this function is provided by the masonry walls, with

Fig. 12. Reconstruction of the town of Polistena, South Italy. (Reprinted from Sarconi 1784.)

Fig. 14. Timber truss system, characterized by the presence of Saint Andrew's crosses. (Image by Nicola Ruggieri.)

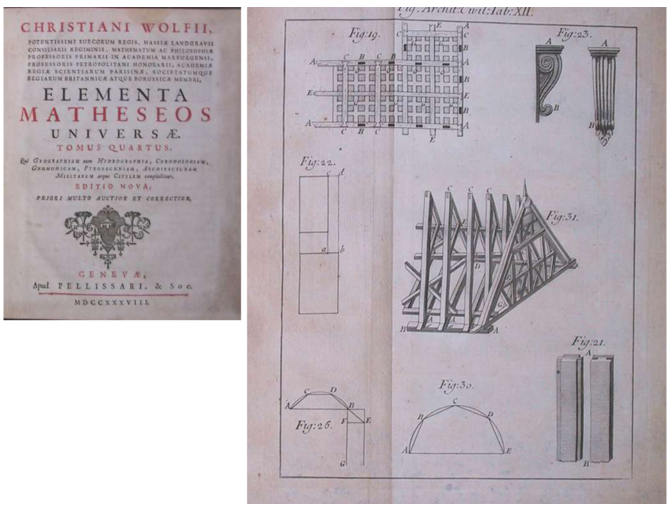


Fig. 13. Wolff's *Elementa Matheseos Universae*. Fig. 19 shows the foundation detail.

the timber grid merely representing a separation layer from the waterlogged ground underneath. Moreover, in the Greek case, the soft, marshy soil represents a daily problem, whereas in the Italian one, the separation between the timber-frame system and the ground, produced by a masonry base, had the primary function of preventing rising moisture, allowing a better preservation of the structural elements, especially those in timber.

Section 9 of the Borbone Code (Ruggieri 2017) highlights the need for a building base made exclusively of masonry; the depth of such a base would depend on the soil bearing capacity; the wooden frame should be erected starting from this. This "masonry base … can rise up to 5 palms from street level" (corresponding to approximately 125 cm) and serves to isolate the timber structure from the soil, a possible vehicle for moisture, which could generate favorable conditions for biotic attacks, hence a weakening agent for the durability of timber elements. This recommendation was partially implemented at the Bishop's Palace in Mileto, where part of the wooden frame is separated from the ground by a masonry portion, approximately 1 m thick, totally lacking timber reinforcement. In this base, stones are characterized by organization, mineralogical composition, and size that are different from the rest of the façade. The palace foundation, apparently, does not present any wall setback or base enlargement. Hence, rather than a typical foundation with thickness enlargement, it can be considered a simple continuation of masonry walls into the ground.

Roof and Slab Structures

In line with local building traditions, timber was adopted as the construction material for slab and roof structures both in Italy and in Greece. Normally, the roofs are constituted by truss systems that do not transfer horizontal actions to the supporting walls; the structural joints are made exclusively of timber elements, perfectly cut and interlocked, and fastened by nails and, sometimes, metal collars (Fig. 14). Within the Southern European tradition, Italian roof structures present a peculiarity, which is the presence of Saint Andrew's crosses, arranged perpendicularly to planar trusses; these serve to provide stiffness to the roof's longitudinal direction, preventing the truss stacking effect produced by seismic forces acting in that direction.

The floor slabs in the Bishop's Palace are constituted by roughly squared beams with a 25×20 cm cross section and a spacing of approximately 80 cm; a timber boarding was fastened to the supporting members by means of nails. The beams were arranged orthogonally to the main façade and connected to the wooden perimetric ring, which is part of the frame, through half-lap joints. In this structural system, one peculiarity is the diagonal corner elements located at the slab's lower side [Fig. 15(a)]. Such devices were intended to reduce the in-plane floor deformability to some extent and, above all, to improve the link between the façade and the slabs. A similar timber element can be found in the Greek tradition as well; in this case, however, rather than being straight, it is curved.

Global View of the Traditional Systems' Seismic Performance from a Modern Perspective

Timber-reinforced masonry buildings, despite common aspects and similar needs, can nonetheless vary and differ in some details within the same geographical area, in relation to the use of local resources, as reflected in, for example, the wall corner connection, the timber-frame design, the material adopted for the ground floor, and so forth. In general, however, due to its own nature, this specific architectural type cannot easily be divided into subcategories.

The features that characterize these building systems underscore, first of all, their uniqueness and fragility. In relation to this, it must also be considered that because most of the timber-frame systems suffer from the effects of weather conditions, they probably constitute one of the most vulnerable parts of Europe's cultural heritage. The main peculiarities of both systems are noted and compared in Table 1, where each structural element is characterized by its role and construction material.

Both of the earthquake-resistant systems examined, like other construction technologies of empirical origin, are in line with certain key concepts of modern building codes. To better understand the potentialities and effectiveness of these traditional construction types, an attempt was made to read and interpret the traditional structural design with reference to modern design criteria.

This simplified yet meaningful comparison is intended to demonstrate the real value of these solutions, also showing that empirical knowledge is not in contrast with a scientific approach.

As previously discussed, both types and, in general, all the traditional timber-frame systems, are characterized by clear structural hierarchy (Tampone 1996) and by a strong awareness of the importance of maintenance right from the earliest design steps. Such systems are based on a clear idea of the path of seismic load transmission, which is reflected in well-defined roles for single structural elements and construction details.

(a) (b)

Fig. 15. Timber floors were present at all story levels both in (a) the Italian (image by Nicola Ruggieri); and (b) the Greek tradition (image by Sandra Tonna).

The rational, regular placing of structural elements corresponds to well-established construction procedures; it also makes the replacement of single elements easier, ensuring optimum and continuous performance for a building (Touliatos 2001).

Such concepts are consistent with design principles based on Eurocode 8 (CEN 2004), where the following criteria are presented as suitable to reduce seismic vulnerability: "In seismic regions, the aspect of seismic hazard shall be taken into account in the early stages of the conceptual design of a building, thus enabling the achievement of a structural system which, within acceptable costs, satisfies the fundamental requirements. … The guiding principles governing this conceptual design are:

- structural simplicity;
- uniformity, symmetry, and redundancy;
- bi-directional resistance and stiffness;
- torsional resistance and stiffness;
- diaphragmatic behavior at story level; and
- adequate foundation."

The Borbone and traditional Lefkada systems can be analyzed and evaluated with reference to these key points.

In both situations, the global arrangement is simple, well defined, and strictly symmetrical in plan and regular along the height, which is often characterized by biaxial symmetry. In short, this is a regular configuration, which limits both torsional behavior and stress concentration under the effect of earthquake action. The interior layout, indeed, follows a well-defined criterion with a central stairwell and partitioning obtained by perpendicular walls, constituted by lighter timber-frame structures or simply by partitioning panels made of reeds and mortar that do not play any structural role.

In both cases, buildings are conceived as single structural units, characterized by similar dimensions in plan and height, with a reduced plan area that remains constant over the height.

The global structural system presents a satisfactory level of connection among the structural components, due to the tie action developed by the timber elements. Indeed, to achieve an effective box-like behavior of the building and a consequent three-dimensional effect in response to seismic forces, particular care in the detailing of connections can be recognized (Ruggieri et al. 2015).

In the Greek system, the bidirectional resistance to horizontal loads is mainly guaranteed by both the diagonal elements located within the timber frame and by the internal separation panels, which serve the role of light bracing.

Moreover, to follow the principle of mass reduction along the height, masonry walls are present in the first interstory only. In this way, a significant part of the building's stiffness is concentrated at the ground floor, in direct connection with the foundation system. The building's lower part, therefore, turns out to be a large stiffer

Table 1. Comparison between the main peculiarities of both systems

Characteristic	Borbone system	Lefkada system
Foundation system	• Shallow foundations (masonry) • Deep foundations (timber poles)	• Masonry wall with hydraulic mortar • Masonry wall with lime mortar, lying on timber grid
Ground level	Masonry structure, 60 cm thick, reinforced with timber frames located at variable depth inside the walls	Masonry wall, approximately 60 cm thick, made of sandstone blocks and lime mortar
Upper levels	In general, the timber frame is present at all stories (typically, one single floor or two floors)	Timber frame with a brick and lime mortar infill
Floor slabs	Timber floor slabs constituted by beams and wooden boarding	Timber floor slabs with a double series of beams (main beams and joists)
Roof system	Wooden truss	Wooden truss
Peculiarities	Longitudinal bracing system in the roof structure (Saint Andrew's crosses)	Timber columns running parallel to the masonry walls (internal side)

block, which plays a positive role in relation to both the soft soil condition, typical of the city of Lefkada, and the need to transfer horizontal loads to the ground evenly (Tonna et al. 2014).

The clear distinction in the structural scheme between the two different macroelements (i.e., the masonry ground floor and the timber upper part) has proved successful in responding to high-magnitude seismic events. Indeed, timber frames at the first and second floor connected to the basement through the second-ary supporting system of the timber columns have proven deformability properties sufficient to counterbalance the effects of damage or partial collapse occurring in the masonry walls (Kazantzidou-Firtinidou et al. 2016).

Similar behavior has been exhibited by the Borbone system in several circumstances; in this case, a recurring damage modality, typically suffered during the 1905 and 1908 catastrophic earthquakes, is relative to cases with a single timber frame along the internal leaf and consisted of the overturning of the wall's external leaf, with the timber frame remaining almost undamaged (Ruggieri et al. 2013).

For both construction types, therefore, it is worth highlighting that under the effect of seismic action, the structure can retain good levels of bearing capacity toward gravitational loads; at the same time, residual strength and stiffness resources are present, sufficient to counter the effect of aftershocks and, in any case, ensure the pres-ervation of human life. Indeed, a collapse of the wall panel (Lefkada system) or the external leaf (Borbone system) does not involve the collapse of the entire building, thereby guaranteeing the occupants' safety. This can be read as a kind of resistance hierarchy, in which the masonry, the sacrificial element, collapses first but does not prevent the wooden frame, the roof structure, and the floor slabs from remaining efficient.

Moreover, it must be emphasized that in both systems, in the event of structural failures due to an earthquake, the damage suffered by the masonry is easier to repair than damage to the wooden structure.

From all the aforementioned properties, well-defined seismic behavior can be identified for both the Italian and the Greek systems, well in line with the principles characterizing the Eurocode 8 conceptual design for earthquake-resistant structures. Indeed, the main concern in modern codes, such as Eurocode 8, has to do with life protection; to this end, the design is based on a limit-state situa-tion, with the structure undergoing severe damage yet preserving its original configuration, residual stiffness, and resistance to horizon-tal action. Moreover, the concept of repairability is also present in modern codes, in the sense of replacing specific structural parts where the damage is concentrated.

In addition to evaluation of a building's seismic behavior, a few considerations might also be developed in relation to the natural ventilation inside the houses from the Greek tradition. To preserve the main construction material, wood, the historical center of the city of Lefkada was planned in such a way as to facilitate drainage and the natural flow of rainwater to the sea and to take advantage of a frequent wind condition, blowing from north to northwest, which helps to reduce humidity. With reference to studies developed at the National Technical University of Athens (Touliatos 2001; Vintzileou and Touliatos 2004; Tsakanika 2008), it can be observed that this criterion has also been followed at an architectural scale: openings are arranged symmetrically in the plan, and to protect the timber structures at upper levels from humidity, the outer façade is covered with wooden boards; the airflow follows a well-defined path inside the house by linking the porch, staircase, and first-floor veranda, which are suitably arranged to achieve this goal.

Conclusions

The traditional systems discussed present a satisfactory level of effectiveness to withstand earthquake action and, over the centuries, have been able to maintain resistance to seismic events without the aid of additional strengthening systems. Moreover, from the point of view of construction materials, they blend well with the surrounding environment. Such systems, therefore, represent smart solutions in relation to the seismic needs and a starting point for the reassessment of some areas too long considered marginal. Through them, innovative solutions could be designed, inspired by the intrinsic effectiveness of the empirical approach, based on the use of available materials only, but still competitive on the market and able to meet the demands of everyday life. Such issues go beyond the conventional boundaries of architecture or seismic engineering, embracing social and environmental policies and life quality. What is required for the survival of traditional construction techniques is given simply by continuity in the transmission of the knowledge by which they were generated, which is based on the endemic ancestral culture of the place to which they belong.

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