SEISMIC RETROFITTING

Learning from Vernacular Architecture

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Preface

Local communities have adapted for centuries to challenging surroundings, resulting from unforeseen natural hazards. Vernacular architecture reveals often very intelligent responses when adjusting to the environment. So, the questions were: How did local populations prepare their dwellings to face frequent earthquakes? How could seismic retrofitting perseverance be identified in vernacular architecture? It was to respond to this gap in knowledge, that the research project 'Seismic-V: Vernacular Seismic Culture in Portugal' was submitted for approval by the Portuguese National Research Agency FCT. The Foundation for Science and Technology validated the project with an excellent evaluation and funding. The jury panel enhanced the project's outcomes, as an important contribution for the population's safety.

The research project was coordinated by Escola Superior Gallaecia, as project leader, and by the Departments of Civil Engineering at the University of Minho and the University of Aveiro, as partners. Relevant findings and project results were accomplished thanks to a consistent cross-collaboration between the three institutions, which addressed a complementary expertise within the research project.

The fundamental contribution and aims of this publication were to enhance the disciplinary interest in vernacular architecture and its contribution to risk mitigation in responding to Natural Hazards; to encourage academic and scientific research collaboration among different disciplines, while contributing to the improvement of the vernacular architecture, which more than half of the world's population, still inhabits nowadays.

This publication is structured in 6 parts: the first is dedicated to the framework of the research; the second part concerns Local Seismic Culture (LSC) around the world; the third part focusses on the identification of LSC in Portugal; the fourth part is devoted to the LSC assessment by regions, the fifth part concerns the typology performance study related to 3 identified housing typologies; and finally the sixth part, closing the publication, concerns the conclusions of the project and its recommendations.

The emerged findings brought consistent and systematic outcomes, reaching different publics, through different publications and the project's website. The entailed research methodology also emerged as a result of the project, as it could be extrapolated and applied to other contexts, creating further findings. The research revealed the existence of a local seismic culture, in terms of reactive or preventive seismic resistant measures, able to survive, in areas with frequent earthquakes, if properly maintained.

'Seismic retrofitting: learning from vernacular architecture' brings together 43 chapters with new perspectives on seismic retrofitting techniques and relevant data addressing vernacular architecture, an amazing source of knowledge still relevant, in the present world. The publication gathered the contributions of international researchers and experts, invited as key-references in the disciplinary field. 50 authors presented case studies from Latin America, the Mediterranean, eastern Asia and the Himalayas region. There are references to examples from at least 18 countries, on 4 continents. This is the case of Algeria, Bolivia, Bhutan, Chile, China, Egypt, El Salvador, Greece, Haiti, Italy, Japan, Mexico, Morocco, Nepal, Nicaragua, Peru, Romania, Taiwan, and a closer detailed analysis of Portugal.

The research project and this publication were possible thanks to the funding granted by FCT – Foundation for Science and Technology, in the framework of the Portuguese research project Seismic-V (PTDC/ATP-AQI/3934/2012), Scientific Research Projects and Technological Development Program. The research project received the Aegis of the Chair UNESCO – Earthen Architecture | ICOMOS – CIAV | ICOMOS-ISCEAH | PROTERRA Iberian Network and the Institutional support provided by UNIVEUR-Ravello, Italy, and the DRCN – Northern Portugal Regional Directorate for Culture.

To all the authors, collaborators, and consultants that contributed to the research project and to this publication, with quality, consistency and high standards, thank you.

Mariana R. Correia, Paulo B. Lourenço, Humberto Varum
Editors of the publication, July 2015

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Opening remarks

The Escola Superior Gallaecia (ESG) is a university school in architecture and urban design, art and multimedia, located in the north of Portugal. The school is a member of the *UNESCO Chair-Earthen Architecture and Sustainable Development*, since 2005 – one of five European institutions, and of 44 institutions worldwide. Due to achieved results, in 2012, UNESCO Chair agreement with ESG was renewed. This brought a new reflection on the school's scientific research and cooperation, with R&DT having a significant contribution for Gallaecia's strategy and scientific impact.

CI-ESG, Research Centre at ESG (http://www.esg.pt/ciesg/) was then created with 3 main broad scientific research areas: Architecture & Heritage; Urban Design, Territory & Landscape; and Arts & Design. Each includes different fields of study and expertise. In Architecture & Heritage, four specific research areas were identified: Earthen Architecture, Sustainable Architecture, Vernacular Heritage and Military Heritage. Scientific research is addressed through formal projects integrated in financed programmes, but also through consultancy to regional Portuguese authorities, as well as Galician entities, in Spain.

Regarding research projects, the school has submitted and won several projects, funded by national and international research programmes: *One National project*: CATPAP – Architectural and Landscape Heritage Catalogue of Alto Minho region (2004–2006) (http://esgallaecia.inwebonline.net); *Two Iberian project*: CADIVAFOR – Cataloguing, Digitalization and Return of Value to the Defensive Fortresses of the frontier Galiza-North Portugal (2006–2007) (www.cieform.org); Natura Minho-Miño: digital database of the region's landscape (2008–2013); *Three European projects*: "Houses and Cities Built with Earth: Conservation, Significance and Contribution to Urban Quality" (2005–2006); "Terra Incognita – Conservation of European Earthen Architecture" (2006–2007); "Terra Europae – Earthen Architecture in Europe" (2009–2011) (http://culture-terra-incognita.org).

In 2012, two projects were approved with ESG, as project leader: The European project "VerSus – Lessons from Vernacular Heritage to Sustainable Architecture" (2012–2014) (www.esg.pt/versus) and the National FCT scientific project "SEISMIC-V – Vernacular seismic culture in Portugal" (www.esg.pt/ciesg). This was of major importance as it acknowledged the school's expertise to lead projects and to establish new front lines of research. Both research projects had a wide scientific dissemination and relevant data collection for an integrated literature review, through the international conference CIAV 2013 | 7°ATP | VerSus (www.esg.pt/ciav2013), organized in October 2013, by ESG and ICOMOS-CIAV, and held in Vila Nova de Cerveira, Portugal.

Furthermore, since 2005, the university school made an important effort to co-publish and support the edition of twelve books, concerning CI-ESG research (http://www.esg.pt/index.php/en/publicacoes). The increase of financial approval of ESG research projects at national and international level, proved a firm progress, in terms of rigor and quality of results. The strengthening of inter-institutional cooperation and the accomplishment of R&DT findings resulted in an interdisciplinary cooperation with excellent results. The potential of current developments, predict a solid growth of Gallaecia, as a higher education institution at national and international levels.

We renew our commitment for quality and high-standards, towards a scientific, cultural and educational high-level institution.

Mariana Correia
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Escola Superior Gallaecia, Vila Nova de Cerveira, Portugal

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Research project framework

PROJECT IDENTIFICATION

SEISMIC-V: Vernacular Seismic Culture in Portugal

FUNDING ENTITY

FCT – Portuguese Foundation for Science and Technology

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Main Scientific Area: Environment, Territory and Population – Architecture
Project Reference: PTDC/ATP-AQI/3934/2012
Prime Investigator (IP): Mariana Rita Alberto Rosado Correia

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AEGIS

Chair UNESCO – Earthen Architecture, Building Cultures & Sustainable Development
ICOMOS-CIAV – International Council on Monuments and Sites |
International Scientific Committee for Vernacular Architecture
ICOMOS-ISCEAH – International Scientific Committee on Earthen Architectural Heritage
PROTERRA – Iberian-American Network on Earthen Architecture and Construction

INSTITUTIONAL SUPPORT

DRCN – Northern Portugal Regional Directorate for Culture, Portugal
UNIVEUR – European University Centre for Cultural Heritage, Ravello, Italy

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PROJECT LEADER

escola superior gallaecia

Fundação Convento da Orada

PARTNERS

Universidade do Minho

universidade de aveiro

AEGIS

Organisation des Nations Unies pour l'éducation, la science et la culture

uniTwin Chaire UNESCO Architecture de terre

ICOMOS - CIAV International Committee of Vernacular Architecture International Council on Monuments and Sites

ICOMOS - ISCEAH International Scientific Committee on Earthen Architectural Heritage International Council on Monuments and Sites

PRO TERRA

INSTITUTIONAL SUPPORT

GOVERNO DE PORTUGAL
SECRETÁRIO DE ESTADO DA CULTURA

CENTRO UNIVERSITARIO EUROPEO
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Local seismic culture in the Mediterranean region

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ABSTRACT: In contexts of high seismic activity, such as the Mediterranean area, many local communities have developed strategies for managing such a risk, adapting all available resources for creating earthquake-resistant rules, shaping not just a particular building culture, but a complex local seismic culture. Over the centuries, the Mediterranean area has known an unequalled variety of building experiences thanks to the continuous exchanges and the dissemination of innovative solutions. The paper investigates and analyses the contribution of Mediterranean local building culture in the strategies of defence against earthquakes, through their conditions, logic and specific devices. This text presents those technical building devices, which are strictly connected to the local seismic culture, describing the techniques used to reinforce and to absorb horizontally loads in earthen, stone, and brick masonries.

1 REGIONAL SEISMICITY IN THE MEDITERRANEAN CONTEXT

The Mediterranean Basin is a complex environment, where over the centuries widely diverse cultures and communities came into contact, through trade and the exchange of goods and ideas. Indeed the circulation and the mingling of cultures and beliefs have shaped a composite civilization, consisting of tangible as well as immaterial factors, which is deeply rooted in our social and cultural imagination as Mediterranean culture.

Despite of local bioclimatic variations – with outstanding contrasts between the geographical extremities of the Mediterranean area – the territories surrounding the Mediterranean sea share a mild climate, with hot and dry summers, soft and wet winters, and rainy springs and autumns. Two thirds of the lands of the Mediterranean area are constituted of limestone, which characterise the natural landscape, and provides the most widely used building material throughout the Mediterranean area (AA.VV, 2002). The alluvial surfaces of the Mediterranean banks produce instead soil that is rich in clay, which has played many roles and functions in the vernacular architecture: it has been used for the body of the wall (brick or compacted earth), the mortar, and the protection rendering.

The environmental context, the climatic condition and the available resources and materials have influenced the development of building typologies and techniques, which present in all the Mediterranean basin common elements and attributes (i.e. heavyweight fabric, with an high thermal inertia, building types with a simple and compact geometric shape, compact urban fabric, etc.), and an amazing amount of variations, depending on the local environmental cultural and socio-economic characters.

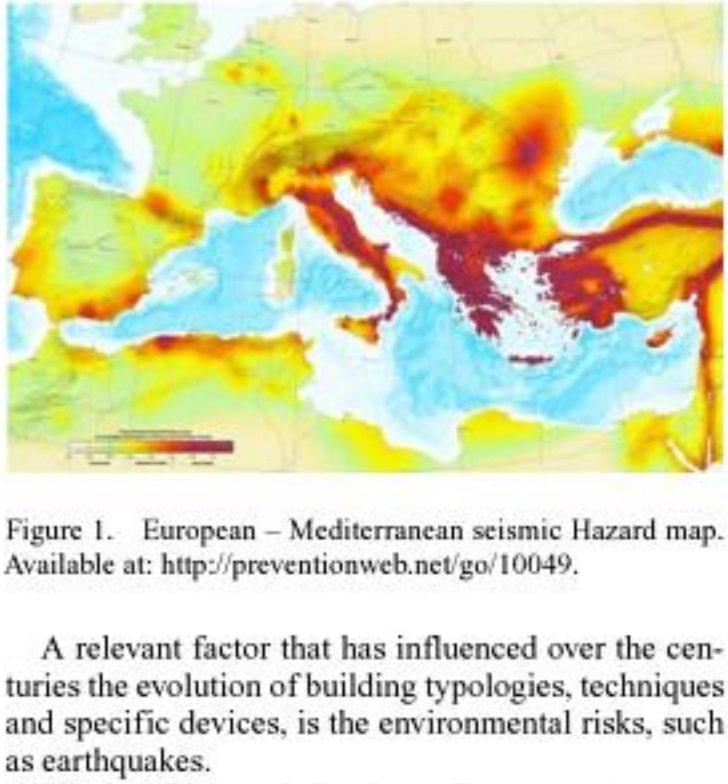


Figure 1. European – Mediterranean seismic Hazard map. Available at: http://preventionweb.net/go/10049.

A relevant factor that has influenced over the centuries the evolution of building typologies, techniques and specific devices, is the environmental risks, such as earthquakes.

North Africa and Southern Europe represent a region, around the Mediterranean, that is often prone to earthquakes. Seismicity in this area is especially due to the interaction along the boundary between the African and Eurasian plates.

Seismic events are not uniformly distributed along these boundaries. The oceanic crust of the Mediterranean basin is divided into two parts by the Italian peninsula, with the western part belonging to the Eurasian plate, and the eastern to the African plate. Typically, earthquakes with moderate magnitudes are widespread in all the area, while large earthquakes take place mostly along the Hellenides, and around the Aegean. Other segments of the boundaries are seismically less active, such as the Tunisian part of

Table 1. List of the larger earthquakes (magnitude >6.5) of the last 300 years (Levent Erel & Adatepe, 2007; Marturano, 2002; Utsu, 2002; USGS, 2012; USGS, 2014).

Year	Location	Casualities	Magnitude
1802	Vrancea region, Moldavia	3 in Bucharest	7,9
1810	Crete, Greece	2.000	7,5
1837	Galilee, Palestine	6.000–7.000	>7
1857	Basilicata, Italy	11.000	6,9
1881	Chios, Turkey	7.886	7.3
1894	Gulf of Izmit, Turkey	1300	7,9
1903	Malazgirt, Muş, Turkey	600	6,7
1903	Southern Greece	NA	8,4
1905	Calabria, Italy	557–5.000	6,7–7,9
1908	Messina, Italy	75.000–200.000	/,1
1909	Provence, France	6000	7,3
1912	Mürefte, Turkey	2800	7,3
1912	Mürefte Tekirdağ, Turkey	216	7,3
1914	Burdur, Turkey	4000	7,0
1915	L'Aquila, Italy	30000+	7,5
1920	Garfagnana, Lunigiana, Italy	171	6.5
1924	Horasan, Erzurum, Turkey	60	6,8
1928	İzmir, Turkey	50	6,5
1930	Irpinia, Italy	1404	6,6
1930	Hakkari, Turkey	2514	7,2–7,5
1932	Ierissos, Greece	491	7,0
1938	Kırşehir, Turkey	160	6,6
1939	Dikili, İzmir, Turkey	60	6,6
1939	Erzincan, Turkey	32.700	7,8
1940	Vrancea, Romania	1000	7,3
1942	Erbaa, Tokat, Turkey	1100	7,3
1943	Ladik, Turkey	4000	7,6
1944	Gerede, Turkey	2790	7,4
1953	Yenice-Gonen, Turkey	1070	7,3
1954	Ionian Islands	31	7,1
1954	Chlef, Algeria	1250	6,8
1954	Spain	NA	7,9
1956	Amorgos Island, Greece	53	7.8
1960	Agadir, Morocco	15000	5,7
1962	Bu'in Zahra, Qazvin, Iran	12225	7,1
1963	Skopje, Macedonia	1100	6,0
1964	Western Turkey	7,0	36
1966	Varto, Turkey	2529	6,8
1967	Mudurnu Valley, Turkey	173	7,3
1968	Western Sicily	231	6,5
1969	Portugal-Morocco area	13	7,8
1970	Gediz, Turkey	1086	6,9
1971	Bingöl, Turkey	1000+	6,9
1975	Eastern Turkey	2300	6,7
1976	Northeastern Italy	1000	6,5
1976	Turkey-Iran border region	5000	7,3
1978	Greece	50	6,6
1980	El Asnam, Algeria	5000	7,7
1980	Southern Italy	2735	6,5
1981	Greece	16	6,8
1983	Erzurum and Kars, Turkey	1342	6,9
1992	Erzican, Turkey	498	6,8
1999	Izmit, Turkey,	17.000+	7.6
1999	Düzce, Turkey	894	7,2
2003	Northern Algeria	2266	6,8
2006	Southern Greece	3	6,7
2011	Van Province, Turkey	604	7,2

Northern Africa, or the boundary between the Mid Atlantic Ridge and the Strait of Gibraltar (Udías, 1985, Vannucci et al, 2004; Marturano, 2002) (Fig. 1). In such regions, affected by frequent and medium to high intensity earthquakes, local communities have developed vernacular strategies to protect themselves from the risk, such as building systems or specific devices that are the result of a natural selection, dictated by the climatic context and locally available materials (Dipasquale et al., 2014).

Seismic vernacular reinforcements in the Mediterranean area are numerous, and often depend on available materials, local building cultures and the skills of the builders. The local seismic cultures include the earthquake-resistant regulations, which have not been formally laid out in written code, but which are still visible in the building characteristics, in the choice of the site, and in the general layout of the territory (Ferrigni et al., 2005).

Table 1 includes the larger earthquakes (magnitude >6.5) of the last 300 years. However, to understand the reason for the development of a seismic culture, seismic episodes of lower intensity should be also considered. In fact, the development and improvement of seismic retrofitting systems in a building culture is not only linked to the intensity of the earthquakes, but also to their recurrence, which is the factor that changes communities' practices and behaviours. Indeed, the origins and persistence of a local seismic culture can be determined, both by the scale of intensity and the frequency with which the earthquakes occur, and the economic and social conditions, including resource availability and the cultural traditions (Ferrigni et al., 2005). In Italy, for instance, violent catastrophic earthquakes have led most of the time to spend all the human and material resources for quick reconstructions (Marturano, 2002). After the disaster, often new seismic code have been improved, but only in few areas – e.g. in Lunigiana and Garfagnana, where earthquakes are endemic – a real seismic culture has been developed. On the other side, in the Balkans or in Turkey, where small and large seismic episodes occur frequently, local communities have developed behaviours and buildings with a good seismic resilience.

2 HISTORICAL SEISMIC RETROFITTING BACKGROUND IN THE MEDITERRANEAN AREA

In the Mediterranean area, amongst the ancient cultures, the Cretan (2000–1200 BC) and Mycenaean (in the 14th century BC) had developed a great sensitivity towards earthquakes. Archaeological excavations have revealed the systematic use of timber elements to reinforce bearing structures of palaces and villas in the Minoan Crete of the late Bronze Age (Tsakanika, 2006). Even if wooden elements have not survived to the present day, their location and dimensions are evidenced by vertical, horizontal or oblique holes in the masonry (Vintzileou, 2011). Another seismic retrofitting device found in the Minoan palace in Crete – which can be considered as an ancient system of seismic isolation – is the predisposition of alternate layers of sand and gravel under the foundation plan, useful to dampen the vibrations transmitted from the ground (Rovero & Tonietti, 2011). The use of timber reinforcement has been revealed by archaeologists as well in Akrotiri (Santorini, Greece): inside the large stone blocks, they found the housings of large pins crossing the rocks to accommodate wooden connecting elements, with the purpose of keeping the various blocks connected, and to give a strong plasticity to the whole structure (Touliatos, 2005).

In Anatolia the technique of timber frame structures with adobe blocks infill is employed from the Late Chalcolithic Age onwards. In general, that use of timber frames and adobe has a long documented tradition in nearly all Anatolia, in Northern Syria and in Egypt; all of them regions with a constant seismic activity (Didem Aktaş, 2011; Lloyd and Müller, 1998).

Wooden frame systems were documented also in many buildings of the ancient Roman Provinces. One of the most ancient examples in Italy of timber-frame reinforced buildings techniques is the *opus craticium* by Vitruvius; today visible in some of the surviving houses of the archaeological sites of Herculaneum and Pompeii (Fig. 2a). The structural grid of the *opus craticium* consists of squared uprights (*arrectarii*, of 8–12 cm per side) and horizontal elements (*trasversarii*, of 6–8 cm in width), arranged so as to form frames of 60 × 70 cm. The connections are made through joints and rivets (Langenbach, 2007).

Furthermore, in ancient Roman building traditions, rows of bricks were set down horizontally, through the conglomerate wall section, functioning, not only to connect and reinforce, but at the same time, serving to interrupt the possible spreading of cracks. This technique is still visible in many stone walls in Italian historic cities (Fig. 2b), and its wide use by the Romans is confirmed by the presence of continuous belts of red bricks in the old stone walls of Istanbul (Langenbach, 2007, Omar Sidik, 2013).

3 SEISMIC-RETROFITTING TECHNIQUES IN MEDITERRANEAN VERNACULAR ARCHITECTURE

3.1 *Masonry reinforcement measures*

In the Mediterranean region the traditional construction technology is commonly based on load-bearing masonry walls.

Masonry buildings are vulnerable to seismic events, since they are constituted by the assembly of heterogeneous elements and materials (such as stones, or earth), whose characteristic is the not tensile strength. The seismic forces are transmitted through the soil at the base of the building, as horizontal actions. These forces give rise to a rotation out of lane, at the base of the wall perpendicular to the direction of the earthquake, which tends to an overturning and a consequent partial or general collapse of the masonry building. If the bonds between the orthogonal walls are effective, the building shows a box-like behaviour: the overturn is avoided, and the horizontal actions are transferred onto the walls in the direction of the earthquake, as shear actions that produce diagonal cracks, primarily distributed along the mortar joints.

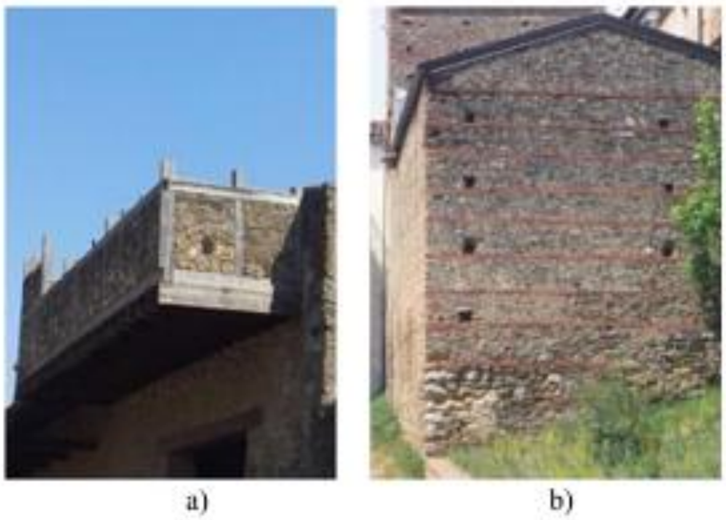

a) b)

Figure 2. Roman Seismic retrofitting in ancient Roman building tradition. a) Opus craticium in Pompei, Regio I Insula XII. b) Random rubble masonry with horizontal layers of bricks, Lamezia (credits: L. Dipasquale).

Under seismic action, in order to avoid the first kind of damage, the structure has to guarantee a box-like behaviour, which can be achieved through the structural and dressing quality of the wall, such as good connections in the corners between perpendicular walls, and effective horizontal tying elements. Indeed certain parts, such as corners, lintels, jambs of openings and base plates, are more solicited than others, and they must better perform. For this reason ashlar blocks or bricks are often used to strengthen the structure in these more solicited parts.

In seismic areas where stone, earth or bricks masonry is the prevalent building technique, the most frequent prevention and/or reinforcement measures consist of adopting the mechanism of mutual contrast between parts of the buildings, to counteract horizontal forces.

The most common traditional devices used with the purpose of contrast and seismic reinforcement in Mediterranean vernacular masonry buildings are described below.

- *Buttresses*, or *counterforts*, are elements used both in vernacular and in monumental architecture in almost all the Mediterranean area. They are made of strong materials, such as brick or stone, and present a rectangular or trapezoidal cross-section. These elements are placed against and embedded to the wall in more stressed areas, to resist the side thrust created by the load on an arch, or a roof. Buttresses can be added to existing walls, or they can be built at the same time as the building, with the purpose of reinforcing corners or walls (Fig. 3). The traditional *loggia*, used mostly in Italy (interesting examples

Figure 3. Buttress of random rubble masonry in Asni, Morocco, and buttress made of ashlar masonry in Naples, Italy (credits: L. Dipasquale).

Figure 4. Loggias in Ischia, Italy (photo: A. Picone).

can be seen in Sicily, the Amalfi coast, Ischia and Procida), in Croatia, and in southern France –, can be seen as an evolution of the buttress system (Ferrigni et al., 2005). It is used as reinforcement at the base of the building, and at the same time it provides a shading space at the entrance of the house

- *Anchor or patress plates* are metal plates connected to a tie rod or bolt, the purpose of which is to assemble the braces of the masonry wall against lateral bowing, holding the exterior wall from bowing out. Tie rods are stretched across the building from wall to wall, creating a horizontal clamping between the outer walls of the building. Anchor plates are made of cast iron, and sometimes of wrought iron or steel, and can be also fixed to the ends of the wooden floor beams (Pierotti & Ulivieri, 2001). The plates are mostly placed at the height of the floors, and are used in brick, stone, rammed earth, adobe or other masonry-based buildings (Fig. 5). There are many different designs of end-plate: square, circle, cross, double C, S or I shaped, etc. The shape is often an element characterising the local building culture. The dimension of the plate is bigger when the masonry is made of less resistant materials, such as earth or of smaller pieces as bricks. Following the 1909's earthquake in Provence, the use of wall tie plates to reinforce building walls on each floor was officially recommended (Ferrigni et al., 2005).
- *Reinforcement, contrast or discharging arches* are stone or bricks masonry arches, set between two opposed buildings separated by a small street or a narrow passage. They allow the transmission of horizontal constraints to the opposite building at the level of the floor. In this way, buildings behave as an ensemble of dynamic blocks, and not as isolated elements. Reinforcements arches are visible in many historical towns situated in seismic areas, where stone and bricks are the prevalent building material (Pierotti & Ulivieri, 2001; Giuliani, 2011) (Fig. 6).

Figure 5. Anchor plates connecting two adjacent buildings in Florence, Italy (credits: L. Dipasquale).

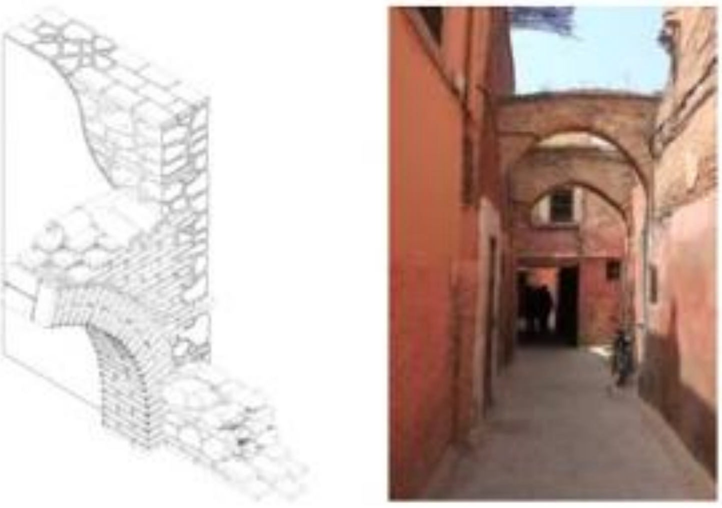


Figure 6. Contrast arch in Marrakech, Morocco (credits: L. Dipasquale).

Figure 7. Vaulted street in Lunigiana, Italy (credits: L. Dipasquale).

Figure 8. External staircase in Sicily and Apulia, Italy (credits: L. Dipasquale).

- *Lowering the centre of gravity.* Several techniques were used to increase the stability of buildings, by concentrating their mass closer to the ground. The most common solution is the use of increasingly lighter materials. The ground floor walls are often made by strong and compact stone (able to resist water pounding the base of the building), heavier and deeper, while the upper floors' walls are thinner, and often made of a combination of lighter elements and materials (in the seismic areas of the western Mediterranean they are generally made of timber, filled with small stones, bricks, or earth blocks). A frequent strategy to lower the centre of gravity of the building is the use of vaulted spaces at the ground floor. An example can be seen in some villages in the Lunigiana region (Italy), where many streets are vaulted, forming a single block with the adjacent buildings (Pierotti & Uliveri, 2001) (Fig. 7). Another example can be found in South-East Sicily, where after the earthquake of 1793, almost all the ground levels of reconstructed buildings have been covered by a masonry vaulted structure, while the intermediate floor structures are made of wood.

Also buttresses and staircases at the base of walls contribute to lower the centre of gravity of the building (Fig. 8).

3.2 *Seismic-retrofitting systems using wooden elements*

The difference between the solution described before and the following, is that the first group of devices aims to counteract horizontal forces; while the systems using wooden reinforcement are developed to metabolise, rather than counteract, these shearing motions, by favouring the deformation of single parts and junctions (Ferrigni et al., 2005). In areas where earthquakes are endemic, the use of wooden elements as seismic-retrofitting is a recurring strategy, and sometimes it defines an architectural typology, which characterises the local building culture.

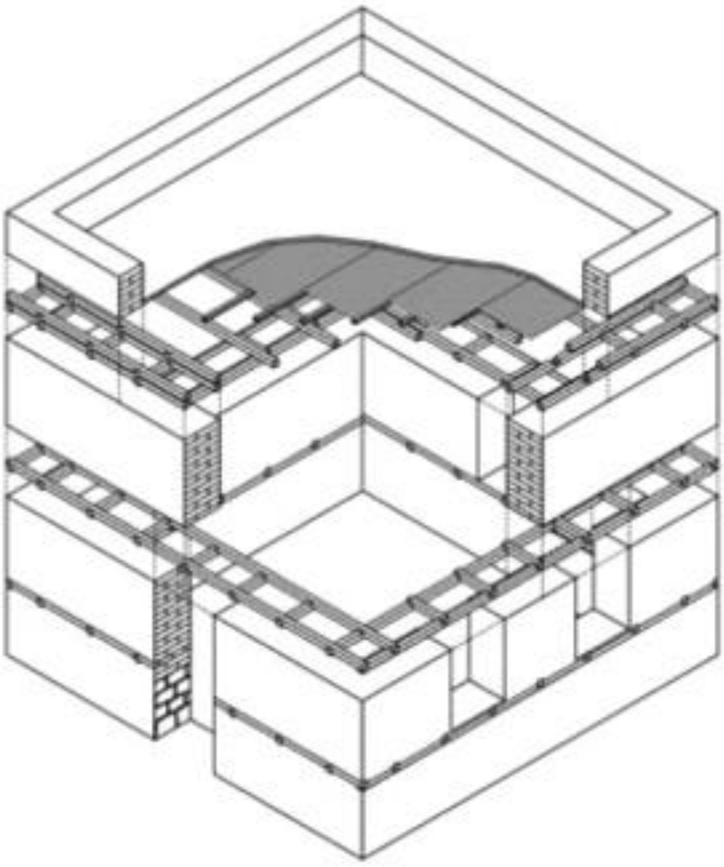


Figure 9. Building structure of hooping wooden system as seismic-retrofitting (credits: D. Omar Sidik).

The great elastic properties of wood, its characteristics of flexibility, lightness and deformability without reaching the breaking point, offers good resistance capacity against horizontal loads, and enables the dissipation of substantial amounts of energy. Moreover, timber elements divide the structure into sections, which prevent the spread of cracks occurring in portions of the masonry. By creating horizontal and vertical connections, wooden devices applied to structures with good compression behaviour (such as stone, adobe or brick masonry), can improve the resistance to shearing, bending and torsion forces. Therefore, in the case of an earthquake, whereas the rubble-stone walls may collapse, the wood is ductile enough to ensure that the building does not, thereby, saving lives (Dipasquale et al., 2015).

There can be various uses of wood as earthquake-proof reinforcement material: timber may be embedded in stone masonry walls to tie the stone units together, reinforce corners or, if braced, offer lateral resistance. Two main categories of systems that use timber structures have been identified: the *hooping* and the *frame systems*.

The first – *hooping*– provides the arrangement of circular or square section wooden beams, horizontally disposed, within the load-bearing masonry during the construction phase (Fig. 9). In many cases two beams are used, one on the inner side of the wall, and the other on the outer; connected by transverse wooden pieces. The empty spaces between the beams are filled with fragments of brick or stone. Interlocking systems of nailing are used for the connections between perpendicular elements. The ring beams can be inserted at the height of the floors, in correspondence to the openings

Figure 10. Two storeys adobe building with timber ties in Kastaneri, Greece (credits: S. Mecca).

and lintels or regularly distributed along the height of the construction, and they could prevent the propagation of a diagonal cracks in the wall during seismic actions.

This system can be found elsewhere in seismic regions in the Mediterranean: from the Balkans to Turkey, the Maghreb and Greece (it was systematically used in houses in Akrotiri on the island of Santorini). In Algeria wooden chaining is also used in the portico of the courtyards, as it can be seen, for example, in the Bey Palace in Algiers, where three beds of acacia logs have been inserted between the capitals and the beginning of the arch structure (Rovero & Tonietti, 2011).

In eastern Anatolia (in the area near Erzurum and Arapgir) runner beams (*hatil*) are aligned with the edges of the walls, at intervals of 50–100 cm, and they are crossed and overlapped at the corner with a scarf joint or half lap joint (Inan, 2014, Langenbach, 2007). In the town of Mut (Southern Turkey) wooden horizontal beams (*köstek)* – are placed every 50–150 cm inside and outside of the 50–75 thick masonry walls. These two beams are bounded with thin smaller wooden elements (Çelebioğlu & Yergün, 2014).

In northern Greece horizontal timber ties are almost always used to reinforce adobe bearing masonry: the ties are spaced at 70–100 cm intervals, passing at the level of the floor, or at the openings (Bei, 2011) (Fig. 10).

This building system has been documented also in Albania: the historical towns of Gjirokastra and Elbasan (fig. 11), for instance, conserve traditional dwellings with limestone bearing masonry, reinforced by horizontal wooden timber ties, located on both sides of the wall, and ensured with a diagonal tie element at the corner (Pompeiano & Merxhani, 2015; Rovero & Tonietti, 2011).

Figure 11. Stone masonry reinforced by horizontal wooden timber ties (credits: L. Rovero).

In Algeria, wood logs of *tuja*, about 2 m in length, are embedded in the masonry thickness at intervals of 80/120 cm. Only in some cases logs are overlapped at the corners, more often they are used to connect adjacent buildings (Omar Sidik, 2013).

The second category of seismic-retrofitting systems using wooden elements includes *wooden frame systems*, which are articulated in round or square section beams and pillars, and frequently, diagonal bracing elements. The constructive system is always based on a grid of wooden poles making the main structure, while infill techniques vary depending on the locally available materials (stones, bricks, adobe, cob, daub or mixed materials).

If the beams are not as long as the entire wall, timbers are connected together through elaborate interlocking systems. In some cases, the longitudinal beams are held together in the thickness of the wall by transverse elements that are wedged or nailed, and the corners present additional reinforcement.

Wooden frame construction systems are widespread, both in rural houses, and townhouses in all the countries that have been subjected to the influence of the Ottoman Empire. The design principles of this building tradition, known worldwide as the Ottoman house, has been well-established as a building tradition since the 16th century in Turkey: from the Western Aegean Region it was successfully applied to a vast area, from Southern Middle Anatolia to the Black Sea Coasts of Romania and Bulgaria, as well as in Macedonia, Bosnia Herzegovina, Croatia and the north of Hungary (Didem Aktas, 2011; Langenbach, 2007).

The Ottoman house is based on the use of masonry laced bearing wall constructions on the ground floor level, and lighter infill-frames for the upper stories (Fig. 12). The intervals between the vertical, horizontal and diagonal timber elements of the upper floors

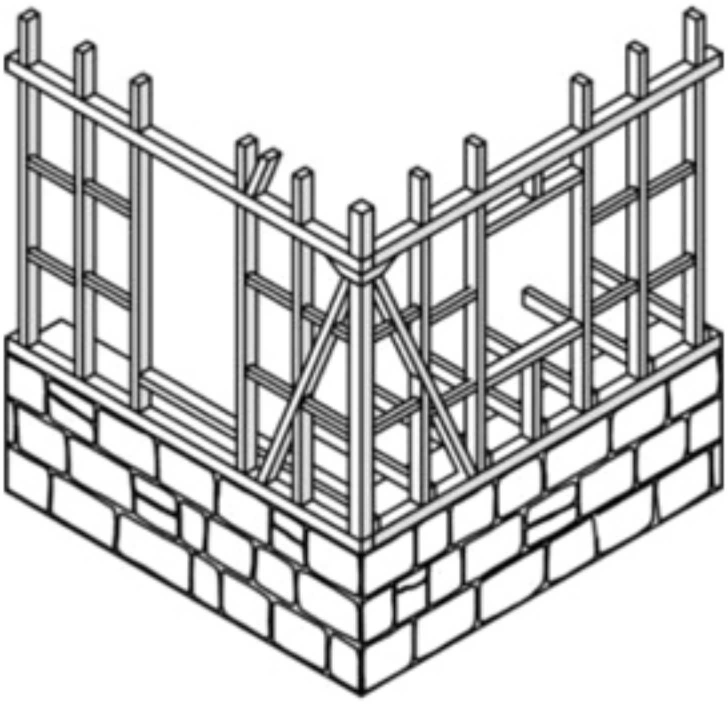


Figure 12. Ottoman house building system (credits: D. Omar Sidik).

Figure 13. *Hımış* building Safranbolu (credits: Uğur Başak).

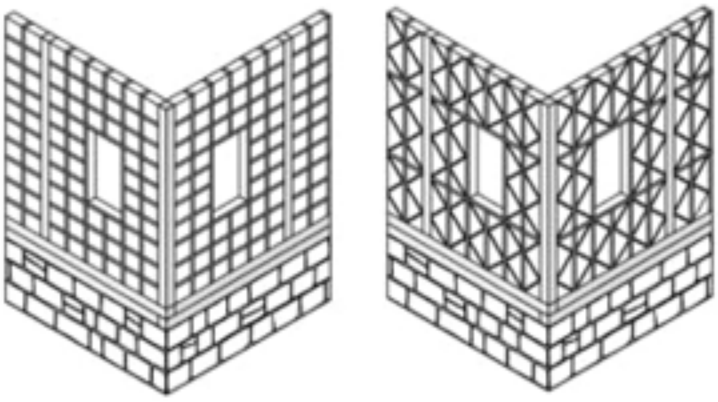


Figure 14. Building structure of *goz dolmas* and *muskali dolma* (credits: D. Omar Sidik).

are filled with bricks, adobe or stone – depending on the material availability of the region–, which are generally set with an earthen mortar. The ground floor masonry walls are often laced with horizontal timbers; these elements can be thin timber boards laid into the wall or squared wooden beams.

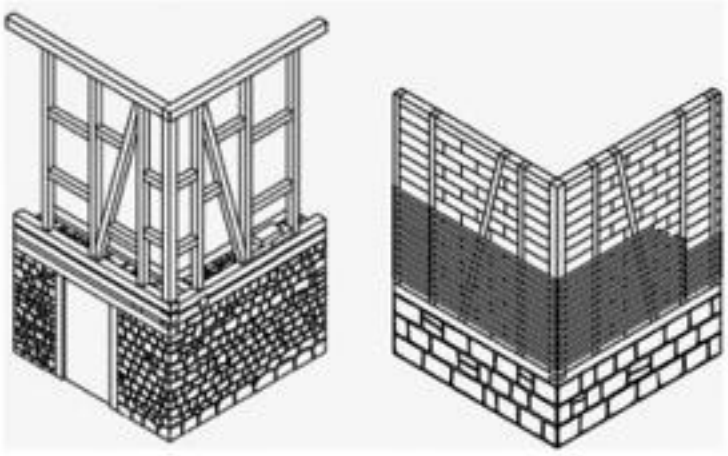
There are numerous reports demonstrating the validity of the Ottoman house as a seismic-proof building system. Many reports are based on observation, made after historical or contemporary earthquakes, and show that such buildings have been more resistant than other construction types, such as reinforced concrete and/or masonry structures (Gulkan, & Langenbach, 2004; Langenbach, 2007, Homan, 2001). Scientific researches have validated the empirical assessment, showing the different performance of structures with different infill materials, and also demonstrating that the location of failure nearly often coincides with the connections. (Aktas et al., 2010; Dikmen & Er Akan, 2005; Didem Aktas, 2011).

Turkish buildings called *hımış*, *bağdadi*, *muskali dolma* and *goz dolmasi*, can be considered as variations of the Ottoman house. All of them have a regular plan, two or three floors; the timber frame is often left in sight; and the upper plans projecting over the ground floor. The substantial differences between these techniques reside in the warping of the frame, as well as in the filling system opted.

The *hımış* timber skeleton, composed of horizontal, vertical elements and diagonal braces, is fastened to the ground floor masonry walls via the wooden beams embedded within the upper part of masonry (Gulkan & Langenbach, 2004) (Fig. 13). The cross-sections of the timber elements are approximately from 9 × 9 to 15 × 15 cm for the main elements, and 5 × 10 cm for the secondary ones. The interval between the studs varies between 50 cm (in Ankara) and 150 m (in North-western Anatolia) (Didem Aktaş, 2011; Omar Sidik, 2013). Diagonal braces were used in a variety of configurations and inclination angles (in North-western Anatolia, the angle is 30 to 45°). A single frame, forming the façade of a room, is the smallest module forming the timber frame section (Didem Aktas, 2011). The walls of the ground floor are generally 50–70 cm thick, and they can be made of rubble stone, cut stone or alternating courses of stone and brick or adobe, with timber lintels (hatıls) at regular intervals (Gulkan & Langenbach, 2004; Tanac Zeren & Karaman, 2015).

Typological variation of the *hımış* house are *muskali dolma* and *goz dolmasi* buildings (Fig. 14), where the secondary elements of the timber structure generate a very dense frame, made of triangular or square hole, of 15–30 cm width, which are filled with little stone or earthen mortar (Fig. 15). These techniques require a large use of wood, which is available in great quantities in the region. The joints between elements are accurately made, without the use of metal connectors (Omar Sidik, 2001).

The *bağdadi* typology consists of light exterior wooden laths, which are nailed onto the timber frame, filled with a mortar of straw and earth, sometimes gravel, and then covered with an external plaster (Dikmen & Er Akan, 2005; Şahin, 1995). This type of construction is typical in northern Greece and in Turkey



Figures 15 and 16. Building structure of *bağdadi* and *bondruk* (credits: D. Omar Sidik).

Figure 17. *Tsatma* structure in Antartiko. (credits: Luca Lupi).

(mostly in Ankara) (Tampone et al. 2011) (Fig. 15). In Lesbos (Greece), and other areas in Greece, it is used for the upper stories of townhouses, which project out over the streets, creating shaded areas (Jerome, 2014).

In Macedonia, timber frame buildings are called *bondruk*, and their structural configuration is comparable to the *himis* house (Namicev & Namiceva, 2014) (Fig. 16). Half-timbered architecture, mostly combined with earth, is also present in the south of Hungary, in the North-West and Central regions of Bulgaria, and in Macedonia, with high-quality architectural form and construction, revealing the influence of the Ottoman building culture (Vegas et al., 2011). In Bulgaria the main timbers consist of horizontal beams (*tabani*), vertical posts (*diretsi* or *mertetsi*) – placed every 60–70 cm, and diagonal braces (*payanti*). The houses are usually rendered and white-washed, so it is difficult to distinguish, at first sight, the material used for the filling (brick, adobe, wattle and clay daub or, rarely, stone).

In northern Greece (regions of west Macedonia), in mid-mountain areas, the second floor, upon the stone bearing walls, is traditionally made with timber framed walls, infilled with adobe, known as *tsatma* (fig. 17).

Figure 18. Building structure of Lefjkada traditional house. (credits: D. Omar Sidik).

The walls had a top layer of earthen plaster, which covers all empty voids (Bei, 2001).

In some Greek islands timber frame was firstly used as reinforcement to repair buildings affected by earthquakes, and only from the 19th century on, has it formed part of the new building structure (Ephessiou et al., 2005).

In the island of Lefkada stone and wood are combined in a unique indigenous dual system, where the timber frame is independent from the masonry, (Karababa & Guthrie, 2007). Buildings have masonry walls on the ground floor, while the upper floors are infilled timber frames; the walls of the upper floor are supported by both the ground wall masonry, and by a secondary structural system (offset at 5–10 cm from the masonry walls), consisting of timber columns, with a typical cross-section between 15 and 20 cm. This secondary system of support – locally called *pontelarisma* – makes the upper floors statically independent from the stone masonry, and it is able to safely sustain vertical loads, in case the masonry is severely damaged owing to a seismic event, giving the time that is necessary for repair or reconstruction of the damaged masonry system (Fig. 18) (Vintzileou, 2011; Ferrigni et al., 2005).

In Italy, the inheritance of the Roman system *Opus Craticium* has been almost lost over the centuries, although there are testimonies of vernacular buildings, widespread in the regions of Basilicata, Campania, Calabria and Sicily until the early 18th century, called *baracca*. These present a wooden frame structure, hidden by the exterior wall covering: this system was the model for designing seismic proof buildings in the phase of reconstruction after the disaster earthquake of 1783 in Calabria. The new building system called *casa baraccata*, designed by Giovanni Vivenzio (Fig. 19), presents a more rigorous architectural scheme, where specific devices act to create solid connections and to develop a good box-like action between all the elements of the building. The system consists of timber

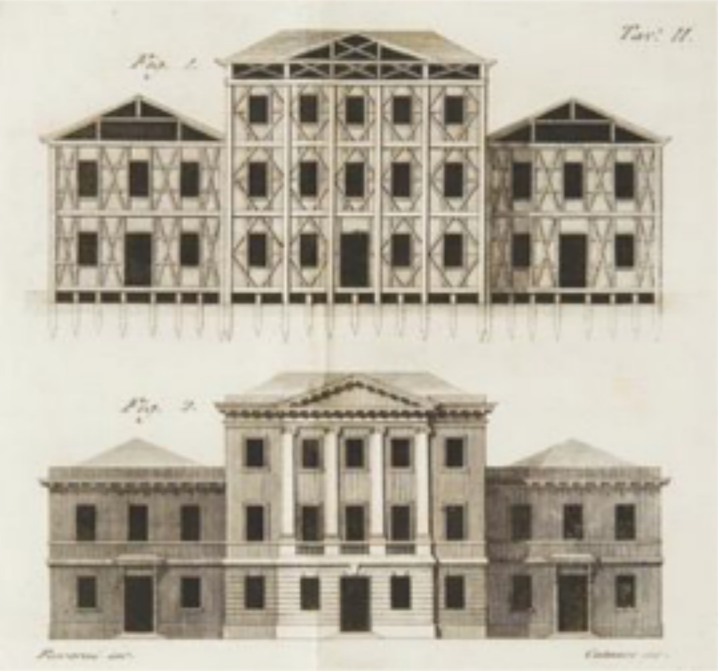


Figure 19. Casa *baraccata* in drawings (credits: Giovanni Vivenzio).

frame structures with stone or adobe infill. The external walled structure is made of straight vertical and horizontal pieces, with a square section of 10–12 cm. The internal load bearing walls include sloping timbers as braces, giving extra support between horizontal or vertical members of the timber frame. The connections between the wooden beams and pillars should take the form of snaps and rivets. The frame elements are covered externally with mortar, thus protected from the deterioration caused by atmospheric agents and by insects (Ruggeri, 1998; Tobriner, 1997; Dipasquale et al., 2015)

The good anti-seismic performance of this system was tested during the earthquakes that struck Calabria in 1905 and 1908: the buildings suffered few significant damages, and limited portions of masonry have collapsed. In the following decades the *baraccata* system has not been implemented with the original rigor, and it often presents insecure timber connections. In the last decades it was definitely abandoned. In 2013, a research conducted by the Italian National Research Council (CNR-Ivalsa) and the University of Calabria, scientifically demonstrated the validity of this building system as an effective seismic resistant solution.

4 CONCLUSION

The built environment of the Mediterranean, characterised by a balance between established tradition and continuous transformation, in an area with a high seismic activity, is a resource of knowledge, from which the scientific community could glean to better assess the seismic vulnerability of the existing buildings, as well as to identify strategies to improve the seismic safety of our building heritage.

Observing the traditional earthquake resistant structures, are understood some common rules that can improve the seismic inertia of the buildings, such as: a good execution of the work, a good connection between the elements of the buildings (walls, floors, roof, façade elements, etc.), a progressive reduction of the weight of materials, from the bottom to the top of the building, devices capable of counteracting horizontal forces, and systems able to increase the ductility of the buildings.

The awareness of the extraordinary quality of many traditional solutions, and the interest in the preservation of this heritage and the building culture, represents essential achievements, through which models for appropriate effective rehabilitations, future sustainable architectures and settlements can be composed.

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