An overview of seismic strengthening techniques traditionally applied in vernacular architecture

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ABSTRACT: Specific architectural elements can be identified in vernacular constructions located in regions frequently exposed to earthquakes. Such elements are the result of a seismic culture which has been empirically developed during centuries so that the vulnerability of the buildings is reduced. This research is based on the fact that vernacular architecture may bear important lessons on hazard mitigation. Traditional earthquake resistant technologies can be successfully applied to preserve and retrofit surviving examples without prejudice for its identity. Few papers have focused on strengthening solutions emerging from vernacular architectural heritage.

Research is particularly focused on case studies in Portugal where traces of Local Seismic Culture have been identified and documented through direct visual inspection, published information and local narratives. The main goal of this study is the identification and understanding of traditional construction solutions and detailing that, in many cases, have shown to improve the seismic performance of vernacular constructions.

Keywords: Seismic strengthening, vernacular architecture, traditional construction, Local Seismic Culture

1 INTRODUCTION

This paper is encompassed within the FCT funded research 'SEISMIC-V: Vernacular seismic culture in Portugal' that aims at the identification of seismic resistant architectural elements and techniques that local population developed to prevent or repair earthquake damage. The focus is on seismic strengthening solutions for and emerged from vernacular architecture [1]. The existence of a Local Seismic Culture was recognized by Ferrigni [2], consisting of a comprehensive application of architectural elements with empirical technical knowledge resulting in an efficient ensemble to reduce the impact of earthquakes [3]. The continuity of traditional building systems and techniques is fundamental for vernacular expression, and essential for its preservation.

This research attempts to verify if Local Seismic Culture has been developed in seismic prone areas in Portugal. An overview of aseismic features and solutions traditionally applied in vernacular architecture in other highly seismic regions of the world is thus relevant in order to confirm this hypothesis. This is the main objective of this paper.

Its significance will contribute to: firstly, understanding the essence of vernacular architecture by illustrating its close relationship with its natural environment; secondly, explaining the factors needed for a seismic culture to arise; thirdly, exemplifying different ways in which local communities react to crises and undertake measures for minimizing earthquake damage; fourthly, explaining the main parameters affecting a structure's seismic vulnerability with examples found in vernacular architecture

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both in Portugal and across the world; and finally, presenting a review of the seismic performance of traditional buildings in large earthquakes.

2 VERNACULAR ARCHITECTURE AND NATURAL ENVIRONMENT

Vernacular construction is always a result of a tight relation between men and environment. When local communities have to erect their buildings and dwellings, satisfying their needs and ambitions, they respond to their surrounding environment and climate through empirical knowledge acquired along generations. This inherited way of building, an accumulation of knowledge, understanding and intuition, has eventually apprehended how to make the best use of the available natural resources.

Vernacular architecture reflects the traditions and life style of a community, and the inhabitants' bonding with the natural environment. It is an architecture intimately associated with a place, the territory and its history. The predominant construction materials are always locally available, conditioned by economic principles intended to save both energy and the effort involved in extracting, transporting and constructing [4]. Indeed, the presence of exogenous materials or techniques indicates specific intentions or concerns and could be a sign of a Local Seismic Culture.

The construction materials traditionally used in vernacular architecture are stone, brick, wood and earth. Their application in a region and their exact use depends therefore on the characteristics of the soil and sub-soil, the proximity to rich forests resources, the available stones in the area and the climatic conditions. As a result and opposite to the current world's homogenizing tendency, vernacular architecture is extremely heterogeneous (Figure 1) and constitutes an invaluable heritage throughout the world worthy of preservation. But also, due to this great variety of building types, work on the built vernacular heritage requires a deep knowledge and investigation of the place, the traditional techniques and materials, and should be cautiously approached in order to undertake a successful intervention [5] [6].

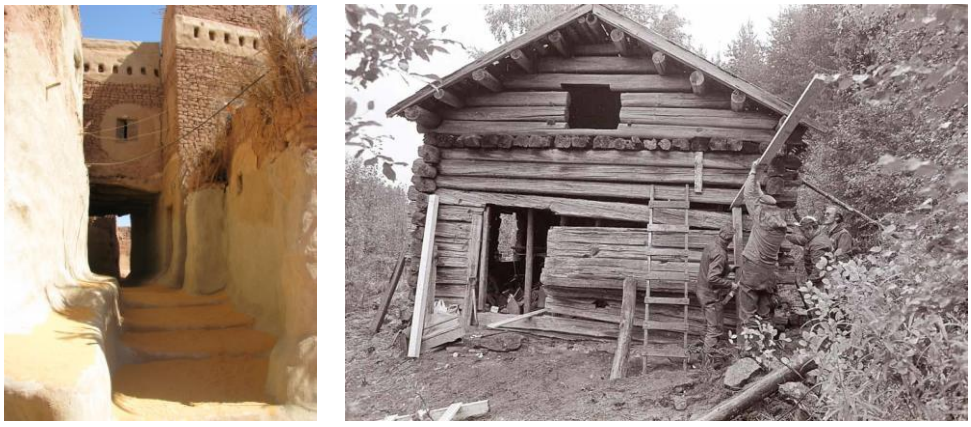


Figure 1. Examples of the adequacy of vernacular architecture to its surrounding natural environment: (left) earthen vernacular architecture in the Egyptian desert [7]; (right) timber vernacular construction in the Norwegian forests [8]

In the case of Portuguese vernacular architecture, there is also a wide variety in construction materials and techniques used in different regions, expressing the geographical and climatic asymmetries of the country [9]. This diversity was thoroughly documented during the fifties, by national enquiries led by the Union of Portuguese Architects, which produced 'Popular Architecture in Portugal' [10]. The important publication highlighted the different spatial and building typologies found across the country. Generally, stone masonry (mainly granite and schist) can be seen in all the regions, but it is more common in the north region of Portugal. Earth (adobe, rammed earth or 'taipa', and wattle and daub or 'tabique') is also widely used in regions like *Estremadura*, *Alentejo* or *Algarve*, where there was easy access to water and clay soils, given the scarcity of stone in these locations. Wood is also present in timber frame walls, with structural elements associated to different typologies, such as 'pombalino' and 'tabique' walls, which indeed have a seismic reinforcement origin.

3 VERNACULAR ARCHITECTURE AND NATURAL HAZARDS

The adaptation of the built vernacular heritage to the environment constraints also includes the natural hazards. Inhabitants are aware of the specific local hazards such as avalanches, flood-prone areas, landslides, hurricanes or earthquakes. Consequently, they have to react to these crises and efforts must be made if the physical community is going to survive, developing a local risk culture [4]. Not all risks have an influence on the building techniques employed or do not produce risk awareness in people, however, in seismic prone areas, the regularity of the event does seem to lead to the development of traditional seismic resistant constructions. It emerges from the need of local communities to respond to earthquakes, either as preventive or reactive measures.

Vernacular building is a continuous process, characterized by its flexibility to adapt to the new functional and formal changes that the community requires. These changes may include earthquake safe features added following a seismic event which has caused damage. Methods proved as dangerous are either abandoned or modified and reconstruction works copy the designs which have withstood the event. Eventually, these aseismic features can take root in the building culture of the region [11].

For a seismic culture to develop, people have to be aware of earthquakes and their effect on the built environment and thus not only the communities subjected to large earthquakes are likely to develop it, but also communities which experience frequent tremors even if of less intensity. The development of a Local Seismic Culture is driven by the intensity and the frequency of registered earthquakes, a certain degree of homogeneity of the seismic history and range of the earthquake Mercalli assessment [12]. Moreover, similarly as they develop, seismic culture can disappear and be abandoned if communities lose awareness of risk and adopt changes in their behavioral patterns because of the loss of the collective memory of past events.

A Local Seismic Culture manifested in construction techniques can be identified in earthquake prone areas in the world such as Italy, Greece, Turkey or Japan. Portugal is classified as a moderate-risk country relative to its vulnerability to earthquakes but several devastating and deadly earthquakes have struck the country throughout its history [1] and it is likely to have earthquake occurrence and damage in the future. In the search for traces of Local Seismic Culture in the country, some seismic prone regions have already been selected because of their seismic history: Lisbon; Benavente and Samora Correia; Alcácer do Sal; Évora; Safara and Sobral da Adiça; and the Azores [12].

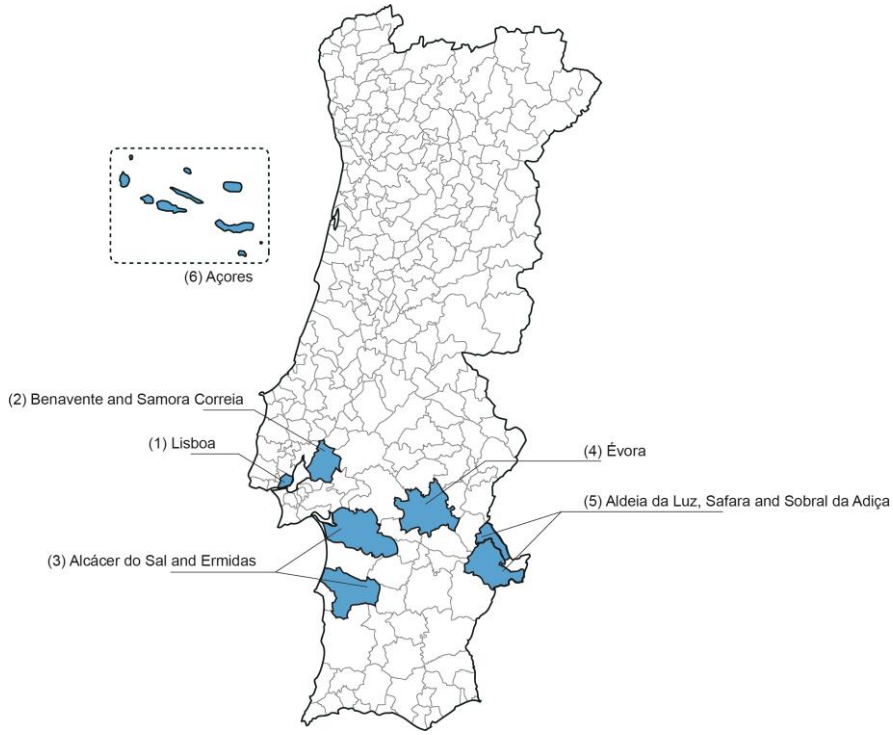


Figure 2. Seismic prone regions in Portugal selected as case studies

4 TRADITIONAL RESPONSES TO EARTHQUAKES

The way as the groups of people react to crises, such as earthquakes, reflects the cultural identity of a community and their relationship with nature. According to Ferrigni et al. [4], there are two main cultural approaches on how communities can undertake measures of consolidation and prevention of the built environment in order to minimize future deaths and damage from earthquake: the flexibility approach and the rigidity approach. The adoption of a specific approach will also depend considerably on the local available materials.

The rigidity approach is based on the use of materials and techniques that are able to resist by themselves to the effect of the horizontal forces induced by an earthquake. The materials, structural elements and connections must be rigid enough to counteract the motion by their ability to absorb the deformation caused by the tremors. On the contrary, the fundamental principle of the flexibility approach is the dissipation of the energy through friction, by allowing some controlled movement and deformation of single parts and junctions.

Some cultures understand earthquakes differently, accepting the destruction and damage caused by them, building structures that can be easily reconstructed and using materials that can be reused. Ferrigni et al. [4] consider that this passive approach is typical of oriental cultures. An example of accepting partial controlled collapse can be found in the Greek island of Lefkas. Here, buildings are constructed with load bearing stone masonry walls. There is also a second structure made in wood independent from the first one. The masonry walls can collapse in the event of an earthquake but the timber structure will continue to stand, so that the walls can be easily and rapidly repaired (Figure 3).

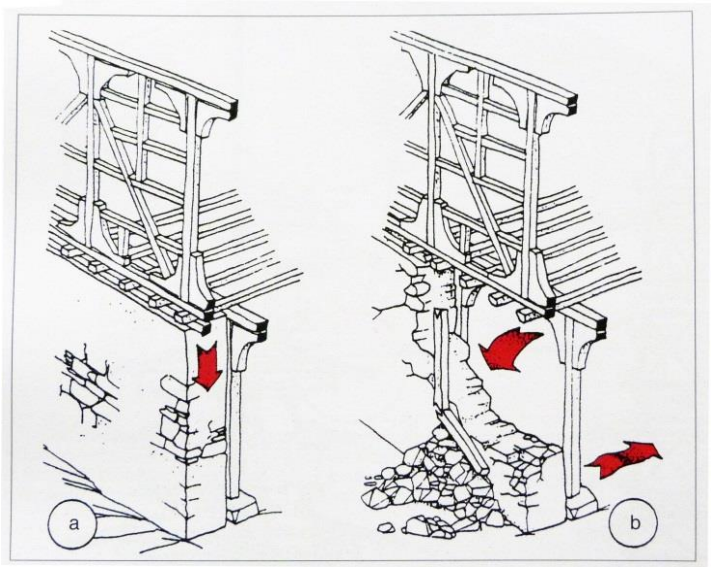


Figure 3. Dual bearing structure in Lefkas, an example of controlled partial collapse [4]

Sometimes earthquake protection regulations are designed and introduced by central governments after an earthquake. The development of these regulations can induce the adoption of the proposed seismic resistant construction techniques by local communities and become endemic in some regions. This happened in Portugal after the destructive 1755 Lisbon earthquake, when a timber frame construction based on the naval experience of Portuguese sailors [13] was implemented in the new city plan. The system, known as ‘Pombalino’, has been widely studied [14] [15] and consists of a resistant and flexible cage structure composed by vertical, horizontal and diagonal timber members filled with light masonry, and used in the interior of each building. Now, examples of ‘pombalino’ construction applied in vernacular architecture can be found in many parts in the country (Figure 4). In Italy, the government introduced a similar system, known as ‘casa baraccata’, after a series of earthquakes in 1783, in Calabria [16]. Now, also wooden interior frames can be observed in many buildings in the region (Figure 4).



Figure 4. (left) 'Pombalino' wall in a house in Alcácer do Sal, Portugal [12]; (right) Internal wall showing the timber frame structure characteristic of the 'casa baraccata' system in Calabria, Italy [16]

5 PARAMETERS AFFECTING SEISMIC VULNERABILITY

In order to detect patterns of Local Seismic Culture, the understanding of the parameters which make a building more vulnerable to earthquakes is necessary to be addressed. Two questions arise: Which are the main causes of earthquake-induced damage? Inadequate structural configuration, inadequate links between structural elements, inadequate resistance, incorrect application or inadequate previous consolidation intervention, etc. What kind of damage is induced due to a poor construction solution regarding the parameters that affect the building's seismic vulnerability? Overturning of the wall, detachment of masonry leaves, oblique cracks and fractures, etc.

5.1. Position within urban fabric

The interaction between buildings has a significant influence in the seismic performance of structures. Different responses to the seismic action by adjacent buildings can cause damage in the connecting points, where stress concentrations are present. Different stiffness of the bodies, for instance, reinforced concrete frame buildings adjacent to masonry houses, has direct implications on the seismic behavior of the structures and a severe risk of hammering can take place. This phenomenon has been reported in many earthquakes, such as L'Aquila earthquake in 2009 [17]. The separation of adjacent buildings by sufficiently wide joints is commonly found in seismic prone countries like Japan.

However, this interaction between buildings can have beneficial effects and even prevent earthquake damage. Buildings can be grouped in such a way as to generate mutual counteractions which they both exert, working as reinforcement to one another. This is possible and more often when buildings were built at the same time. Actually, alterations over time on the urban fabric such as the addition of floors to the existing buildings originate vulnerability in the structures.

Traditional knowledge for earthquake mitigation can be also detected in the urban layout. A regular pattern of large open spaces in the urban structure provides emergency escapes in the event of an earthquake [11] and assures that rescue squads can reach every part of the built-up area.

5.2. Geometry: Plan and elevation configuration

Essentially, regarding shape, what make a building significantly more resistant to the shearing and torsional stress produced by the earthquake are a regular plan and volume, and a symmetrical plan in terms of mass and stiffness. Lacking of shape regularity in plan implies different absorption of the seismic forces due to the eccentricity of the mass center with relation to the stiffness center, enhancing the torsional effects of the earthquake and making the building to twist. Vernacular architecture in seismic areas has therefore usually a simple plan configuration, symmetrical and commonly rectangular (1:2 or similar ratio).

Regularity is equally important in elevation. The lateral stiffness and the mass of the individual stories shall remain constant or decreasing from bottom to top. Discontinuities can cause problems and in seismic resistant constructions are usually avoided. Soft-story ground floors, i.e. much less

stiffer and lighter ground floors, make the building to sway and thus very vulnerable to tremors. Cantilevered or poorly attached protruding structures, such as chimneys or niches are another vulnerable element in the event of an earthquake.

Lowering the center of gravity is a common practice in highly seismic regions, providing greater stability to the structure by concentrating more mass towards the ground. The combination of two different structural systems with the lighter one used on the upper floors is common in Turkey or Greece, where stone and wood are available as local materials. The ground floor is built in stone and wood is used in the upper floors. Decreasing the thickness of the wall or the use of lighter stone masonry in upper floors is a common technique in some masonry constructions in Italy [4].

5.3. Construction solutions and materials

The characterization of the material properties and traditional construction solutions is critical for the understanding of the resisting mechanisms and the seismic behavior of vernacular buildings. A comprehensive study of the geometry, structural solutions and construction materials is fundamental to investigate how these parameters can influence in the seismic performance of vernacular buildings and to detect their structural fragilities.

(a) Wall typology

In the case of masonry construction, the used masonry fabric typology affects the performance of the building under an earthquake. Typologies can differ in the constituent material (stone, brick, adobe, rammed earth, etc.), in the type of masonry used (ashlar range stone masonry, rubble random stone masonry, roughly shaped stone blocks, random bricks, etc.), in the masonry layout (irregular/regular horizontal courses, irregular/regular section, multiple-leaf, lack of connection between faces, etc.), or in the type of mortar used, if any. The quality of the masonry determines the capacity of the building to bear vertical forces and to withstand the horizontal forces resulting from seismic load. As an example of its importance, reference values of the mechanical parameters for different types of masonry are given in the Italian code [18]. Insufficient quality of the type of masonry used and absence of good connection between the leaves can lead to its detachment or to the overturning out-of-plane of part of the wall.

In vernacular seismic-resistant construction, it is usually preferred walls with carefully worked horizontal surfaces combined in such way that the stones are prevented from sliding. Horizontal courses should be respected as well as not-aligned mortar head joints. Parallelepiped-shaped stones or bricks provide better mechanical behavior and the use of through stones, i.e. stiff large stones which cross the entire thickness of the wall and allow the adequate bracing between the leaves, enables the better distribution of efforts through the whole section, which is very effective against horizontal stresses. Another anti-seismic feature can be wall thicknesses that exceed those usually observed in buildings of equal height, erected in the same materials and located in similar climatic environments.

An effective seismic-resistant technique often observed in vernacular buildings is the insertion of wooden horizontal elements in the masonry wall. Stone masonry walls with embedded timber beams can be observed in many highly seismic regions in the world, such as Turkey [19], India [20], Pakistan [21], Macedonia [22] or Italy. The timber beams are usually positioned parallel to walls in both sides, and other timber elements are positioned perpendicularly, linking both beams and creating a ladder like arrangement (Figure 5a). This timber lacing technique ties the wall together, keeping them from spreading and out-of-plane overturning, and also imparts ductility to the system. The capacity for energy dissipation is very high due to the inherently high friction of the system (stone-stone and stone-timber) [20]. In Portugal, horizontal timber elements can also be found inserted in rammed earth walls in some regions, most likely also as a seismic reinforcement (Figure 5c).

Another favorable effect of this technique is the arrest of cracks development within the masonry wall. For this same purpose, horizontal brick bands extended through the walls and subdividing the masonry have been also widely used historically. They can be observed in Italy, in Turkey, in rammed earth construction in Peru [24] and also in Portugal [12].



Figure 5. (5a-left) Timber horizontal elements, known as 'hatil', embedded in a masonry wall in Turkey [19]; (5b-middle) Traditional house with horizontal timber beams in Erzurum, Turkey [19]; (5c-right) Horizontal timber elements embedded in rammed earth wall in Alentejo, Portugal [23]

(b) Floor/rood typology

The use of wooden floors is an historical seismic-resistant building system, aimed at performing two main tasks: first, to connect and to couple the surrounding walls; second, as a flexible horizontal element, to absorb seismic shocks by accommodating the movement of the perimeter walls [25], working as a diaphragm. Proper connections between walls and floors are needed so that the vertical structures do not behave independently and the coupling effect is achieved. Excessive deformability of the floors is counterproductive.

For a long time, reinforced concrete floors, aimed at making the diaphragm more rigid and stronger, substituted wooden floors. Results were detrimental and this alteration caused many collapses in earthquakes, as instead of damping the vibrations and dissipating the energy, the heavy floors increased the horizontal forces and hammered the masonry walls.

Regarding the roofs, low load roofs improve the seismic performance of a building and thus non-thrust light-weight wooden roofs are characteristic of seismic regions constructions, such as Italy [25] or Nepal [26]. Also, roofs contribute to the strength of the building, by linking the walls together, if adequate connections are used.

(c) Construction details: connections

Connections between structural elements are a key aspect for effective seismic-resistant construction. Ensuring the 'box behavior' of a building, where the horizontal forces are absorbed by walls in the same plane, is the most effective measure against earthquakes. However, a full multi-connected box is often very far from reality in vernacular architecture. In many cases, the single walls work separately, having to bear by themselves the portion of load that acts on them.

Improving connections between elements: wall-to-wall, wall-to-floor and wall-to-roof, is a basic seismic strengthening technique. Traditionally, quoins have been used to improve the connections between walls at the corners. The best quality large squared stone blocks were used at the corners to improve the 'box behavior' of the building and preventing the façade to overturn. However, the efficacy of the quoins is limited when coupled with poor fabric or internally unconnected masonry which tends to become loose [17]. Connection to the internal walls can also prevent the global overturning of external walls.

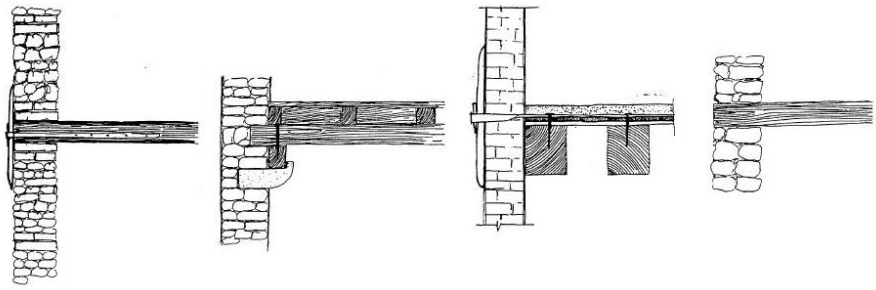


Figure 6. Examples of floor to wall connections in Veneto region, Italy [25]

The improvement of wall to floor and wall to roof connections has been traditionally achieved by the piercing of the masonry wall with wooden floor beams and roof rafters. The empirical solutions to assure a tight connection between walls and floors and walls and roofs were wooden pegs or beams resting on the whole width of the walls. Metal brackets and ties were also applied [25] (Figure 6).

(d) Construction details: joints

In vernacular architecture, the jointing system for wooden elements can also be an effective energy dissipation system. Commonly, flexible housed joints and wedges are used because, while allowing the tightening of the joints, they effectively act as pin joints and allow some movement within the joints. This controlled movement of all the wedges and joints present in the building leads to a good deal of earthquake energy absorption. They are extensively used in traditional buildings in earthquake prone areas, such as India [11], Nepal [26], China [27], Japan, Italy [25] or Turkey [19] (Figure 7).

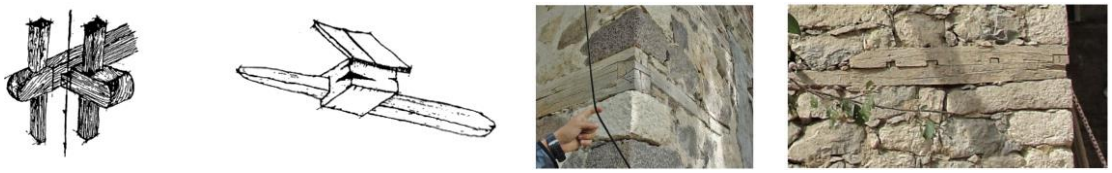


Figure 7. (7a-left) Wedge details in Veneto, Italy [25]; (7b-middle and 7c-right) Corner joint details in Turkey [19]

5.4. Opening characteristics

The presence of openings always indicates a potential vulnerability of the building. Bad positioning, such as openings near the edges, causes stress concentration and cracks to arise. Too many openings, or openings with oversized dimensions lead to excessively slender piers in the masonry wall, which is a weak feature in case of an earthquake. An irregular distribution of openings leads to uneven distribution of stiffness and shear capacity among the piers so that some might be more vulnerable than others [17]. Crack lines often follow the distribution of the façade openings, proving the vulnerability induced by these elements. The presence of openings facilitates in-plane mechanisms to take place and cause shear diagonal cracks, lesions would start from their edges, where a greater concentration of stress is present.

Aseismic vernacular architecture usually presents a reduced number of openings and symmetry in its layout. Closed-up openings can be commonly detected in seismic prone areas, showing the inhabitants' awareness of these elements' vulnerability. The use of relieving or discharging arches over the opening lintels is also usual in these regions in order to better distribute the load path.

Regarding the windows and doors lintels, there is an evident concern in seismic cultures about reinforcing the openings frames. Two methods are usually put in practice: the use of big stone lintels, aimed at promoting enough resistance to bending stresses; the use of a deformable frames, using highly seismic-resistant joints, which preserve the original shape without breaking. If the latter solution is chosen, timber frames are used on both sides of the thick walls, with appropriate linkage [25] [26].

5.5. Strengthening devices

Anti-seismic reinforcement features and post-earthquake repairs are easier to identify. Actions that can be observed are: mended cracks and fractures; devices which enhance the connection between structural elements (ties and reinforcing rings); and construction elements that counteract the horizontal forces in earthquakes (buttresses and reinforcement arches).

(a) Ties

As previously stated, the importance of making effective links between the structural elements in order to ensure the 'box behavior' of the building is critical. Ancient communities were already aware of this fact and, as a result, metal and wooden ties have been applied for a long time as a reinforcement measure in highly seismic regions such as Italy (Figure 8a). This type of strengthening measure has been also widely applied in Portugal in order to improve the structural stability [13] and they can still be observed in many examples of Portuguese vernacular architecture (Figure 8b & 8c).



Figure 8. (8a-left) Metal ties can be easily found all over Italy [17]; (8b-middle) Tie-rods on a gable rammed earth wall in Safara, Portugal [12]; (8c-right) Tie-rods in vernacular building in Melides, Portugal (Photo by CI-ESG, 2013)

(b) Buttresses and other reinforcement elements

Buttresses can be built at the same time as the building, as a deliberated feature, or they can be added on to older masonry, as a reinforcement measure. Buttresses can counter the rotation of the façade thanks to their sheer mass. They can be found again, in most of the highly seismic regions, where masonry is the main construction system, such as Italy, Peru [28] or India [29] (Figure 9a & 9b). In Portugal, buttresses are also common in vernacular architecture, being introduced in earthen constructions to counteract the lateral forces exerted by roofs, arches and vaults [10]. They may also have a seismic concern origin and they can still be found in many vernacular buildings (Figure 9c).



Figure 9. (9a-left) Stone buttress in adobe masonry chapel in Peru [28]; (9b-middle) Rubble stone corner buttress reinforcing the earthen walls of an ancient Buddhist temple in the Western Himalayas in India [29]; (9c-right) Buttress reinforcing a ruined rammed earth vernacular construction in Melides, Portugal (Photo by CI-ESG, 2013)



Figure 10. (10a-left) Counter arch in Lisbon, Portugal [12]; (10b-middle) Counter arch in front of the rose window in Igreja do Espírito Santo, Évora, Portugal [12]; (10c-right) Counter arches in Évora, Portugal [12]

In urban environments, other elements that perform a similar reinforcement task are external stairs, counter arches in between buildings, vaulted passages and loggias. These reinforcement types are very much present in villages built mainly on stone, such as Italians [4], but in Portuguese cities like Lisbon and Évora, many of these features can also be found (Figure 10).

5.6. Maintenance, alterations and previous damage

Another key factor affecting the building seismic vulnerability is maintenance. Generally, a fundamental reason for the vernacular heritage to be so vulnerable to earthquakes is the fact that they are in an advanced state of deterioration, as a result of poor maintenance practice and abandonment. Adoption of modern materials and techniques, together with a sudden rupture of the traditional principles led to the neglect of a huge number of vernacular constructions. Increase in vulnerability is strictly correlated with an increase in the deterioration of the materials and structural elements.

Alterations and inadequate interventions also threaten the still existing heritage. The structural history of the building is very important for its performance under an earthquake. Addition of floors and new parts, and application of strengthening solutions change fundamentally the structural behavior of the original building. Moreover, previously applied strengthening solutions can be questionable and have the opposite of the desired effect, increasing the seismic vulnerability of the building. Experience of the Umbria and Marche earthquake in 1997, for example, proved that previous consolidation interventions were incorrect technical choices and caused many collapses.

The previous damage suffered by a structure has also a big influence on its seismic performance. Existing cracks increase the vulnerability of certain points of the construction but also give hints about its weak parts. A crack and damage survey is therefore important to understand the structural behavior of a building and should be carried out prior to the endeavor of any intervention.

6 PERFORMANCE OF TRADITIONAL BUILDINGS DURING EARTHQUAKES

Experience of many historical earthquakes has confirmed the adequacy and good behavior of several traditional techniques in the event of an earthquake. The examination of the damage pattern after the Armenia earthquake in 1988 [11], showed that destruction was caused mainly to reinforced concrete buildings or buildings of mixed construction (masonry with reinforced concrete). Masonry buildings with timber floors and roofs suffered only slight damage. Seismic-resistant horizontal timber elements embedded in the masonry could be found, as well as timber floors tying the structure and simple volumetric configurations. Traditional timber framed structures with different infill materials in Turkey also showed better performance than new reinforced concrete buildings in the 1999 Marmara Earthquake [30]. In the 1996 earthquake in Lijang, China, traditional buildings remained intact while more modern ones collapsed [11]. During 2005 earthquake in Kashmir, damage on the Indian side of the border was much less, as the performance of the timber-laced traditional construction, which were much frequent on this side, performed very well and presented no, or very little, damage [20].

Nonetheless, vernacular constructions are extremely vulnerable to earthquake damage and they need awareness and protection. The use of poor materials, the scarcity of resources of generally poor communities and the poor maintenance, among other factors previously discussed, highly increase their seismic vulnerability. In any case, emphasis on traditional building techniques is therefore justified because, and opposite to what it may appear, their potential resilience to earthquakes is considerable and worthy to be studied and recognized. Vernacular architecture is an outstanding inheritance from which different architectural solutions can be found. Understanding traditional reinforcement techniques and simple rules for safe earthquake resistant architecture can also prevent people to perceive the buildings where they are living as potentially hazardous. It can also contribute to its successful application to retrofit surviving examples is also respectful to their identity.

7 CONCLUSIONS

To associate changes or innovations in the construction techniques to the existence of a seismic culture is difficult. However, even if they were or not consciously developed to minimize the damages produced by an earthquake, a sort of natural selection of the successful designs that have continually proved to withstand earthquakes have most likely occurred. If something has become traditional is because it must have proved effective in resisting past seismic events in the region and moreover, it can resist seismic events in the future. As a result, a commonality in the use of specific seismic-

resistant features can be observed in highly seismic regions across the world. They usually share similar housing typologies, structural systems and materials. Research in seismic strengthening for vernacular architecture specifically focused in traditional solutions is therefore justified.

After a general overview of these traditional aseismic features and seismic strengthening techniques in the world, it can be concluded that most of these widespread techniques can also be identified in Portugal, even if more scarce or essentially abandoned. This means that there is, or there was, a seismic concern and awareness, and earthquake-resistant techniques have been part of the indigenous knowledge. It is thus appropriate and necessary, for this awareness to be active again, as the appreciation and successful protection of the vernacular heritage depends on the involvement and support of the community, continuing use and maintenance. Thus, to contribute to the awareness of local communities and the dissemination regarding Local Seismic Culture is a must.

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REFERENCES

[1] Correia M., Carlos G., Rocha S., Lourenço P.B., Vasconcelos G., Varum H.: *SEISMIC-V: Vernacular seismic culture in Portugal*, in: *Vernacular Heritage and Earthen Architecture: Contributions for Sustainable Development*, eds. Correia, Carlos & Rocha, Taylor & Francis Group, London 2014, 663-668.

[2] Ferrigni F.: *S. Lorenzello: à la recherche des anomalies qui protègent*, Conseil de l'Europe et Centre Universitaire Européen pour les Biens Culturels, Ravello 1990.

[3] Garnier P.H., Moles O.: *Aléas Naturels, Catastrophes et Développement local. Strategies intégrées de gestion des risqué par le renforcement des dynamiques locales: de la reconstruction vers le prevention*, Cultures Constructives et Développement Durable, CRAterre Editions, Grenoble 2012.

[4] Ferrigni F., Helly B., Mauro A., Mendes Victor L., Pierotti P., Rideaud A., Teves Costa P.: *Ancient Buildings and Earthquakes. The Local Seismic Culture approach: principles, methods, potentialities*, Centro universitario europeo per i beni culturali, Edipuglia srl, Ravello 2005.

[5] Australia ICOMOS: *The Burra Charter. The Charter for the Coservation of Places of Cutural Significance*, Australia ICOMOS, Sydney 1979.

[6] ICOMOS: *Charter on the built vernacular heritage*, ICOMOS, Mexico 1999.

[7] Dabaieh M.: *Back to the future of dying vernacular past. Conservation of Desert Vernacular in Egypt, Practical Study of Balat Village in Dakhla Oasis*, in: *CIAV Annual Meeting and Seminar*, Finnskogen 2010.

[8] Johnson H.: *The Changing of the building traditions among the Forest Finns*, in: *CIAV Annual Meeting and Seminar*, Finnskogen 2010.

[9] Martins L., Vasconcelos G., Lourenço P.B.: *Architectural heritage of the north eastern Portugal: History, construction and valorization*, in: *Vernacular Heritage and Earthen Architecture: Contributions for Sustainable Development*, eds. Correia, Carlos & Rocha, Taylor & Francis Group, London 2014, 325-330.

[10] A.A.P.: *Arquitectura Popular em Portugal*, 3ª ediçao, Associação dos Arquitectos Portugueses, Lisboa 1988.

[11] Jigyasu R.: *Reducing Disaster Vulnerability through Local Knowledge and Capacity. The case of Earthquake Prone Rural Communities in India and Nepal*, PhD Thesis, Norwegian University of Science and Technology, Trodheim 2002.

[12] Correia M., Merten J.: *Report of the Local Seismic Culture in Portugal*, in: *Taversism Project – Atlas of Local Seismic Cultures*, EUCCH, Ravello, Italy 2001.

[13] Pinho F.F.S.: *Paredes de Edifícios Antigos em Portugal*, Laboratorio de Engenharia Civil (LNEC), Lisboa 2000.

[14] Lopes dos Santos V.M.V.: *O Sistema Construtivo Pombalino em Lisboa: em Edifícios Urbanos Agrupados de Habitação Colectiva – Estudo de um Legado Humanista da Segunda Mitade do Séc. XVIII*, PhD Thesis, FAUTL, Lisboa 1994.

[15] Mascarenhas J.M.D.: *Baixa Pombalina, Algumas inovações Técnicas*, in: *2º Encontro Sobre Conservação e Reabilitação de Edifícios, Vol. II*, LNEC, Lisboa 1994.

[16] Tobriner S.: *La Casa Baraccata: earthquake-resistant construction in 18th century Calabria*, The Journal of the Society of Architectural Historians,1983, 131-138.

[17] D'Ayala D., Paganoni S.: *Assessment and analysis of damage in L'Aquila historic city centre after 6th April 2009*, Bulletin of Earthquake Engineering, 2011, 9, 81-104.

[18] Consiglio Superiore dei Lavori Pubblici: *Circolare 02 febbraio 2009 n. 617. Istruzioni per l'applicazione delle "Nuove norme tecniche per le costruzioni" di cui al D.M. 14 genaio 2008*, Gazzetta Ufficiale della Repubblica Italiana n. 47, Supplemento Ordinario n. 27, Roma 2009, C8A.2.

[19] Inan Z.: *Runner beams as a building element of masonry walls in Eastern Anatolia, Turkey*, in: *Vernacular Heritage and Earthen Architecture: Contributions for Sustainable Development*, eds. Correia, Carlos & Rocha, Taylor & Francis Group, London 2014, 721-726.

[20] Langenbach R.: *DON'T TEAR IT DOWN! Preserving the earthquake resistant vernacular architecture of Kashmir*, UNESCO, New Delhi 2009.

[21] Hughes R.: *Cator and Cribbage Construction of Northern Pakistan*, in: *Proc. of the International Conference on the Seismic Performance of Traditional Buildings*, Istanbul, Turkey 2000.

[22] Sumanov L.: *Transfer of knowledge for saving human lives living tradition: Use of traditional horizontal timber belts as anti-seismic elements*, in: *14th ICOMOS General Assembly and International Symposium: 'Place, memory, meaning: preserving the intangible value in monuments and sites'*, Victoria Falls, Zimbabwe 2003.

[23] Correia M.: *Taipa no Alentejo: rammed earth in Alentejo*, Argumentum, Lisboa 2007.

[24] Jurina L., Righetti M.: *Traditional building in Peru*, in: *XVI IIWC International Conference and Symposium*, Florence-Venice-Vicenza 2007.

[25] Barbisan U., Laner F.: *Wooden floors, part of historical anti-seismic building systems*, in: *Earthquakes in the Past. Multidisciplinary Approaches*, eds. E. Boschi, R. Funiciello, E. Guidoboni & A. Rovelli, Annali di Geofisica 38, 1995, 775-784.

[26] Tiwari S.R.: *Traditional Architecture of Kathmandu valley – Responsiveness to earthquakes through empiricism*, in: *Workshop on Seismic Design of Buildings organized by CEC, Institute of Engineering*, Pulchowk, Lalitpur 1998.

[27] Zhiping Z.: *Traditional Buildings of China and their performance in Earthquakes*, in: *Proc. of the International Conference on the Seismic Performance of Traditional Buildings*, Istanbul, Turkey 2000.

[28] Grau P.N., Neumann J.V., Beas M.: *Seismic Retrofitting Guidelines for the Conservation of Doctrinal Chapels on the Oyón Highlands in Peru*, in: *Proceedings of the Getty Seismic Adobe Project 2006 Colloquium*, eds. M. Hardy, C. Cancino & G. Ostergram, The Getty Conservation Institute, Los Angeles, CA 2009, 135-143.

[29] Sikka S., Chaudhry C.: *Research on the Upgrade of Traditional Seismic Retrofits for Ancient Buddhist Temples in the Region of Spiti and Kinnaur in the Western Himalayas*, in: *Proceedings of the Getty Seismic Adobe Project 2006 Colloquium*, eds. M. Hardy, C. Cancino & G. Ostergram, The Getty Conservation Institute, Los Angeles, CA 2009, 109-119.

[30] Gülhan D., Güney I.Ö.: *The Behaviour of Traditional Building Systems Against Earthquake and its Comparison to Reinforced Concrete Systems: Experience of Marmara Earthquake, Damage Assessment Studies in Kocaeli and Sakarya*, in: *Proc. of the International Conference on the Seismic Performance of Traditional Buildings*, Istanbul, Turkey 2000.